Development and evaluation of modulated arc technique for total body irradiation radiotherapy

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Development and evaluation of modulated arc technique for total body irradiation radiotherapy

Master thesis

Master of Advanced Studies in Medical Physics

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Abstract

Total Body Irradiation (TBI) is a type of Radiation Therapy (RT) technique, used for irradiation of the whole patient body. The standard way of TBI is based on static photon beams with more than 3 m long distance between the radiation source and the patient. But it is often not possible in smaller size radiation therapy rooms in many RT centers.

Modulated Arc (mARC) technique for TBI, is one of the techniques to perform TBI with standard linear accelerator in smaller size RT rooms and does not require special equipment. Commercial treatment planning systems (TPS) for RT, at least Varian Eclipse® used in University Hospital Zurich (USZ), does not offer a dedicated planning option for ARC mode TBI.

In this work, a new calculation method for mARC parameters has been developed. It is based on an optimization algorithm from Python 3 library SciPy, calculating the ratio of field weights in mARC, which leads to optimized dose distribution in the patient. Optimization can be customized according to the size of the patient and required dose homogeneity. The method was tested on virtual water phantoms mARC planning in TPS and with confirmative measurement on linear accelerator with long solid water slab phantom. An example of treatment plan in mARC mode was prepared and evaluated using CTs of real TBI patient. The proposed mARC method performed well in the preliminary evaluations, and we can recommend it to be considered for clinical use in TBI therapy in USZ.

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1 Introduction

Total Body Irradiation (TBI) with megavoltage photon beam is a type of external Radiation Therapy (RT) technique, used for irradiation of the whole patient body. It is often used as conditioning regime prior to bone marrow or blood stem cell transplantation to suppress the recipient's immune system and preventing rejection.

TBI represents challenging technical problem, how to deliver a homogeneous dose to so big target, using a standard linear accelerator (linac), dedicated for much smaller target size. The standard method is to use wide static beams with more than 3 m long distance between the radiation source and the patient. But it is often not possible in smaller size radiation therapy rooms in many RT centers. With improving RT technology in the last decades, several other alternative TBI techniques have been developed to overcome this limitation and could be used in smaller RT rooms with standard linac.

In Radiation oncology department at University Hospital in Zurich (USZ), TBI therapy is based on the translation couch technique. TBI patient is lying on a special motorized couch translating the patient through a static photon beam of standard linac. For the case of potential technical failure of the motorized couch, the backup treatment plan, in form of several static beams with manual patient repositioning on the couch, is always prepared for the actual patient. There is the idea, that the modulated ARC technique could be used as a replacement for the actual translation technique.

Modulated ARC (mARC) technique for TBI therapy is an alternative way to perform TBI with standard linear accelerators in smaller RT rooms. The patient is lying on a couch close to the floor under the linac gantry, irradiating the whole patient body in ARC mode. To deliver a homogeneous dose to the whole patient body, the beam intensity must be modulated with changing gantry angle. Commercial treatment planning systems (TPS) for RT, at least for example widespread Varian Eclipse®, does not offer a dedicated planning option for ARC TBI. Therefore, treatment planning and modulated ARC optimization are performed differently in each RT center, where the mARC technique is used.

The aim of this work was to perform a preliminary evaluation of the mARC TBI technique in the conditions of RT department in USZ. The new mARC optimization method was developed, results for phantom models evaluated and tested on one real TBI patient treatment plan in the TPS.

2 Background

2.1 TBI indications and treatment regimes

Total body irradiation (TBI) with megavoltage photon beams is one component used in treating several diseases, including multiple myeloma, leukemias, lymphomas, and some solid tumors. In combination with chemotherapy, TBI is most commonly used as part of the conditioning regimen before hematopoietic stem cell transplantation. TBI provides a uniform dose of radiation to the entire body, penetrating areas such as the central nervous system (CNS) and testes, where traditional chemotherapy is ineffective. Additionally, it allows tailoring of the therapy with the ability to shield or boost the dose to certain regions as necessary. The purpose of TBI is threefold: to eliminate residual cancer cells, to provide space for stem cell engraftment through bone marrow depletion, and to prevent rejection of donor stem cells through immunosuppression. (Wills, 2016)

Total dose and fractionation regimes can differ, but the overall trend of radiation regimes is prescribed total dose (D_0) of 10 - 14 Gy to central midline of the patient body (with dose reference point usually at midline level under umbilicus), delivered in 4 - 6 fractions, at 1 - 2 fractions per day. Dose homogeneity requirement is in range ±10% of the D_0 at all depths in the patient body, although extremities and some non-critical structures may exceed this specification. Generally lower dose rates around 6 to 15 cGy/min and dose reduction to sensitive organs as lungs and kidneys is recommended to reduce the risk of developing interstitial pneumonitis, or renal failure. Most centers keep the mean lung doses at 80% - 85% of D_0. (Peters, 2015) (Khan, 2014)

2.2 Basic physics of TBI

TBI therapy is prescribed to patients with a wide variety of physical dimensions – from small children to adult patients, thus resulting in RT target size in the range 1 – 2 m in length and about 10 – 30 cm in anterior-posterior AP or up to 50 cm in lateral body thickness. Photon radiation is attenuated exponentially with the thickness of the medium, and the attenuation rate decrease with increasing of the photon beam energy. To get similar radiation dose levels through all depths and on both sides of a patient's body, photon beams of energy high enough to penetrate through the patient body at its maximal thickness must be used. To compensate for attenuation along the beam path, at least two opposing beams are used. Cobalt–60 beams were used in the early days to deliver TBI, but nowadays standard linear accelerator (linac) offers a

better choice of the photon beam energy and dose rate. The choice of photon beam energy is determined by the patient's thickness and the limits of dose uniformity. Variations in the patient body thickness and different beam paths length (changing with distance from diverging photon beam central axis in the body) are geometrical parameters affecting the dose distribution. Generally, the thicker is the patient, the higher is the beam energy required to produce acceptable dose uniformity for parallel opposed fields and generally. The higher the beam energy, the greater is the dose uniformity for patients of any thickness.

Another geometrical factor significantly influencing dose distribution is the source to surface distance (SSD). The intensity of diverging photon beam from a point source is inversely related to the square of the distance from the source, referred to as an inverse square law, and is valid regardless of the beam energy. The longer is the SSD, the smaller is the beam intensity difference along its way through the patient thickness and the better is the dose distribution in the patient in longitudinal and lateral directions.

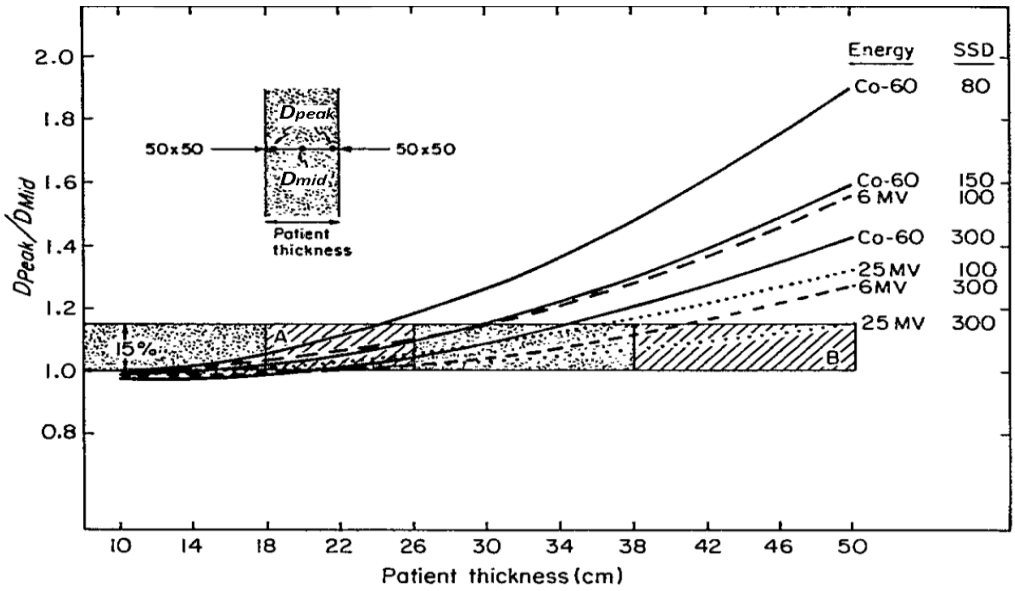


Figure 2.2-1: Ratio of maximum dose to midplane dose (D_{peak}/D_{mid}) on the beam central axis versus patient thickness and photon beam energy with different SSD. The horizontal shaded region represents a 15% spread in this ratio. Cross hatched region A represents the typical range of adult patient diameters in the anterior-posterior direction while cross hatched region B represents the range of adult patient diameters in the lateral beam direction. Beam energy in combination with different SSD (in cm) has strong influence on the dose distribution. From (VanDyk, 1986)

Figure 2.2-1 shows dose distribution, depending on beam energy and SSD. If the maximum thickness of the patient parallel to the beam central axis is less than 35 cm and SSD is at least

300 cm, a 6-MV beam can be used for parallel opposed TBI fields without increasing the peripheral dose to greater than 10% of the midline dose. For patients with thickness greater than 35 cm, energies higher than 6 MV should be used to minimize the maximum dose to midplane dose ratio. (Khan, 2014).

Photon beam energy has the main influence on distance z_{max} of the dose maximum D_{max} under the patient skin, due to the dose buildup effect. The higher is the beam energy, the longer is z_{max} and the lower is the relative dose at the surface. Other factors affecting z_{max} are, increasing SSD increases z_{max}, and z_{max} decreases with increasing beam angle relative to the surface perpendicular. Approximate values of photon beam z_{max} in water are: 0.5 cm for Co-60 (1.25 MV), 1.5 cm for 6 MV, 2.5 cm for 10 MV, 3.5 for 18 MV (Podgorsak, 2005). Skin sparing based on the dose buildup effect is usually unwanted in TBI. Large spoiler screen from 1 – 2 cm thick optically transparent Plexiglas (PMMA, acrylic material) positioned close to the patient body is used to increase surface dose and usually allows also mounting of shielding compensators.

2.3 TBI delivery techniques

Limitations and requirements for TBI in practice

Not all RT centers are providing TBI therapy. It is logical considering that the number of TBI patients is only a very small fraction of the amount of all RT patients. Furthermore, TBI treatment often requires special equipment, treatment procedures, and an experienced team. TBI patients are treated mainly using standard linac and the used technique is dependent on local resources, conditions, experience, or preferences of RT teams. There is a high degree of variation between RT centers in how TBI is prescribed and delivered. (Studinsky, 2017)

Probably the most used and simple method of TBI delivery is the irradiation of the whole patient's body by a wide beam with large SSD from opposing sides. Typical linac as radiation source provides relative flat radiation beam with maximum field of view (FOV) circa 40 × 40 cm^2 in 1 m distance from the source. To cover adult patient in standing or lying position by the beam requires the patient to be placed in at least 3 m source to skin distance (SSD). Using longer SSD (3 - 5 m) is further minimizing dose inhomogeneity due to inverse square law, and reduces the beam path length and attenuation increase with distance from the central beam axis in the patient body. But in conditions of many standard RT treatment rooms, it is not possible to use SSD > 3 m, and so other TBI techniques have been developed for limited SSD conditions.

Another requirement is the possibility of controlled dose reduction to sensitive organs. This is often solved by placing custom-shaped lead or Cerrobend blocks to cover the patient organs (lungs, kidneys, or brain) close to the patient skin. Patient CT image is needed for calculation of the block thickness and customized shaping in the planning process. Patient positioning setup should allow precise compensator placing, confirmed with x-ray imaging. Due to the low dose rate, TBI fractions takes relative long time, requiring patient immobilization for about 10 – 20 min. in one position, plus time needed to correct shielding blocks placing, what can be problematic for some patients, especially when their physical conditions are worsening during days of TBI treatment. Patient comfort and ability to keep the required position for a long time and reproducibility of correct block placing are considered factors influencing the final effectivity of used TBI technique.

2.3.1 TBI using static field and large SSD

Irradiation with opposing static beams in large SSD has been for long time the most common way to perform TBI. Patients are fully covered by wide fields in anterior-posterior/posterior-anterior (AP/PA), or in bilateral direction. Usually, one beam source is used and the patient is rotated 180º to get dose from both sides during each fraction. Patients are treated in upright standing, semi-sitting, or lying on a couch position. Schematic representation of techniques and the patient positioning is on Figure 2.3-1. Extended SSD > 3 m is used usually with the collimator in 45º diagonal position to cover the whole patient's body in one beam. After irradiation from one side, the patient is irradiated from the opposing side. TBI in AP/PA position has more advantages – a patient thickness in AP/PA is smaller than in lateral direction, resulting in better dose distribution and this position also allows more practical and precise positioning of shielding compensators. Thickness variations of the body parts – head, legs, neck, head vs pelvis in the case of bilateral TBI position is often compensated using additional compensators. The advantage of bilateral positioning could be in the more comfortable position for patients during relatively long (10 – 20 min) irradiation times in one fixed position as a patient weakness is in common occurrence due to the combined toxicity of TBI and chemotherapy. (Rusu, 2013)

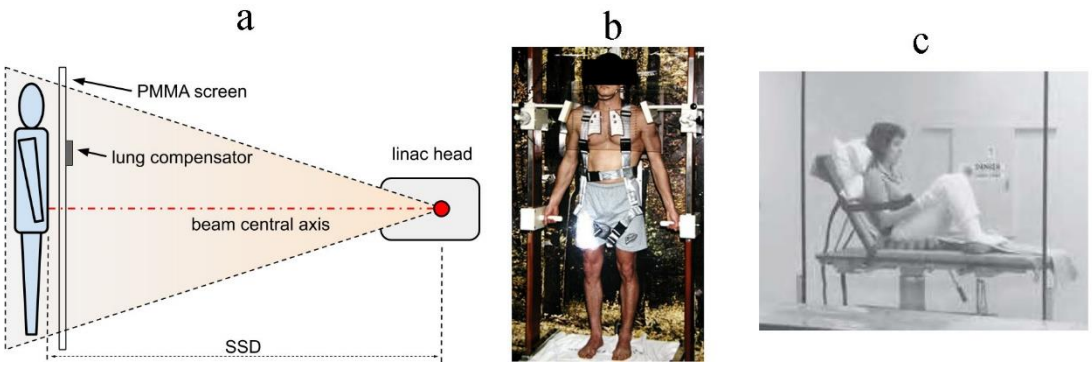


Figure 2.3-1: TBI techniques based on static beams with extended SSD. a) Scheme of TBI with standing patient and AP/PA opposing beams irradiation. Extended SSD > 3 m are usually used. b) Patient standing in special construction for AP/PA position TBI which provides patient support and immobilization, with plexiglass screen with attached lung compensators, from (Wong, 2018). c) Patient sitting in semifetal position on TBI couch for bilateral technique, from (Khan, 2014)

2.3.2 Translational couch technique

In this technique patients lie on the couch in supine and prone positions and are transported through a beam under the linac gantry in 0º position. The technique scheme is in Figure 2.3-2. It is a common solution of TBI in RT centers where static fields with long SSD are not available. Dose to the patient is determined by the couch velocity, which is calculated with respect to physical parameters such as the patient's dimensions, beam geometry, and the dose rate. In treatment settings with only constant couch speed, determined usually by the patient thickness at umbilicus level, overdosing of less thick body parts, like knee, ankle, and neck are common (Sarfaraz, 2001), but it can be reduced by equalizing the thickness differences using bolus pillows. Improved solution is using couch with variable velocity during the treatment, varying according to the thickness of the body part actually under the beam, when uniform dose distribution, with an average deviation of less than 1% at mid-plane can be delivered (Chrétien, 2000).

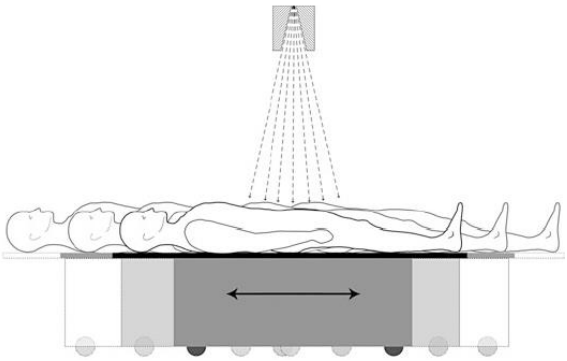


Figure 2.3-2: Schematic illustration of TBI with translational couch.

The advantages of the technique are for patients comfortable lying positions and more precise and reproducible placement of shielding compensators, which can be placed directly on the patient skin. Shielded organs (e.g. kidneys) remain in the lying patient closer to the planning

CT situation than if the patient is in a standing position. Disadvantages are in the need of special equipment - the motorized couch with controlled speed with the driver interface connected to the treatment linac, and more challenging dosimetry due to moving couch. Direct compensators placing at the patient skin minimizes the penumbra, but moving couch brings opposing effect, what should be considered in the compensator design. This technique, with static couch speed, is also used for TBI treatment in University Hospital Zurich.

2.3.3 Sweeping beam and modulated ARC techniques

The basic principle of these techniques is irradiation of the patient lying on a couch close to the floor (to maximize SSD), in prone and supine position under a linac gantry, which is rotating over the patient with continuous sweeping beam, resp. in ARC mode, irradiating the whole patient body from AP/PA directions in one gantry rotation, as is illustrated in Figure 2.3-3. Comfortable prone and supine positions allow compensators placing directly to the skin, or on the beam spoiler.

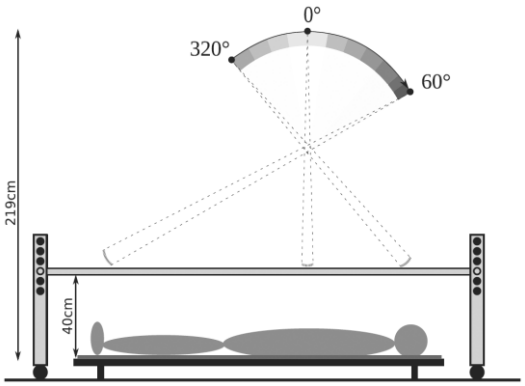


Figure 2.3-3: Illustration of an ARC TBI, with beam spoiler screen above the patient. From (Jahnke, 2014)

One of the first reported sweeping beam technique was based on for TBI dedicated linac with gantry rotating around the axis close to the source, and with extended SSD = 190 cm. The geometry of this setup allowed to use unmodulated 4 MV photon beam with constant intensity during rotation, with the dose to the patient midline with tolerance ±5% of D_0 (Pla, 1983). But common linac gantry rotates around its isocenter in 1 m distance from the source, what leads to higher ranges of SSDs and angles between the beam and the patient during the gantry rotation. To compensate for changes in the beam intensity due to inverse square law and changes of beam path length in the patient, the beam intensity, resp. photons fluence output must be modulated during the gantry rotation in ARC mode. The range of the gantry rotation and optimal beam intensity modulation depend on FOV size, setup geometry, and the patient dimensions. Several methods of beam intensity

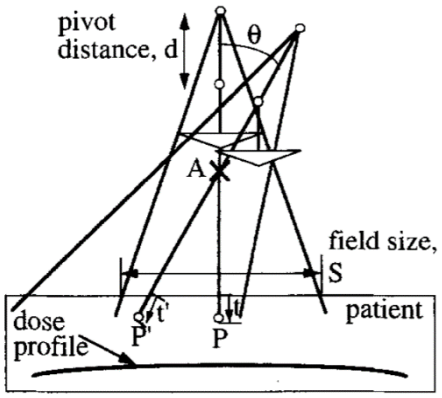


Figure 2.3-4: Scheme of a gravity oriented compensator. From (Chui, 1997)

modulation have been reported. Probably the oldest is the method developed by Chui et al., (1997) based on gravity - oriented compensator of triangular shape, attached to wedge mounting on the linac head, in the way that the apex is always pointing downwards. As the gantry rotates to the side from the vertical position, the beam goes through progressively thinner parts of the compensator. Beam intensity is so continuously modulated through the ARC resulting in more flat dose distribution at the target horizontal level, as illustrated in Figure 2.3-4. Authors reported dose uniformity of ±5% D_0 at 10 cm depth in a flat polystyrene phantom in distance ±90 cm from the phantom center, for FOV of 40 x 40 cm^2 and 6 – 18 MV photon beams.

In the last decade, there have been reported more clinical implementations of the ARC TBI working without the need of special equipment, based on the dynamic change of the actual dose rate, resp. linac monitor units per degree (MU/1º) in dependence on actual gantry angle during the ARC mode irradiation. But not all common RT treatment planning systems (e.g. actual versions of Varian Eclipse®) include option dedicated for modulated ARC TBI technique with extended SSD, so optimal plan settings must be calculated in another way. Manual calculation of optimal beam intensities in MU/1º for individual fields of the ARC, based on analytical fit of geometrical factors: inverse square law and primary beam attenuation on path in RW3 phantom was used by Jahnke et al., (2014). The ARC covering length of 200 cm was divided into 10 fields with FOV 10 x 40 cm^2 (Figure 2.3-3, Table 2-1). The field weight *wf(α)*, resp. fluence output in MU/1º of each field was calculated as the ratio of the radiation intensities I_0 of 0º field to the intensity $I(\alpha)$ of field with angle α, according to the Equation 2.3-1 where $p(\alpha)$ is the distance the beam has to travel through the phantom to reach its midline level, $s(a)$ distance in beam spoiler, μ_p, μ_s corresponding attenuation coefficients of the materials, the initial intensity is and $r(0º)$ and $r(\alpha)$ the radii at

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

Equation 2.3-1: Field weight *wf(α)* calculation formula from (Jahnke, 2014)

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

Table 2-1: Intensities of the fields of the modulated ARC for phantom thickness of 16 cm: Arc16, and 20 cm: Arc20, from (Jahnke, 2014)

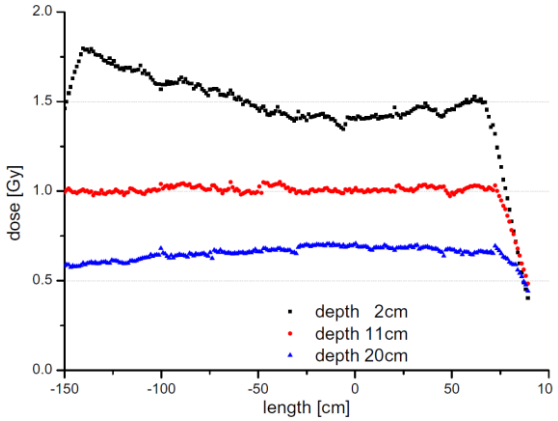


Figure 2.3-5: Film dose profiles for arc20 in a 22 cm phantom at a depth of 2, 11 and 20 cm. From (Jahnke, 2014)

gantry angle 0º and α. (it is not explicitly explained in the article how $r(\alpha)$ were determined). Midline dose profiles flatness in phantoms of 14 – 24 cm thickness were measured experimentally, with reported flatness in acceptable range below 10% in all thicknesses and the technique was implemented in local clinical practice. Further improvement of the technique by the same group was reported a year later, when total irradiation time, resp. total MUs for the modulated ARC were decreased using wider FOV with 40 × 40 cm^2 size and midline dose flatness was improved by dividing the ARC into smaller fields with 5º angle steps (Polednik, 2015). The authors first measured dose profiles of each field of unmodulated ARC at the phantoms, after dose profile optimization was performed manually by varying the weighting factors of the fields. Measured dose profiles of such optimized modulated ARCs for solid water phantoms of thickness 18 and 28 cm with this modulated 6 MV ARC technique are shown in Figure 2.3-6. From their reported results: for 18 cm thick phantom: mean dose at midline / surface = 98.8% / 102.5%, and for 28 cm: midline / surface = 95.9% / 111.9%, averaged over central 200 cm length. According to the authors, this approach is acceptable for a patient of diameter up to 28 cm, when over the length of the torso the dose homogeneity is within required limits of the AAPM TG17 (VanDyk, 1986) recommendation. But there is not (in a reproducible way) described the calculation method of the field weights of the modulated ARCs, and their values are not published in the article.

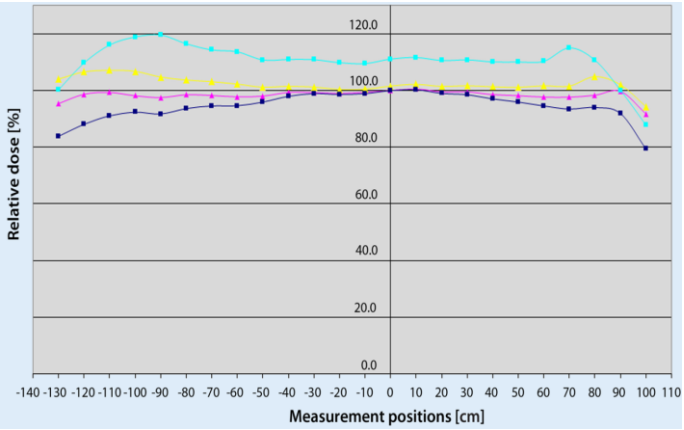


Figure 2.3-6: Cumulative measured dose profiles of modulated ARC, for phantom thickness 18 cm: pink = midline, yellow = surface (2 cm depth), and thickness 28 cm: blue = midline, turquoise = surface (2 cm depth). From (Polednik, 2015)

Modulated arc TBI technique "MATBI", optimized for individual patient and based on inverse planning in Pinnacle^3 commercial TPS was described by Kirby, (2012). The treatment planning starts with full patient CT, the modulated ARCs individual for AP and PA deliveries, are divided into static fields with 5º angle steps and FOV 40 x 40 cm^2 and optimal MUs/field are calculated in the TPS in the way to optimize the volume of the body within 10% of the prescription dose.

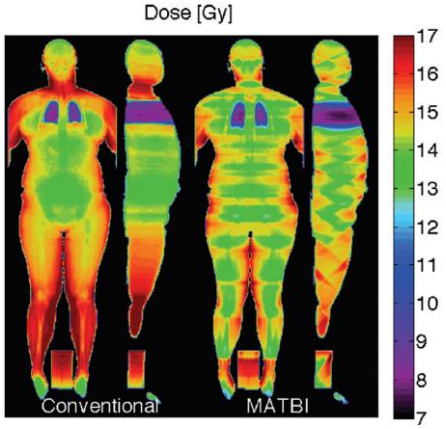


Figure 2.3-7: Dose distribution in conventional long SSD TBI vs MATBI, prescribed dose was 13.5 Gy. From (Kirby, 2012).

Sensitive organs are shielded by Cerrobend compensators placed on the skin. MATBI technique delivers a more homogeneous dose than previously used long SSD static beam AP/PA TBI in the local department, as is visualized in Figure 2.3-7.

Modulated ARC TBI technique with incorporation of volumetrically modulated arc treatment (VMAT) using inverse optimized multi-leaf collimator (MLC) to shield organs at risk, was recently developed and to clinical practice implemented by Pierce et al., (2019). They used the modulated ARC optimization method as described above (Equation 2.3-1) from (Jahnke, 2014), centered on the umbilicus of a patient lying in prone/supine positions on a customized couch under the linac gantry in SSD = 175 cm, FOV = 10 x 40 cm^2. With inverse MLC planning on the commercial TPS (Varian Eclipse) optimizer based on the patient CT, it is possible to spare lungs and improve overall dose distribution. Dosimetric measurements at extended SSD matched closely with predicted data from the TPS (Figure 2.3-8c). This way of TBI without the need for manufacturing and positioning of customized shielding compensators is robust and patient sensitive (Pierce, 2019).

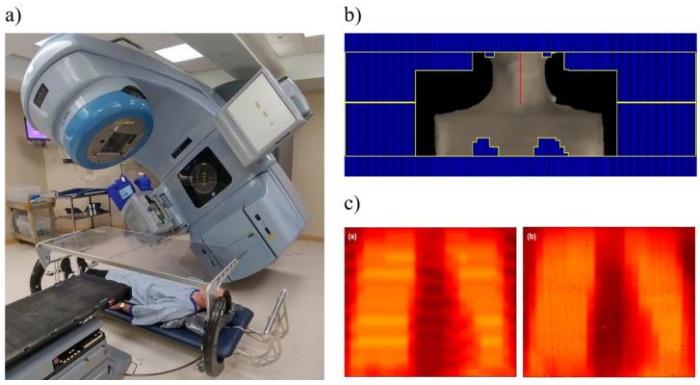


Figure 2.3-8: Selected images from the article of Pierce et al., (2018): a) photo of the treatment setup, b) Beams eye view at the patient chest, c) predicted (left) and with the film measured (right) dose of the lungs.

2.3.4 TBI with Linac - based VMAT and helical Tomotherapy®

Probably the most homogeneous dose delivery in TBI, with controlled OAR shielding, or ability of selective total marrow irradiation, are achieved using a linac - based VMAT with conventional SSD, or with helical Tomotherapy®. Individual patient planning with inverse optimization algorithm improves dose delivery results, but the large target requires challenging planning with multiple isocenters and especially dealing with 120 cm target length shifting limitation of a common linac couch, respectively 145 - 160 cm table motion capacity in the case of Tomotherapy® treatment units.

Tas et al., (2018) published results of TBI using linac based VMAT technique study, as feasible, accurate, and reliable in clinical practice. For patients longer than 120 cm up to five isocenters with overlapping arcs and patient repositioning during treatment were used, with average beam on time 55 ± 5 min. Limitation of 120 cm target maximal length on common linac couch was solved by Losert et al. (2019) using newly developed rotatable tabletop easy mounted on

standard linac table, designed for VMAT-TBI in clinical practice at their RT center. The now commercially available tabletop (IT-V, Innsbruck, Austria) consists completely of carbon fibers enable an easy 180° rotation of the tabletop with lying patient, within less than 10 s. The tabletop and VMAT-TBI delivery with usually 6 – 7 isocenters with field size maximum up to 35 cm, has been used in successful implementation in daily clinical practice and helped to keep the treatment times at an acceptable level (Losert, 2019). Maximal MLC field size for VMAT is an important factor to be considered with this method, for example in actual conditions of the RT department in USZ, the maximal field size is 22 cm and TBI with this technique could require challenging planning significant amount of isocenters.

Total body irradiation using another radiation therapy modality - helical Tomotherapy® is also feasible and used in clinical TBI. It allows a very good homogeneity of dose and conformity with an acceptable tolerance. It could deliver higher doses to sites at high risk of recurrence (bone marrow, sanctuary sites) while sparing major normal organs like lungs, liver, and kidneys (Sarradin, 2018), (Hui, 2005).

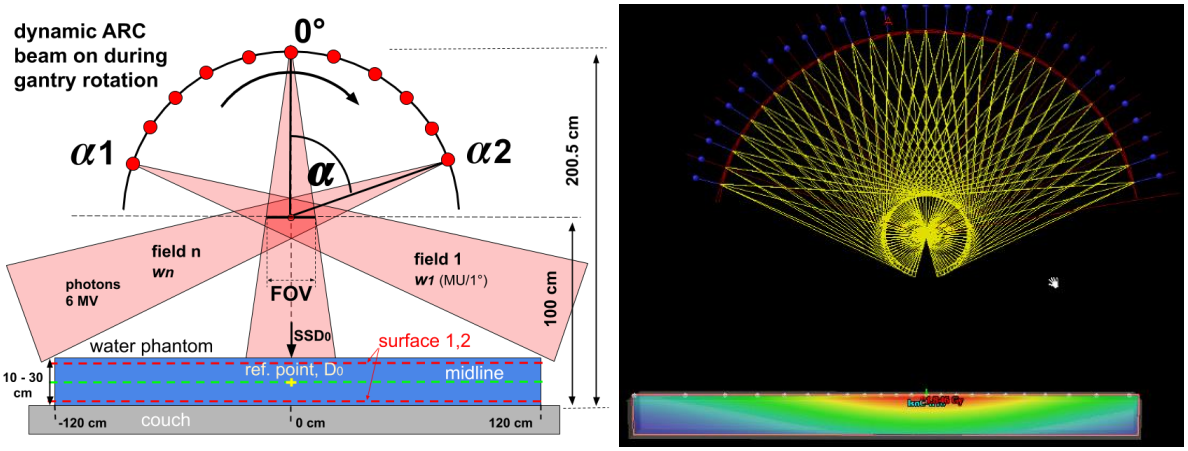
3 Methods

Already mentioned research works and clinical implementation of TBI based on modulated ARC (mARC) methods are showing promising results. But in the literature of our knowledge, there have not been reported details needed for direct implementation of the mARC technique in different local conditions of other RT centers. To evaluate mARC in conditions of USZ, I have tried first to develop a new method for modulated ARC calculation, which could bring similar results as are published in the reference literature about mARC TBI. The method was applied to different size virtual phantoms data from TPS to compare the dose homogeneity results for phantoms with different thicknesses (as basic models of patients). Then confirmative measurement for one mARC plan with real phantom on local linac was made. And finally, mARC TBI plan based on real TBI patient CTs was created and evaluated.

3.1 ARC model data from the TPS acquisition

The basic dose distribution data needed for simulation of TBI with modulated ARC technique in virtual water phantoms were generated with commercial treatment planning systems (TPS) for radiation therapy: Varian Eclipse® (ver. 15.6, Varian Medical Systems, USA), with dose calculation model: AAA 15.6.04., used in clinical practice at Radiation oncology department at University Hospital Zurich. It was shown that photon beam models used in TPS, for example, the AAA algorithm commissioned at standard SSD, can be used to accurately predict dose distributions in water at extended SSD for 6 MV open beams (Hussain, 2010). The beam model of the local linac: Varian Edge, beam energy 6 MV with flattening filter, was used to generate dose data for long water phantoms in dynamic ARC mode (beam on and constant intensity during gantry rotation) with extended SSD. The settings: the couch surface to the source distance with gantry at 0º was 200.5 cm (SSD_0), as is used in local TBI treatments with translating couch technique. In the TPS were created virtual water phantoms of cuboid shape with dimensions covering size ranges of real patients (treated in prone/supine positions with AP/PA beam directions), with dimensions: 10*, 15, 20, 25, and 30 cm (y, vertical thickness) × 30 cm (x, lateral thickness) × 240 cm (z, length), where (x,y,z) corresponds to the TPS coordinate system. * The most thin 10 cm (y) phantom, was designed with lateral thickness x = 20 cm. “Treatment” plans for all phantom sizes, were created with one side ARC (1s ARC)

irradiation to cover the whole phantom longitudinal size, with the couch in 90º position. The ARC was divided into many dynamic fields with the constant FOV size of 10 × 40 cm^2, or 40 × 40 cm^2 ($FOVx \times FOV_y$), without MLC, gantry rotation 5º (or 10º) per field (field step) and with a constant value of the linac monitor units MU/1º for all fields of the ARC. An ARC scheme is in Figure 3.1-1 top left. After the dose calculation, line dose profiles in longitudinal direction through the full phantom length in the phantom center slice, at depths: 1.5 cm as "surface 1", half of the phantom thickness as "midline", -1.5 cm from the bottom of the phantom as "surface 2", containing data of the dose to each point from every field of the ARC, were exported from TPS in text files format. Exported dose profiles were further processed with Python 3 programs. The depth line at 1.5 cm represents the dose buildup region with the maximum dose for 6 MV in water (Podgorsak, 2005).



Field ID	Technique	Machine/Energy	MLC	Field Weight	Scale	Gantry Rtn [deg]	Coll Rtn [deg]	Couch Rtn [deg]	Wedge	Field X [cm]	X1 [cm]	X2 [cm]	Field Y [cm]	Y1 [cm]	Y2 [cm]	X [cm]	Y [cm]	Z [cm]	Calculated SSD [cm]	MU
Field 1	ARC-I	Edge2018 - 6X		0.676	Varian IEC	280.0 CW 290.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00		200.0
Field 2	ARC-I	Edge2018 - 6X		1.648	Varian IEC	290.0 CW 300.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00		200.0
Field 3	ARC-I	Edge2018 - 6X		2.064	Varian IEC	300.0 CW 310.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00		200.0
Field 4	ARC-I	Edge2018 - 6X		2.346	Varian IEC	310.0 CW 320.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00	225.2	200.0
Field 5	ARC-I	Edge2018 - 6X		2.524	Varian IEC	320.0 CW 330.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00	205.1	200.0
Field 6	ARC-I	Edge2018 - 6X		2.614	Varian IEC	330.0 CW 340.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00	193.0	200.0
Field 7	ARC-I	Edge2018 - 6X		2.634	Varian IEC	340.0 CW 350.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00	185.7	200.0
Field 8	ARC-I	Edge2018 - 6X		2.583	Varian IEC	350.0 CW 0.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00	181.7	200.0
Field 9	ARC-I	Edge2018 - 6X		2.583	Varian IEC	0.0 CW 10.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00	180.5	200.0
Field 10	ARC-I	Edge2018 - 6X		2.634	Varian IEC	10.0 CW 20.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00	181.7	200.0
Field 11	ARC-I	Edge2018 - 6X		2.614	Varian IEC	20.0 CW 30.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00	185.7	200.0
Field 12	ARC-I	Edge2018 - 6X		2.525	Varian IEC	30.0 CW 40.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00	193.0	200.0
Field 13	ARC-I	Edge2018 - 6X		2.347	Varian IEC	40.0 CW 50.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00	205.1	200.0
Field 14	ARC-I	Edge2018 - 6X		2.065	Varian IEC	50.0 CW 60.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00	225.2	200.0
Field 15	ARC-I	Edge2018 - 6X		1.650	Varian IEC	60.0 CW 70.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00		200.0
Field 16	ARC-I	Edge2018 - 6X		0.677	Varian IEC	70.0 CW 80.0	0.0	90.0	None	40.0	+20.0	+20.0	40.0	+20.0	+20.0	0.00	-80.50	0.00		200.0

Figure 3.1-1: ARC setup. Top lefht: The scheme of the 1s ARC setup. Top right: illustrative image of 1s ARC with typical dose distribution represented by color spectrum (red – max. dose, blue – min. dose) from the TPS. Bottom: example of mARC fields setup in the TPS.

3.2 Modulated ARC optimization method

Optimization of the modulated ARC (mARC) means here to find optimal weight w_n as the number of relative MUs/1º for every field of the mARC, to get the best possible homogeneous dose distribution at the phantom midline and the surface, after both sides – in AP/PA directions irradiation with the mARCs. The dose in the phantom volume is expected to be in the range between the midline and the surface dose. Programs in Python 3 were created for data manipulations, optimization, and visualization of optimized mARCs dose profiles. Several optimization methods were tested, like manual adjustment of the field weights (manual adjustments, but without published calculation details, was used in *Polednik et al. 2015*), own iterative optimization algorithm programming, and several optimization methods offered in Python 3 library SciPy (scipy.optimize), as linear programming with constraints using function "linprog()", and local multivariate optimization method using function "scipy.optimize.minimize()" (*https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.minimize.html)* for objective function minimizing. The last method performed best and was used for all here published optimization results. Optimization methods based on the minimization of a quadratic objective function is a standard method of inverse planning in RT (Unkelbach, 2016). The general quadratic objective function f_{obj} (*Equation 3.2-1*) for dose distribution in uniform thickness phantom was designed as the weighted sum of squares of midline and surface points dose deviations from prescribed dose D_0, with options to apply additional weighted penalties for midline and surface overdosing, was defined with the formula:

Equation 3.2-1: The general quadratic objective function f_{obj}

$$f_{obj}(D_m, D_s, D_0, w_m, w_{m+}, w_s, w_{s+}, S_c) = \frac{1}{N}\left(w_m \sum_{i=1}^{N_m} (d_i^m - D_0)^2 + w_{m+} \sum_{i=1}^{N_m} (d_i^m - D_0)_+^{\,2} + w_s \sum_{i=1}^{N_s} (d_i^s - D_0)^2 + w_{s+} \sum_{i=1}^{N_s} (d_i^s - S_c \times D_0)_+^{\,2} \right)$$

Where D_m, D_s are (from TPS exported) midline and surface dose profiles in 2D matrix form, where for each point with z_i coordinate (rows in the matrix) along the depth line, are in the matrix columns stored dose increments to the point from each filed of the unmodulated ARC.

d^m_i and d^s_i are values of the total dose of the *i*-th point of the midline and the surface dose profile. D_0 is prescribed dose, w_m and w_s are weights for midline and surface deviations from D_0, w_{m+} and w_{s+} are penalty weights for overdose (applied for points where $(d_i - D_0) > 0$, or $(d_i - S_c \times D_0) > 0$) at midline and surface, S_c is the coefficient determining the dose level for penalized surface overdose, N_m and N_s is the number of midline and surface dose profile points and $N = N_m = N_s$.

The dose profiles data (Dm, Ds, D_0) with adjustable objectives weights $w_{obj} = [w_m, w_s, w_{m+}, w_{s+}, S_c]$ as parameters of the objective function f_{obj} were used as arguments for the optimization algorithm: scipy.optimize.minimize() function used in Python 3 program, with default syntax:

result = scipy.optimize.minimize$(f_{obj}, w_0, (D_m, D_s, D_0, w_m, w_{m+}, w_s, w_{s+}, S_c), bounds = [(w_{min}, w_{max})_n])$

which works as an iterative algorithm trying to find the best solution – the fields weights $w = (w_1,\ldots,w_n)$, where *n* is the number of fields in the ARC, for which (after recalculation of the total dose at each point) returns the minimum value of the objective function f_{obj} (*Equation 3.2-1*). w_0 is by the syntax required array of initial hints of field weights $w_0 = (w_1,\ldots,w_n)$, in my case often 1D array of ones, array *bounds* defines restriction for minimal and maximal values for each field weight (should reflect the linac min. and max. MUs/1 º values, or customized preset of field weight for selected fields is possible).

From the complex information of the returned result object of the optimization function, the solution values of optimized fields weights $w = (w_{1,\ldots},w_n)$ are obtained by calling the result object attribute "x": w = result.x

In this way obtained optimized field weights values $w = (w_{1,\ldots},w_n)$ are relative and can be further normalized and converted to final MUs/fieldº values for modulated ARC plan in the TPS.

3.3 Measurement of modulated ARC dose with the slab phantom

Confirmative measurement for one mARC plan was performed on the clinical linac. The slab phantom was assembled from solid water RW3 material slabs of 0.5 – 2 cm thickness and 30 × 30 cm^2 square shape, stacked on the translation couch to form 20 cm thick × 30 cm wide and

90 cm long phantom. The dose was measured with the set of diodes for in vivo dosimetry (EPD 10, IBA Dosimetry AB, Uppsala, Sweden), with 1.0 cm water equivalent dose buildup cup, which were placed every 10 cm (z), in 1.5 cm, 10 cm, 18.5 cm equivalent depth (considering the diode own buildup cup) to measure the surface and midline dose profiles. When placed inside the phantom, the surrounding space between the diodes and solid slabs were filled with water gel bolus bags. The phantom positioned with the center under the linac isocenter was moved under the linac on the translation couch to cover 240 cm length (-120 cm, 120 cm) and the mARC was repeated until the dose was measured in all points. The mARC from one side was measured once, and the measured dose at both surfaces was added together and the midline dose multiplied by two, to represent both sides (AP/PA directions) mARC cumulated dose.

Conditions: the linac machine was Varian TrueBeam, 6 MV photon beam with flattening filter. Couch surface to source at gantry angle 0º distance: 200.5 cm (SSD_0 = 180.5 cm). The D_0 was 2 Gy (1 Gy for one side ARC), with 600 cGy/min. dose rate. ARC: 280º – 80º, divided to 16 arcs fields with 10º step (beam on during gantry rotation), FOV = 40 x 40 cm^2, variable MUs/field according to the optimized ARC plan, which was optimized with equal weights for surface and midline dose homogeneity with objectives weights: w_{obj} = [1,0,1,0,0] (explained in section 3.2.). The mARC plan field weights values are in Table A1 in the Appendix.

3.4 **Modulated ARC plan based on the real TBI patient CTs**

The evaluation of TBI treatment test plan for one real patient using mARC technique in the TPS, was based on 2 plans sum with the registration of 2 whole body CTs images of the patient (treated previously with translational couch TBI technique in USZ hospital) in prone and supine positions. A patient body parts positions and shapes can differ between prone and supine positions and the CTs registration and plan sum must be made for several body parts separately. Plans dose sum were made separately for 3 body regions: head, torso, legs. The patient was a 9 years old girl, approx.: 140 cm long, head diameter 23 cm, abdomen thickness range 14 – 18 cm, with umbilicus under the linac isocenter and dose normalization point at the patient midline in 5 cm distance in head direction from the umbilicus. The CTs were acquired with the bolus over the neck, knees, and ankles (Figure 3.4-1). Shielding compensators for lungs were not considered in the plan. The modulated ARC plan for prone and supine position was the modulated ARC optimized for: 20 cm thick symmetrical water phantom, FOV 10 cm, field step 10º, couch to source distance 200.5 cm, w_{obj} = [1,0,1,0,0] (Figure 4.2-3a).

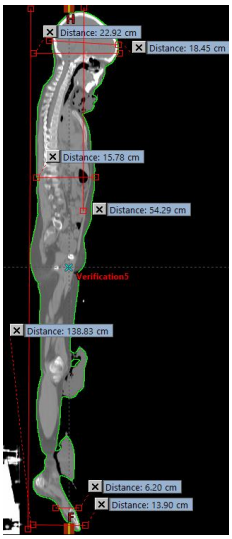


Figure 3.4-1: TBI patient planning CT with marked dimensions.

4 Results

4.1 ARC model based on TPS data

Figure 4.1-1 shows dose profiles for water phantoms thickness of 10, 20, and 30 cm with 240 cm length, acquired from unmodulated ARC plans in the TPS. Dose values are normalized to the dose at the reference point located at the phantom midline under the isocenter (z = 0 cm). Fig. a) shows typical dose profiles after 1s ARC (dashed lines) and cumulative dose profiles (solid lines) for the ARC - simulating both AP/PA deliveries, at the surface (in 1.5 cm depth) and midline. On fig. b) is visible, that the midline underdosing is increasing rapidly with increasing distance and with the phantom thickness. Fig. c) and d) show that in the case of 10 cm thick phantom, the surface and the midline dose have very similar values, but as the phantom thickness increase (15, 20, 25, 30 cm), the local difference between midline and surface dose increase rapidly from about 60 cm distance from z = 0 cm. Phantom thickness 25 cm is with the surface dose 109% D_0 at z = 0 cm, close to the 110% D_0 limits, and for the 30 cm thick phantom, the surface dose is 116% D_0 at z = 0 cm. So it is not possible to get the dose

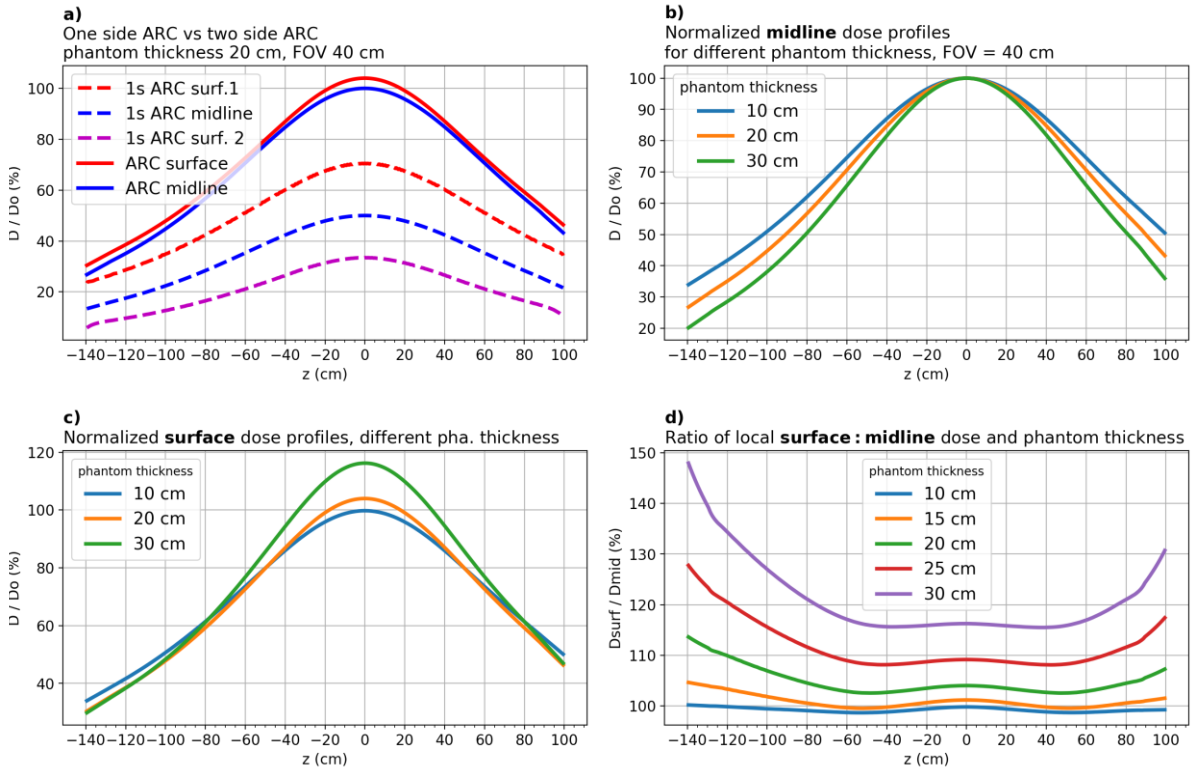


Figure 4.1-1: Unmodulated ARC water phantoms dose profiles, data from the TPS.

distribution not exceeding 110% D_0 at the surface (if we want to keep 100% D_0 at the midline over a longer region) in this setup (ARC, SSD_0 = 170.5 cm) for 30 cm thickness.

Influence of the phantom thickness and FOV size on the needed MUs/1º for 1s ARC, to get 1 Gy dose (or 2 times the value for 2 Gy after both side ARC) at the phantom reference point are showing the data in Table 4-1. Approximately 4.2 times more MUs/1º is needed for FOV_x = 10 cm in comparison with FOV_x = 40 cm.

water phantom (cm)		**ARC**			**1 Gy ref. p.**
thickness	**z1, z2**	**FOVx**	α_1(º)	α_2(º)	**MU/1º**
10	-140, 100	10	305	65	30.84
10	-140, 100	40	290	75	7.42
15	-140, 100	10	305	65	31.50
15	-140, 100	40	285	80	7.52
20	-140, 100	10	300	65	32.47
20	-140, 100	40	285	80	7.73
20	-120, 120	10	295	65	32.47
20	-120, 120	40	280	80	7.73
25	-140, 100	10	300	70	33.68
25	-140, 100	40	280	80	7.94
30	-140, 100	10	300	70	34.66
30	-140, 100	40	285	85	8.20

Table 4-1: Unmodulated ARCs parameters and MUs/1º for 1 Gy at the ref. point. From TPS ARC model.

With known values MUs/1º /1 Gy at the reference point for phantoms of different thicknesses, we can estimate the local dose values in the phantom's (or in the patient) parts with different local thickness, if the value of MUs/1º /D_0 based on the thickness at the reference point, was applied in the ARC.

4.2 Modulated ARC optimization

The objective function f_{obj} (Equation 3.2-1) was designed to work with different combinations of the optimization objectives, like homogeneity of the midline dose, surface dose, overdose

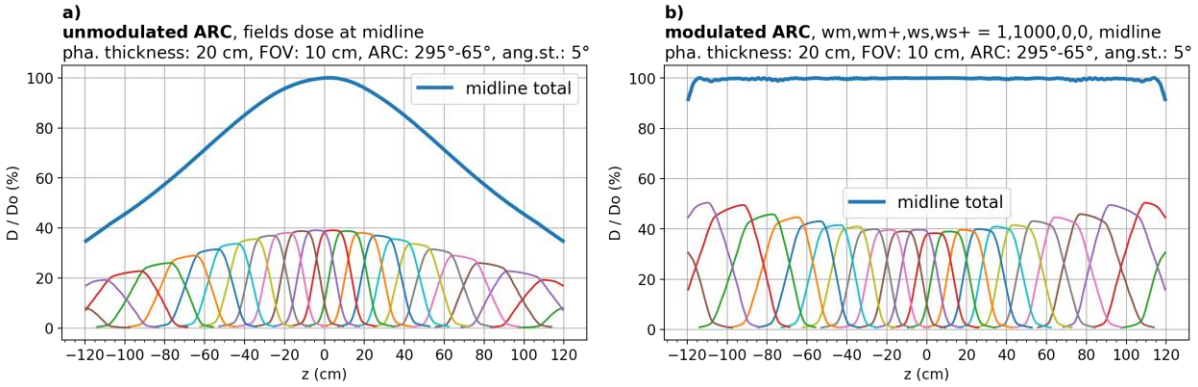


Figure 4.2-1: Unmodulated (a) vs modulated ARC (b), only the midline dose was optimalized. Total midline (blue) and dose profiles from each field of the ARC are plotted. Optimized relative MUs/field, starting from 295º with step 5º are: **[1.05, 3.77, 2.62, 2.17, 1.76, 1.54, 1.37, 1.23, 1.15, 1.08, 1.04, 1.01, 0.98, 1.02, 1.01, 1.04, 1.08, 1.15, 1.23, 1.37, 1.54, 1.76, 2.17, 2.62, 3.76, 1.05]**

above a certain value, and their different combinations, according to the given weight of each objective. Illustrative case for 20 cm thick symmetrical (z_1 = -120 cm, z_2 = 120cm) phantom, when only midline dose was optimized, with the objective weights (f_{obj} parameters) w_{obj} = [*wm*, *wm+*, *ws*, *ws+*] = [1, 1000, 0, 0], is shown in Figure 4.2-1. As example of metric for the dose homogeneity, for the full length (-120 cm, 120 cm) midline dose profile, could be used: [dose minimum, maximum, mean, standard deviation] = [91.56, 100.14, 99.65, 0.83] % D_0, in this case. If we cut off the end regions at both sides, which probably suffers from missing backscatter dose, we have for (-115 cm, 115 cm) region result: [min., max., mean, SD] = [98.63, 100.14, 99.78, 0.29] % D_0, what means the midline dose with inhomogeneity level < ± 1% D_0

If only the midline dose homogeneity is set as objective in the optimization, the surface dose in distant regions can increase above 110% D_0, for a phantom thickness > 15cm, as could be seen in Figure 4.2-2. In the case of 20 cm thick phantom, the surface dose increases above 110% D_0 from about 80 cm distance with FOV_x 10 cm, the red dashed line on fig. a), and with FOV_x 40 cm from about 70 cm – the fig. b). The surface dose can be also included in the objectives. Using the weight for general surface dose homogeneity: w_s, and/or using w_{s+} as penalty for overdose above given level $Sc \times D_0$ (if the surface overdose criterium is +10% D_0 → Sc = 1.10). With combined midline and surface dose optimization for 20 cm thick symmetric phantom, both midline and surface dose can be in the required ±10% D_0 range, as is visible in Figure 4.2-2. The midline dose is in (95%, 100%) D_0, and the surface dose is in (100%, 110%) D_0 range in the region of about -110 cm to 110 cm, for both FOV 10 cm and FOV 40 cm.

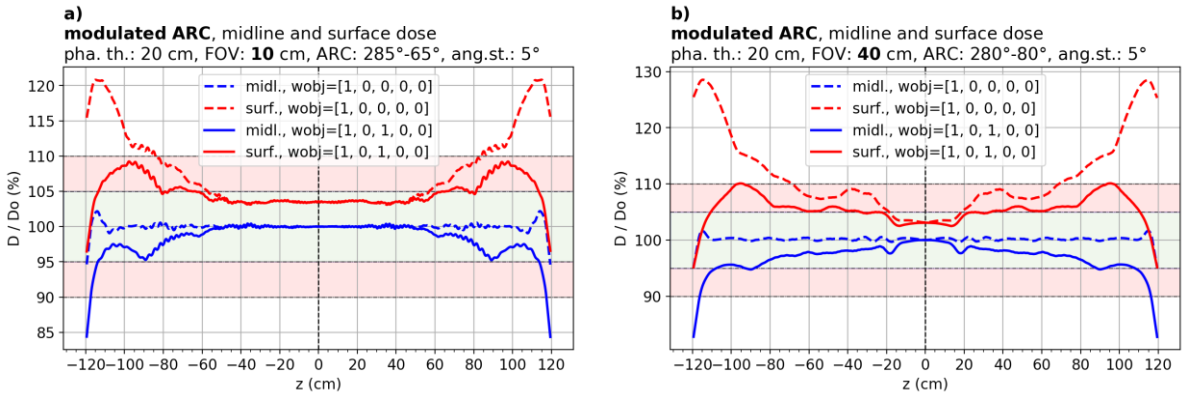


Figure 4.2-2: Modulated ARC dose profiles, phantom thickness: 20 cm, z: ±120 cm, midline only (dashed lines) vs both midline and surface dose homogeneity as the optimization objectives (solid lines), for FOV_x = 10 cm (left) and FOV_x = 40 cm (right).

mARC with the bigger field step: 10º, for 20 cm thick phantom was also tested. When optimized for both midline and surface dose, the results are similar to the case with the smaller 5º field step, and with the dose in ±10% D_0 tolerance at about -115 cm to 115 cm region, as is shown in Figure 4.2-3.

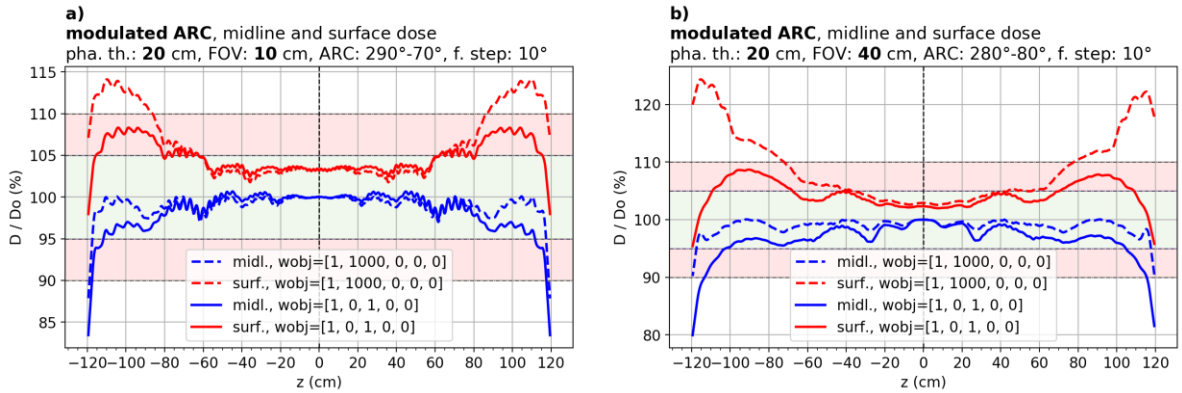


Figure 4.2-3: Modulated ARC dose profiles, phantom: 20 cm x ±120 cm, field step 10º.

More water phantoms with homogeneous thicknesses 10, 15, 20, 25, 30 cm, with ends at positions -140 cm and 100 cm, midline reference point is at z = 0 cm under the linac isocenter, with FOV_x =10 cm and FOV_x = 40 cm, and field angle step 5º were tested. The optimized dose profiles charts are in Figure 4.2-4.

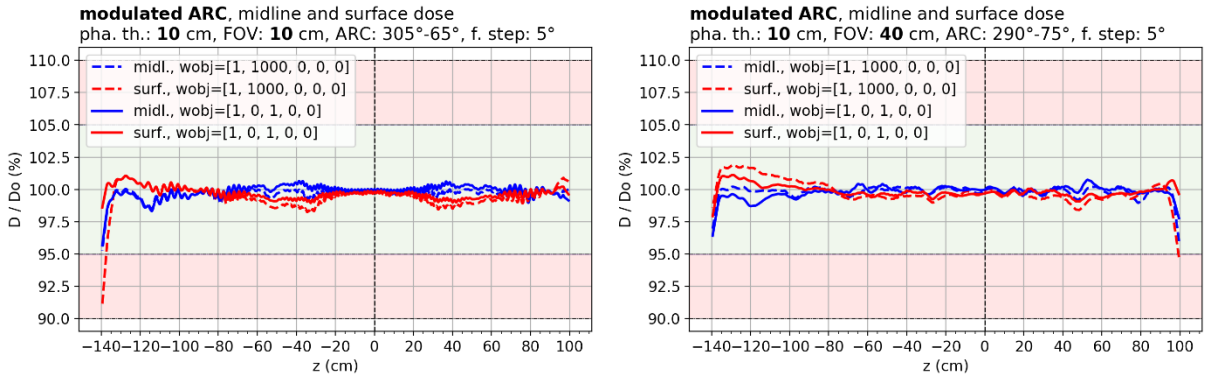


Figure 4.2-4 part 1 (continued on next page)

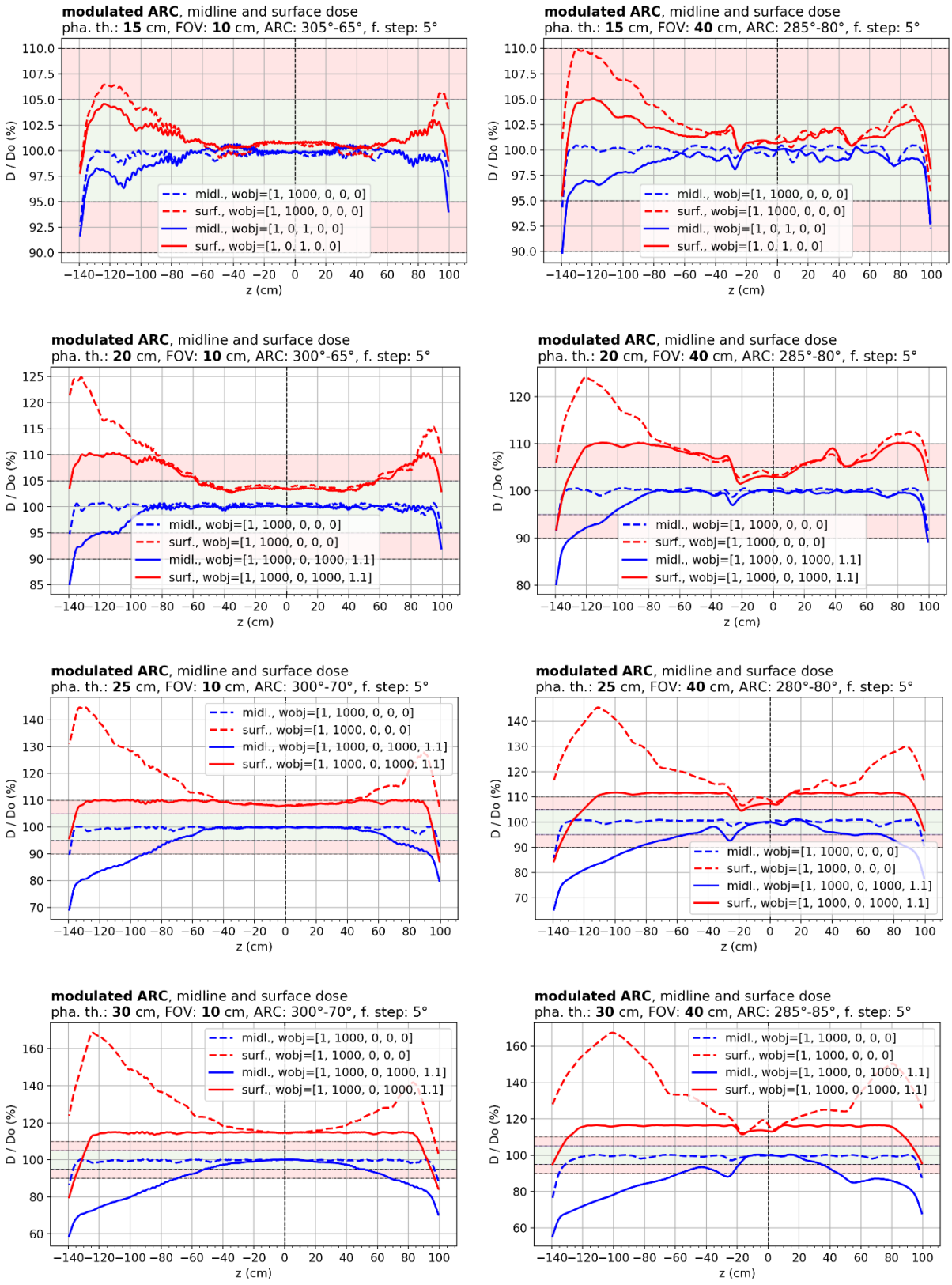


Figure 4.2-4: Modulated ARCs for phantoms with 10 – 30 cm thickness, FOV 10 and 40 cm, with optimization to midline only (dashed lines), and with optimization of both midline and surface dose (solid lines), applied weights of optimization objectives are in legends.

As can be seen on the charts in Figure 4.2-4, for both midline and surface dose optimization results (solid lines), for 10 cm thick phantom, the midline and surface dose are in approx. ±2.5% D_0 interval through all the phantom length and for both 10 cm and 40 cm wide FOV_x. Optimized dose distribution in 15 cm thick phantom stays in ±5% D_0 interval around D_0 dose for both FOV_x 10 cm and 40 cm. For 20 cm thick phantom the dose is in recommended ±10% interval around D_0 along full length for FOV_x = 10 cm, and up to around -130 cm distance in the case of FOV_x = 40 cm. With 25 cm phantom thickness we can keep the dose in ±10% D_0 interval only in approx. -90 cm to 90 cm region with FOV_x = 10 cm. For FOV_x = 40 cm we can keep the midline dose above 90% D_0 on the length approx. -80 cm to 80 cm, but the surface dose is reaching around 112% D_0. The 30 cm thick phantom is outside the physical and the optimization limits to deliver both homogeneous midline and surface dose in ±10% D_0 tolerance at our (SSD_0 = 170.5 cm) conditions in longer region.

Modulated ARC optimized to the patient size

The above mentioned generic modulated ARCs (mARC) for 10,15,20,25 cm thick uniform phantoms with length 240 cm, show long regions of the dose homogeneity in required range ±5% or ±10% D_0, long enough for typical patient size (up to about 190 cm). The question is, if more customized mARC calculated for specific patient length and thickness variations, could bring better results. At first – as length adaptation for 180 cm long patient, the 180 cm long phantom (P.20/180) was created from known 240 long 20 cm thick phantom dose profiles data, 180 cm long region (-110, 70) cm was selected and new specific mARC (mARC 20/180) for this virtual phantom was calculated. *(The reason for the improvised construction of the smaller phantom data from original data from TPS for longer phantom, was in my limited access to the TPS during the Covid-19 crisis in 2020. In comparison with dose data calculated in TPS directly for (P.20/180), we could probably expect the dose differences only in small regions at the phantom ends, due to missing backscatter there, and this was neglected here.) When generic symmetric mARC 20/240 (-120, 120) cm was applied to the shorter 180 cm long phantom, positioned: “legs end”:-110 cm, “head end”: 70 cm, very small dose differences are visible, as shows Figure 4.2-5b), but applying for the phantom size specific mARC 20/180, as shows Figure 4.2-5b), gives a little bit more freedom in midline/surface dose tuning by adjusting the

objectives w_{obj}., what is demonstrated here by lowering the surface dose in (-100,-80) cm and (60, 70) cm regions safely under +10% and +5%D_0 limit.

As basic model of an adult patient with decreasing thickness in the legs regions, the virtual

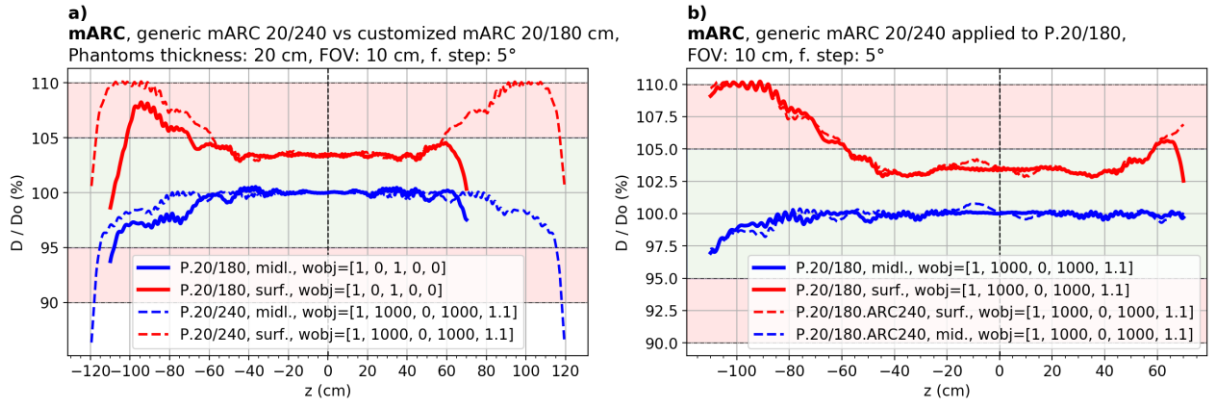


Figure 4.2-5: mARC for the shorter: 180 cm long and 20 cm thick phantom vs generic mARC 20/240. a) mARC 20/180 offers more variability in customizing surface vs midline dose, by varying w_{obj} parameters. b) mARC 20/240 (field weights) applied to shorter phantom, vs mARC 20/180 with the same w_{obj} parameters – very similar results.

water phantom 'Ali180', 180 cm long, with thickness/regions: 10/(-110, -60) cm, 15/(-60, -20) cm, 20/(-20, 70) cm was constructed from P.10/240, P.15/.240 and P.20/240 data. The scheme of the phantom shape is in Figure 4.2-6. (the reason to do it in this way, instead to create the new shape phantom directly in the TPS is explained above in *) With the known values of needed MUs/1º for 1 Gy dose at the reference point for different phantom sizes (Table 4-1), and with known dose profiles, it should be possible to estimate how the local dose changes with the thickness. The simplified situation when 'Ali180' is irradiated with unmodulated ARC, illustrates Figure 4.2-6. The blue polygon represents the phantom thickness variations. In comparison with dose profiles from uniform 20 cm thick phantom (dashed lines), in phantom 'Ali180' the dose (solid lines) increases significantly with longitudinal distance in 15 cm and 10 cm thick regions. (The simulation was based on simplified conditions, when partial dose shielding by the corners of the thicker part around -60 cm,

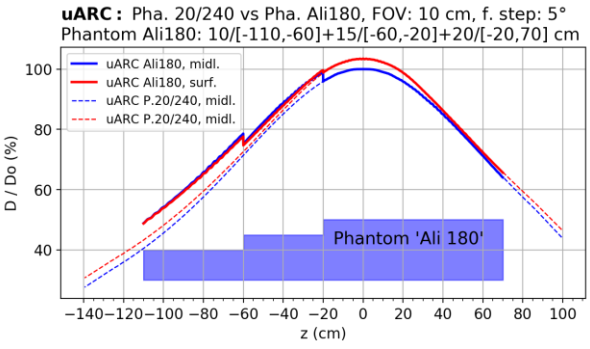


Figure 4.2-6: Constructed uARC dose profiles for phantom 'Ali180' vs dose in phantom 20/240. Blue polygon represents shape of phantom 'Ali180'.

and -20 cm is neglected, and the phantom rearranges to the same shape after rotating on the other side.)

How the thickness change in the leg's region affects the dose distribution in Ali180, if is applied the generic long mARC 20/240, designed for uniform 20 cm thick phantom, is visible in Figure 4.2-7. The generic mARC (dashed lines) performs well in the 20 thick torso region, but in the legs part, where is the local thickness different than in the generic mARC for 20 cm thick phantom conditions, the dose there is increasing above the ideal +5% D_0 range. Although the dose homogeneity is almost still in required max. +10% D_0 range with generic mARC, if new, for phantom Ali180 customized mARC is used, the resulting dose profiles have better homogeneity in the legs region (solid lines) and the dose stays in ±%5 D_0 region for the whole phantom Ali180 size.

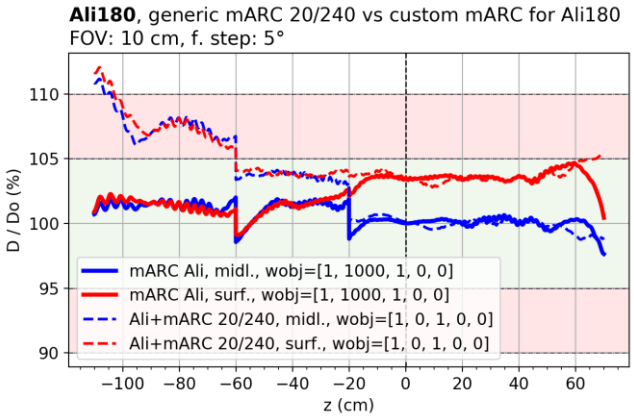


Figure 4.2-7: Simulated dose profiles in phantom Ali180. Using generic mARC 20/240 (dashed lines). Using for the phantom specific mARC Ali results in better dose distribution in ±105% D_0 range.

4.3 mARC with the slab phantom dose measurement

The “treatment plan” based on the modulated ARC plan optimized for 20 cm thick phantom, was applied to 20 cm thick slab phantom on the linac, as described in the Methods part. Measurement results are represented by the chart in Figure 4.3-1. Measured values (circle markers on the lines) vs predicted dose profiles (solid lines) from the modulated ARC plan applied to water phantom in the TPS are displayed. Almost all measured dose points are in approx. ±2% difference intervals from the predicted dose in that position. The measured midline dose is in approx. (95%, 100%) D_0 interval, and the surface dose is in approx. (97%, 107%) D_0 in -110 cm to 110 cm.

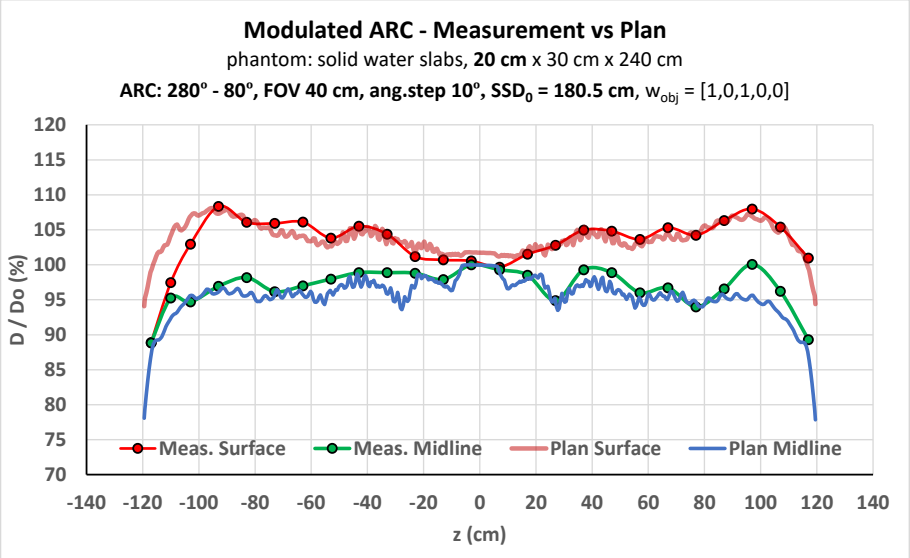


Figure 4.3-1: Measured dose (circle markers) vs dose profiles predicted in TPS for the modulated ARC plan for 20 cm thick phantom.

Note: At a closer look at the chart in Figure 4.3-1, one can notice, that the midline and the surface dose lines of the symmetric phantom, are not fully symmetric with respect to the center at z = 0 cm. The reason is probably in noisy original data. The dose profiles for 20 cm thick water phantom from unmodulated ARC plan in the TPS, were calculated with Acuros dose model algorithm, with a bigger step between the control points. Wave pattern noise in the dose profiles resulted in this slightly unsymmetrical result of dose profiles after the mARC optimization. The mARC field weights are not symmetrical, as one can notice in table A1 row 8, in the Appendix. Later, the noise in the data from the TPS was minimized after change to AAA dose calculation algorithm and with minimizing control points distance in the TPS settings.

4.4 **Modulated ARC plan based on the real TBI patient CTs**

The mARC plan, optimized for 20 cm thick phantom, with FOV_x 10 cm, field step 10º, w_{obj}=[1,0,1,0,0] was applied to the patient CTs in supine and prone positions, and both plans dose sum was performed in the TPS. Prescribed dose D_0 was 2 Gy/fraction. The dose homogeneity in body parts (registered on the CTs) was controlled manually and where the dose was found to be locally outside the ±10% D_0 limits, it was almost everywhere possible to adjust it by manual changes of MUs of the fields affecting the dose in the local region.

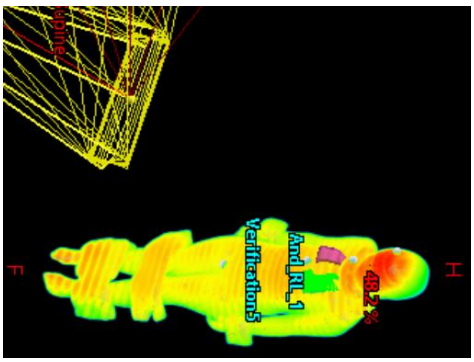
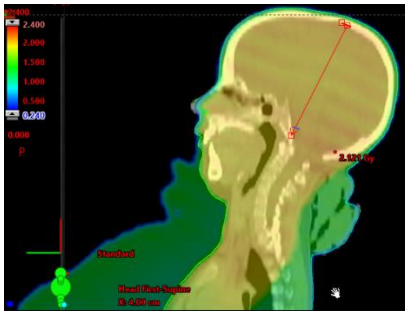
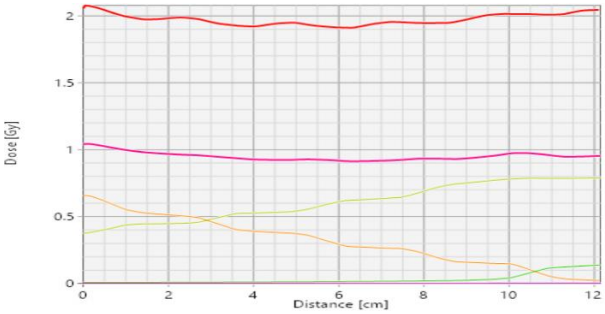


Figure 4.4-1: Illustrative 3D dose, visualization, 1side mARC, patient in supine position. Before final mARC adjustment.

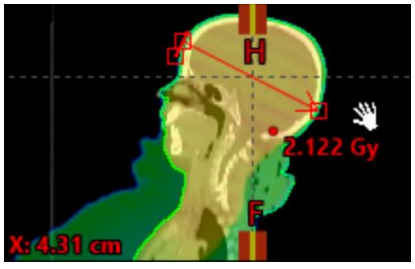
In this way, it was possible to get the dose distribution in recommended ±10% D_0 limits in almost all body volume. Illustrative dose distribution images with corresponding dose profiles are combined in Figure 4.4-2:

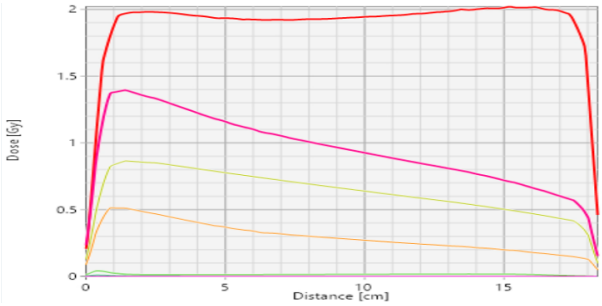
a)



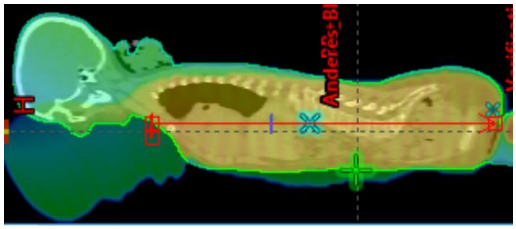


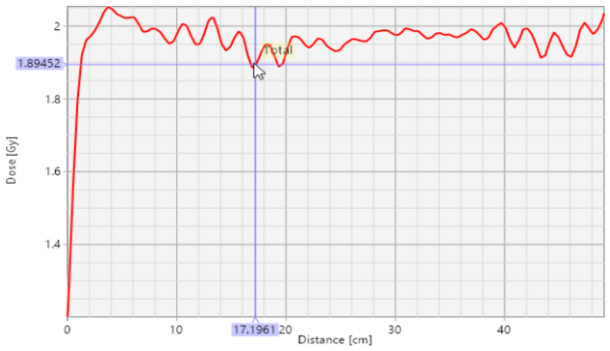
b)



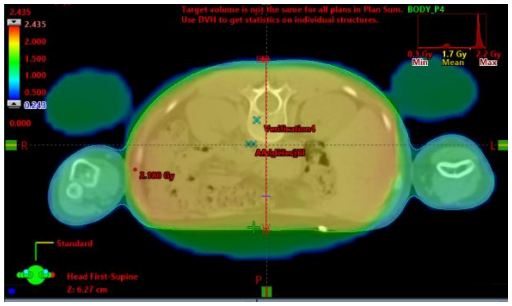


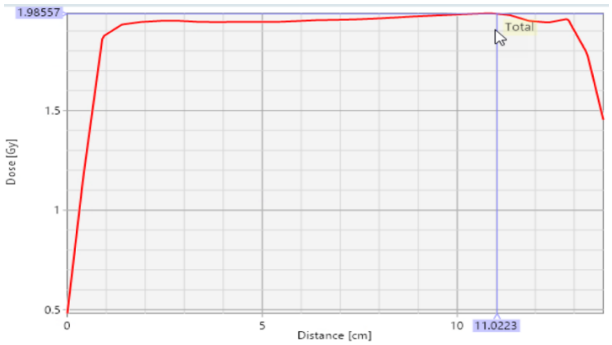
c)



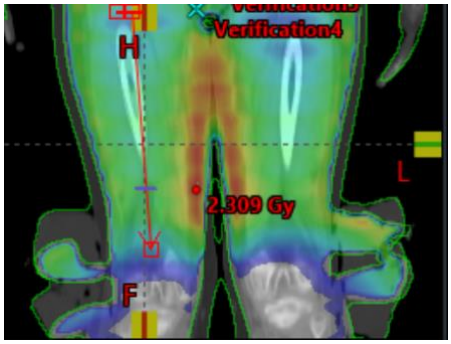


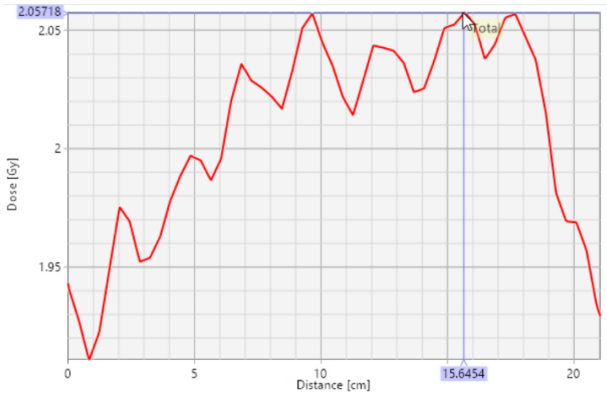
d)



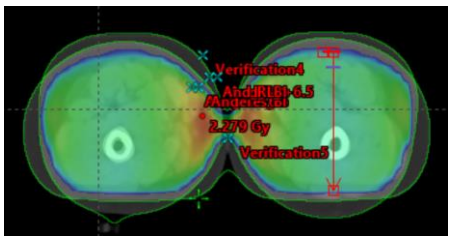


e)





f)



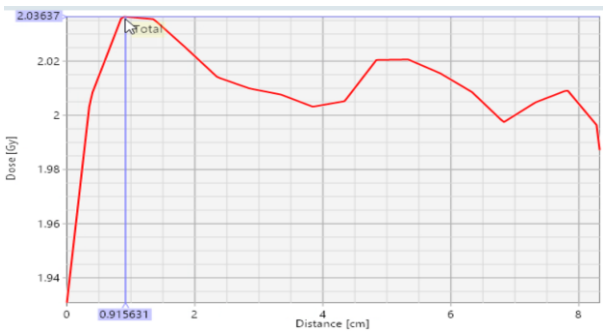


Figure 4.4-2: Dose distribution visualization in the head, torso, and legs, with corresponding dose profiles across the red line visible on the CT slice image. The prescribed dose for 1 fraction was $D_0 = 2$ Gy. For the head dose profile images, the total dose profile is the red line with maximal dose values, and individual fields dose profiles affecting the region are also displayed there.

Manual adjustments of the MUs/field of the fields causing local overdose at several points of the body took about 1 hour (for the author as inexperienced with the RT planning in the TPS). In the places where the local overdose is caused by the nature of the geometrical shape of the body part, like hot spots at inner parts of thighs (Figure 4.4-2 e,f), it could be in practice solved by placing a suitable bolus there.

5 Discussion

mARC optimization method, entry data and results reliability

Here proposed method is based on a mathematical optimization algorithm from Python 3 library SciPy, working with unmodulated ARC dose data for simple virtual water phantoms acquired from the TPS. Based on the known good accuracy of the dose calculation for extended SSD with AAA model used in the TPS (Hussain, 2010), we could consider the dose profiles data as good enough to replace challenging dose measurements with long real phantoms at this research stage. Presented results for optimized modulated ARC show, that this optimization method performs well, with similar results for midline dose profiles in comparison with published works about mARC TBI, for example, Jahnke et al. (2014) and Polednik et al. (2015). Different conditions complicate systematical numeric results comparison between this and the cited works, but for example, in our case, the midline dose for 20 cm thick phantom over 230 cm long region (Figure 4.2-1b) has mean value 99.8% D_0 with SD 0.3%, very similar to the Polednik et al. (2015) results with the mean value 99.8% of D_0, SD 0.5% in 200 cm region of 18 cm thick phantom. The advantage of here presented optimization method is the possibility of simultaneous and adjustable optimization for midline and surface dose homogeneity, which was not explicitly solved in the reference works. Promising reliability of the method applied to virtual phantom data from the TPS, was confirmed by verification measurement on the linac with solid water slab phantom (Figure 4.3-1). Relative dosimetry results are in very good agreement with predicted dose distribution, if we consider the measurement setup uncertainties (precision of diode detectors, the phantom with detectors assembling and positioning, the linac output homogeneity…).

Phantom models mARC results

Modulated ARC results show that for 10 cm and 15 cm thick phantoms it is possible to keep midline and surface dose in $D_0 \pm 5\%$ interval over 230 cm length. For 25 cm thick body, in up to 140 cm long region with midline dose in 95% - 100% D_0, while maintaining surface dose under 110% D_0, looks to be possible (Figure 4.2-4). It gives freedom for the patient positioning in the longitudinal direction, with priority for thicker torso and head to be in better position around z = 0 cm (under the isocenter), where is the central region with better flatness of midline and surface dose located. The patient length is not a limiting factor when a good enough dose distribution in less thick legs region could be delivered to about 130 cm distance. Patients with a thickness of more than 25 cm could be more challenging in the planning process. As is visible on mARC dose profiles for 30 cm thick phantom chart on Figure 4.2-4, in about ±40 cm from z=0 cm region, the midline dose is above 97% D_0 and the surface dose under 115% D_0. With

the speculation to decrease the midline target dose to be about 95% of the prescribed D_0, the surface dose will decrease to about 110% D_0, what could be still in the acceptable range. In special situations, the local surface overdose dose in a limited size at too thick body region could be probably further decreased by applying higher weights for the surface dose in optimization objectives, resulting in increasing weights for fields more aside from the selected region, thus sparing the surface dose there while delivering enough dose to the midline. Smaller FOV_x 10 cm allows better optimization and dose distribution for thicker phantoms, but FOV_x 40 cm gives more dose with the same dose rate at the same time and with still good enough dose flatness in up to 20 cm thickness phantom in relatively long regions. To use bigger FOV_x can significantly save the treatment time and MUs for the mARC plan.

Generic vs customized mARCs

The idea to have prepared several generic mARCs for different size patients groups, as used in the reference mARC TBI works, could save time in treatment planning. Appropriate mARC can be applied to the patient CT in TPS, with additional manual field weights adjustment for local dose corrections. But with this automated mARC calculation method, to create a new individual patient customized mARC parameters data could take only several minutes. The optimization calculation time is about 1 min in average power PC. mARC customized to the patient basic dimensions: length, and thickness in several standard body parts, could probably results in better overall dose distribution in the starting phase of treatment planning with the TPS, thus saving time of additional manual local dose adjustments. The idea to improve the effectiveness of the planning process using customized mARC, was investigated here at a basic level on the phantom “Ali180” case, and showed better results than to use generic mARC, as demonstrated in Figure 4.2-7. More practical experience with real TBI patient’s treatment planning with this method can bring a better trade-off between the time needed to prepare customized mARC and the time for manual field adjustments of generic mARC directly in the TPS.

Notes and ideas for mARC TBI

In acquiring of planning CT of the TBI patient, it should be taken into account the next registration of big body parts in prone and supine CTs for AP/PA plans dose sum in TPS. Minimizing the differences in body parts position on CT table can save the next treatment planning time and improve dose evaluation in TPS.

Penumbra under the shielding blocks is bigger in ARC mode, than in static beam mode with long SSD. It can be more challenging to design right size of the blocks to minimize wide

penumbra effect. Patients could be positioned to have z = 0 cm point closer to the shielding block position, for minimizing the geometrical penumbra of the ARC mode beam there.

Ideas for next improvements

Eclipse Scripting API (ESAPI) - scripting programming interface for Varian Eclipse TPS, offers great opportunities for this kind of treatment planning. Using scripting can be phantoms of different shapes created, with subsequent ARC dose profiles automated acquisition. The ESAPI script could be linked with Python 3 optimization program, or the similar optimization functions programmed in C#.NET (more native to ESAPI). The patient-specific mARCs planning could start with automated creation of the basic phantom simulating the main patient dimensions, then automated dose profiles extraction and transfer to the optimization algorithm, and then automated mARC plan with the optimized field weights could be created, all linked in together in one program. The final dose distribution adjustment could take then less time.

6 Conclusion

The modulated ARC technique for TBI therapy is an alternative way to perform TBI with standard linear accelerators in smaller RT rooms and without special equipment. In the last decade it has been used in clinical practice in more RT centers. Commercial TPSs, at least for example widespread Varian Eclipse®, does not offer a dedicated planning option for ARC TBI with extended SSD, so the treatment planning and modulated ARC optimization are performed differently in each RT center.

The original idea of this master thesis project was to reproduce one of the modulated ARC TBI method described in the literature, and to evaluate it in the conditions of Radiation oncology department at USZ. Because of missing details to reproduce the method from reference works, the own modulated ARC optimization method was developed and preliminarily evaluated.

Dosimetry measurement in long phantom in condition used in local TBI treatment are in good agreement with predicted results, confirming that with this method it is possible to deliver radiation dose with required homogeneity to the whole body for a TBI patients of wide length range. Created example of mARC plan for real TBI patient in the TPS shows good dose distribution in the patient body, fulfilling recommended criteria for TBI therapy (AAPM Report no. 17, VanDyk, 1986).

An important practical advantage of the mARC method is in dosimetry and quality assurance, because it works with individual patient treatment planning in TPS, final applied plan with calculated dose for the patient is stored in the TPS.

The technique does not require additional equipment. The treatment planning time for new patient is at this stage estimated to 1 – 2 hours (without the shielding blocks manufacturing), and with more practical experience could be further shortened.

Based on the actual literature review and here published results, the proposed mARC technique for TBI therapy could be a perspective method used also in Radiation oncology department at University Hospital Zurich.

7 Bibliography

Chrétien, M. et al., (2000). A variable speed translating couch technique for total body irradiation. *Medical physics*, 7(5):1127-30.

Chui, C. et al., (1997). Total body irradiation with an arc and a gravity-oriented compensator. *Int J Radiat Oncol Biol Phys.*, 39(5):1191-5.

Hui, S. et al., (2005). Feasibility study of helical tomotherapy for total body or total marrow irradiation. *Medical physics*, 32(10): 3214–3224.

Hussain, A. et al., (2010). Validation of the Eclipse AAA algorithm at extended SSD. *Journal of Applied Clinical Medical Physics*, 11: 90-100.

Jahnke, A. et al., (2014). Arc therapy for total body irradiation-a robust novel treatment technique for standard treatment rooms. *Radiotherapy and Oncology,* 129: 527-533

Khan, F. et al., (2014). *Khan's the physics of radiation therapy. Chapter 18.* Lippincott Williams & Wilkins.

Kirby, N. et al., (2012). Inverse-planned modulated-arc total-body irradiation. *Medical physics,* 39(5): 2761–2764.

Losert, C. et al., (2019). Novel rotatable tabletop for total-body irradiation using a linac-based VMAT technique. *Radiation Oncology*, 14(1): 244.

Peters, M. et al., (2015). An evidence-based review of total body irradiation. *J Med Imaging Radiat Sci.*, 46(4): 442–449.

Pierce, G. et al., (2019). Extended SSD VMAT treatment for total body irradiation. *Journal of applied clinical medical physics*, 20(1): 200–211.

Pla, M. et al., (1983). Total body irradiation with a sweeping beam. *International Journal of Radiation Oncology, Biology, Physics*, 9(1): 83-89.

Podgorsak, E. B. (editor) (2005). *Radiation oncology physics: A handbook for teachers and students.* International Atomic Energy Agency (IAEA), *British Journal of Cancer*, 98(5): 1020.

Polednik, M. et al., (2015). Accelerating total body irradiation with large field modulated arc therapy in standard treatment rooms without additional equipment. *Strahlentherapie und Onkologie: Organ der Deutschen Rontgengesellschaft,* 191(11): 869–874.

Rusu, I. et al., (2013). Total Body Irradiation (TBI). In Y. T. Brady L.W., *Encyclopedia of Radiation Oncology.* (pp. 904 - 910). Berlin: Springer.

Sarfaraz, M. et al., (2001). A translational couch technique for total body irradiation. *Journal of applied clinical medical physics*, 2(4): 201–209.

Sarradin, V. et al., (2018). Total body irradiation using Helical Tomotherapy®: Treatment technique, dosimetric results and initial clinical experience. *Cancer radiotherapie: journal de la Societe francaise de radiotherapie oncologique*, 22(1): 17–24.

Studinski, R. et al., (2017). Current practice in total-body irradiation: results of a Canada-wide survey. *Current oncology*, 24(3): 181–186.

Tas, B. et al., (2018). Total-body irradiation using linac-based volumetric modulated arc therapy: Its clinical accuracy, feasibility and reliability. *Radiotherapy and oncology: journal of the European Society for Therapeutic Radiology and Oncology*, 129(3): 527–533.

Unkelbach, J. (2016). Intensity-modulated radiation therapy: Photons. In *Khan's Treatment Planning in Radiation Oncology, 4th edition* (pp. 224 - 269). Wolters Kluwer.

VanDyk, J. et al., (1986). *AAPM report No. 17. The physical aspects of total and half body photon irradiation.* American Inst Phys.

Wills, C. et al., (2016). Total body irradiation: A practical review. *Applied Radiation Oncology*, 2: 11-17.

Wong, J. et al., (2018). Total Body Irradiation: Guidelines from the International Lymphoma Radiation Oncology Group (ILROG). *International journal of radiation oncology, biology, physics*, 101(3): 521–529.

8 Appendix

Table A1: **Table of relative field weights for optimized modulated ARCs**

in columns are: 1: phantom thickness, ["legs" position, "head" position], 2: FOVx, (FOVy = 40 cm), field angle step (gantry rotation during each field of the mARC), 3: α_1 - α_2 : start and end angle of the gantry for the mARC, 4. Weights of the optimization objectives: w_m – midline dose homogeneity, w_{m+} - midline overdose penalty, w_s – surface dose homogeneity, w_{s+} - surface overdose penalty, S_c – surface overdose criterium (overdose: $D > S_c \times D_0$), 5: relative field weights, w_1 is for 1st field of the mARC

	1	**2**	**3**	**4**	**5**
no	**phantom thick., pos. (cm)**	**FOV_x, step (cm, deg)**	**ARC α_1 - α_2**	**w_{obj} $[w_m,w_{m+},w_s,ws+,S_c]$**	**w: relative field weight (MUs/field) $w = [w_1,\ldots,w_n]$**
1	20, [-120, 120]	10, 5º	295°-65°	[1, 0, 0, 0, 0]	[1.08, 4.12, 2.64, 2.16, 1.78, 1.54, 1.36, 1.24, 1.15, 1.08, 1.04, 1.01, 0.98, 1.02, 1.01, 1.04, 1.08, 1.15, 1.24, 1.36, 1.54, 1.78, 2.16, 2.64, 4.12, 1.08]
2	20, [-120, 120]	10, 5º	295°-65°	[1, 0, 1, 0, 0]	[0.51, 2.68, 2.81, 1.96, 1.78, 1.51, 1.35, 1.25, 1.14, 1.09, 1.04, 1.01, 0.98, 1.02, 1.01, 1.03, 1.09, 1.14, 1.25, 1.35, 1.51, 1.78, 1.96, 2.81, 2.68, 0.51]
3	20, [-120, 120]	10, 5º	295°-65°	[1, 1000, 0, 0, 0]	[1.05, 3.77, 2.62, 2.17, 1.76, 1.54, 1.37, 1.23, 1.15, 1.08, 1.04, 1.01, 0.98, 1.02, 1.01, 1.04, 1.08, 1.15, 1.23, 1.37, 1.54, 1.76, 2.17, 2.62, 3.76, 1.05]
4	20, [-120, 120]	40, 5º	280°-80°	[1, 0, 0, 0, 0]	[1.26, 10.01, 4.3, 3.0, 2.36, 2.79, 3.27, 2.59, 1.34, 0.5, 0.57, 0.51, 0.5, 0.65, 1.35, 1.9, 1.99, 1.37, 0.66, 0.5, 0.52, 0.57, 0.5, 1.32, 2.56, 3.28, 2.82, 2.37, 3.0, 4.31, 10.01, 1.27]
5	20, [-120, 120]	40, 5º	280°-80°	[1, 0, 1, 0, 0]	[0.51, 2.25, 4.41, 2.47, 2.57, 3.07, 2.5, 2.12, 1.82, 0.51, 0.51, 0.51, 0.51, 0.95, 1.54, 1.43, 1.49, 1.54, 0.94, 0.51, 0.51, 0.51, 0.51, 1.84, 2.11, 2.5, 3.07, 2.56, 2.47, 4.41, 2.24, 0.51]
6	20, [-120, 120]	10, 10º	290°-70°	[1, 0, 1, 0, 0]	[0.51, 2.8, 1.88, 1.42, 1.19, 1.06, 1.0, 1.0, 1.06, 1.19, 1.42, 1.88, 2.8, 0.51]
7	20, [-120, 120]	10, 10º	290°-70°	[1, 1000, 0, 0, 0]	[10.0, 2.92, 1.91, 1.42, 1.18, 1.05, 1.0, 1.0, 1.05, 1.18, 1.42, 1.91, 2.92, 10.0]

8	20, [-120, 120] measurement	40, 10º	280°-80°	[1, 0, 1, 0, 0]	[3.81, 3.4, 2.6, 2.39, 1.02, 0.5, 0.88, 1.43, 1.36, 0.77, 0.5, 1.14, 2.47, 2.46, 3.4, 3.65]
9	20, [-120, 120]	40, 10º	280°-80°	[1, 1000, 0, 0, 0]	[10.0, 3.78, 2.48, 2.1, 1.27, 0.73, 0.89, 1.18, 1.21, 0.96, 0.73, 1.2, 2.1, 2.61, 3.93, 10.0]
10	10, [-140, 100]	10, 5º	305°-65°	[1, 0, 1, 0, 0]	[2.67, 2.01, 1.7, 1.49, 1.34, 1.23, 1.14, 1.08, 1.04, 1.01, 1.0, 1.0, 1.0, 1.04, 1.08, 1.14, 1.24, 1.32, 1.52, 1.67, 2.03, 2.37, 3.15, 4.04]
11	10, [-140, 100]	10, 5º	305°-65°	[1, 1000, 0, 0, 0]	[2.81, 2.02, 1.69, 1.49, 1.34, 1.23, 1.14, 1.07, 1.04, 1.0, 1.0, 1.0, 1.0, 1.04, 1.07, 1.12, 1.25, 1.3, 1.53, 1.65, 2.05, 2.36, 3.2, 1.19]
12	10, [-140, 100]	40, 5º	290°-75°	[1, 0, 1, 0, 0]	[4.64, 2.52, 2.02, 1.73, 2.5, 2.97, 1.95, 1.01, 0.5, 0.5, 0.53, 0.5, 0.7, 1.56, 2.11, 1.68, 1.07, 0.63, 0.55, 0.59, 0.62, 0.74, 2.14, 3.2, 2.88, 2.38, 2.64, 3.58, 5.43]
13	10, [-140, 100]	40, 5º	290°-75°	[1, 1000, 0, 0, 0]	[1.26, 3.6, 2.36, 1.65, 2.05, 1.98, 1.52, 1.33, 0.84, 1.1, 1.02, 0.66, 0.59, 1.3, 1.25, 1.14, 1.16, 0.84, 1.01, 1.23, 0.95, 0.8, 1.93, 2.08, 2.36, 2.56, 3.21, 4.65, 5.68]
14	15, [-140, 100]	10, 5º	305°-65°	[1, 0, 1, 0, 0]	[2.54, 2.1, 1.72, 1.51, 1.36, 1.23, 1.15, 1.08, 1.03, 1.01, 0.98, 1.02, 1.01, 1.03, 1.09, 1.14, 1.24, 1.34, 1.54, 1.69, 2.08, 2.41, 3.39, 3.38]
15	15, [-140, 100]	10, 5º	305°-65°	[1, 1000, 0, 0, 0]	[2.95, 2.14, 1.65, 1.58, 1.3, 1.25, 1.13, 1.08, 1.04, 1.0, 0.97, 1.03, 1.0, 1.05, 1.07, 1.14, 1.24, 1.31, 1.57, 1.67, 2.15, 2.46, 3.44, 3.27]
16	20, [-140, 100]	10, 5º	300°-65°	[1, 1000, 0, 1000, 1.1]	[1.03, 2.59, 2.22, 1.73, 1.56, 1.35, 1.24, 1.15, 1.08, 1.04, 1.0, 1.0, 0.99, 1.01, 1.03, 1.08, 1.16, 1.21, 1.4, 1.5, 1.82, 2.11, 2.48, 3.38, 4.06]
17	20, [-140, 100]	10, 5º	300°-65°	[1, 1000, 0, 0, 0]	[1.06, 3.3, 1.96, 1.91, 1.44, 1.44, 1.19, 1.18, 1.09, 1.02, 1.04, 0.98, 1.0, 1.02, 1.03, 1.09, 1.16, 1.21, 1.42, 1.48, 1.86, 2.08, 2.73, 3.49, 5.53]
18	20, [-140, 100]	40, 5º	285°-80°	[1, 1000, 0, 1000, 1.1]	[1.02, 3.06, 3.22, 2.06, 2.18, 3.36, 2.37, 1.75, 1.01, 0.5, 0.5, 0.5, 0.5, 0.8, 2.04, 1.65, 1.57, 1.12, 0.7, 0.56, 0.58, 0.5, 0.5, 2.74, 2.94, 3.05, 3.05, 2.86, 3.42, 5.21, 1.14]
19	20, [-140, 100]	40, 5º	285°-80°	[1, 1000, 0, 0, 0]	[1.07, 3.66, 4.08, 2.33, 1.95, 2.68, 2.04, 1.72, 1.3, 0.5, 0.78, 1.08, 0.57, 0.63, 1.59, 1.4, 1.27, 1.26, 0.81, 0.51, 1.08, 1.13, 0.54, 2.12, 2.52, 2.8, 3.08, 3.13, 5.05, 8.39, 1.33]
20	25, [-140, 100]	10, 5º	300°-70°	[1, 1000, 0, 1000, 1.1]	[0.82, 2.35, 2.11, 1.63, 1.55, 1.36, 1.24, 1.17, 1.07, 1.05, 1.0, 0.97, 1.03, 0.99, 1.05, 1.09, 1.13, 1.28, 1.36, 1.49, 1.75, 1.93, 2.42, 3.03, 3.95, 0.5]
21	25, [-140, 100]	10, 5º	300°-70°	[1, 1000, 0, 0, 0]	[1.06, 3.41, 2.02, 1.9, 1.53, 1.4, 1.24, 1.16, 1.09, 1.04, 1.0, 0.99, 1.01, 0.99, 1.07, 1.06, 1.17, 1.25, 1.35, 1.63, 1.71, 2.35, 2.66, 3.87, 5.75, 1.07]
22	25, [-140, 100]	40, 5º	280°-80°	[1, 1000, 0, 1000, 1.1]	[1.0, 1.0, 3.07, 2.22, 2.65, 2.9, 2.62, 1.8, 1.24, 1.53, 0.51, 0.51, 0.51, 0.68, 1.4, 1.45, 1.56, 1.22, 1.16, 0.84, 0.66, 0.51, 0.51, 0.51, 3.1, 2.28, 2.63, 2.9, 3.0, 3.16, 4.67, 1.68]
23	25, [-140, 100]	40, 5º	280°-80°	[1, 1000, 0, 0, 0]	[1.05, 1.14, 5.16, 4.84, 2.06, 2.11, 2.83, 2.0, 1.64, 1.2, 0.5, 1.0, 1.2, 0.5, 0.65, 1.49, 1.32, 1.34, 1.17, 0.76, 0.51, 1.22, 1.24, 0.5, 2.2, 2.43, 2.88, 3.3, 3.08, 5.67, 10.09, 2.3]

24	30, [-140, 100]	10, 5º	300°-70°	[1, 1000, 0, 1000, 1.1]	[1.25, 2.3, 1.98, 1.6, 1.5, 1.31, 1.21, 1.16, 1.06, 1.03, 1.02, 0.99, 1.0, 1.01, 1.03, 1.08, 1.14, 1.23, 1.32, 1.45, 1.68, 1.87, 2.3, 2.88, 3.75, 0.52]
25	30, [-140, 100]	10, 5º	300°-70°	[1, 1000, 0, 0, 0]	[1.07, 3.34, 2.18, 1.9, 1.6, 1.38, 1.28, 1.14, 1.1, 1.03, 1.0, 1.01, 0.98, 1.01, 1.06, 1.06, 1.18, 1.26, 1.35, 1.68, 1.73, 2.44, 2.77, 4.11, 6.03, 1.1]
26	30, [-140, 100]	40, 5º	285°-85°	[1, 1000, 0, 1000, 1.1]	[1.24, 2.62, 2.9, 3.78, 2.62, 1.7, 1.53, 0.92, 1.22, 0.53, 0.53, 0.53, 1.2, 1.91, 1.36, 1.16, 0.99, 0.99, 0.81, 0.54, 0.62, 0.53, 0.53, 3.07, 2.73, 2.1, 2.37, 2.96, 3.05, 4.28, 6.55, 0.74]
27	30, [-140, 100]	40, 5º	285°-85°	[1, 1000, 0, 0, 0]	[1.26, 6.52, 4.88, 1.88, 2.39, 2.38, 2.13, 1.55, 1.31, 0.5, 1.49, 0.9, 0.5, 0.69, 1.26, 1.18, 1.3, 1.18, 0.86, 0.66, 1.64, 0.91, 0.5, 2.11, 2.06, 3.0, 3.59, 3.1, 7.38, 10.02, 3.94, 1.12]
28	20, [-110, 70] 'P.20/180'	10, 5º	300°-65°	[1, 0, 1, 0, 0]	[0.51, 0.51, 1.3, 1.62, 1.58, 1.36, 1.21, 1.19, 1.06, 1.05, 1.01, 0.99, 1.0, 1.0, 1.05, 1.08, 1.15, 1.25, 1.32, 1.59, 1.64, 2.18, 2.5, 2.2, 0.51]
29	20, [-110, 70] 'P.20/180'	10, 5º	300°-65°	[1, 0, 1, 1000, 1.1]	[1.0, 1.01, 1.07, 1.81, 1.54, 1.37, 1.23, 1.15, 1.08, 1.04, 1.01, 0.99, 1.0, 1.0, 1.04, 1.08, 1.14, 1.25, 1.34, 1.57, 1.74, 2.17, 2.56, 3.14, 0.76]
30	‘Ali180’ 10-15-20, [-110, -60, -20, 70]	10, 5º	300°-65°	[1,1000, 1, 0, 0]	[0.97, 0.51, 1.28, 1.62, 1.58, 1.37, 1.21, 1.18, 1.07, 1.04, 1.01, 0.99, 1.0, 1.02, 1.03, 1.03, 1.16, 1.18, 1.34, 1.38, 1.71, 1.87, 2.42, 1.33, 1.09]

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