

# Comparison of intensity modulated radiotherapy treatment plans between 1.5 T MR-Linac and conventional linac

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## Research

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# Abstract

**Background** To assess the dosimetric qualities and usability of planning for 1.5 T MR-Linac based intensity modulated radiotherapy (MRL-IMRT) for various clinical sites in comparison with IMRT plans using a conventional linac.

**Methods** In total of 17 patients with disease sites in the brain, esophagus, lung, rectum and vertebra were re-planned retrospectively for simulated MRL-IMRT using the Elekta Unity dedicated treatment planning system (TPS) Monaco (v5.40.01). Currently, the step-and-shoot (ss) is the only delivery technique for IMRT available on Unity. All patients were treated on an Elekta Versa HD™ with IMRT using the dynamic multileaf collimator (dMLC) technique, and the plans were designed using Monaco v5.11. For comparison, the same dMLC-IMRT plan was recalculated with the same machine and TPS but only changing the technique to step-and-shoot. The dosimetric qualities of the MRL-IMRT plans, to be evaluated by the Dose Volume Histograms (DVH) metrics, Homogeneity Index and Conformity Index, were compared with the clinical plans. The planning usability was measured by the optimization time and the number of Monitor Units (MUs).

**Results** Comparing MRL-IMRT with conventional linac based plans, there were no clinically significant differences between any of the DVH parameters studied for multiple tumor sites. However, MRL-IMRT plans had significantly increased dose to skin and low dose region of normal tissue. Furthermore, MRL-IMRT plans had significantly reduced optimization time by comparing conventional linac based plans. The number of MUs of MRL-IMRT was increased by 23% compared with ss-IMRT, and no difference from dMLC-IMRT.

**Conclusions** Clinically acceptable plans can be achieved with 1.5 T MR-Linac system for multiple tumor sites. The planning efficiency of MRL-IMRT was improved due to the reduced optimization time. However the increase in skin dose and low dose region was also observed in MRL-IMRT plans.

## Background

Magnetic resonance image (MRI) guided radiotherapy can provide high and versatile soft-tissue contrast imaging for real-time plan adaptation and target position monitoring during irradiation [1]. Improvements in soft tissue contrast are desirable for a number of treatment sites, for example pelvis or abdominal tumors, where the Cone Beam CT (CBCT) imaging has poor performance [2]. To enable MR imaging prior to and during treatment, the MR-Linac (Elekta, AB, Stockholm, Sweden) from the MR-Linac Consortium has combined a 1.5 T Philips scanner (Best, The Netherlands) and a 7 MV flattening filter free (FFF) linac [3]. This system allows for daily MR image guidance and real-time imaging throughout the treatment fraction, which is ideal for managing and monitoring both interfraction and intrafraction motion, without incurring additional radiation exposure [4, 5, 6].

The MR-Linac is significantly different from the conventional linac in many aspects. An important feature is the presence of a magnetic field which inevitably affects radiation dose distribution. Previous studies using Monte Carlo calculations on phantoms reported that the magnetic field can lead to asymmetric point spread kernels, resulting in reduced build-up regions and asymmetric beam penumbra regions which are also shifted [7]. The magnetic field will change the paths of secondary electrons in tissue, particularly at the tissue-air and

tissue-lung interfaces. For example, exiting electrons at interface will be forced back into the tissue under the Lorentz force, which termed as Electron Return Effect (ERE), and this can lead to significantly different dose distribution at the interface from that of a conventional linac [8]. The presence of a 1.5 T high magnetic field (B-field) in the MR-Linac during beam delivery will enhance the ERE at tissue interfaces, thus leading to an under or overdose at the air cavity walls, along with lung-tissue interface or on the skin [7, 8].

The setup geometry for irradiation with the Elekta Unity is different with a conventional linac. The source-to-axis distance (SAD) for MR-Linac system is 143.5 cm, instead of 100 cm. The extended SAD results in a wider Multi-Leaf Collimator (MLC) leaf width at the isocenter plane, 7.15 mm, compared to 5 mm leaf width of a similar MLC on a conventional linac [9, 10]. Another distinct feature of the Elekta Unity is that only the longitudinal couch movement is available for setting up the treatment isocenter in patient. Also, the Unity system does not allow collimator rotation. The MLC leaves moves only in the cranio-caudal direction.

The existence of magnetic field and the above mentioned technical features with the Unity MR-Linac may have potential implications in the plan qualities compared to using a conventional linac for IMRT. Several studies have investigated the impact of a transversal 1.5 T high field magnetic field on dose distribution, especially at the tissue-air interfaces [8, 10, 11, 12, 13]. However, these studies only involved a single tumor site and only focused on the influence of 1.5 T magnetic field [10, 11, 12, 13]. The purpose of this study is to investigate the feasibility and performance of 1.5 T MR-Linac for treating various tumor sites by comparing the dosimetry, treatment efficiency, and TPS usability with conventional linac based treatment planning.

## Materials And Methods

### Treatment planning

A total of 17 patients (5 for brain, 3 for esophagus, 3 for lungs, 3 for vertebra and 3 for rectum) previously treated with a conventional linac (Elekta Versa HD<sup>TM</sup>) at our institute were randomly selected from the clinical archive. Among the patients, 11 were men and 6 women, and the median age was 54 years (range from 31 to 74). In a routine clinical procedure, a Computed Tomography (CT) simulation (Siemens Somatom<sup>TM</sup>, Munich, Germany) was acquired using 140-kVp X rays, 80-cm field of view, and 0.3 cm uniform slice thickness. The target volume and organs at risk (OAR) were delineated by a radiation oncologist with specialty in that treatment site. The clinical plans were designed using Monaco (v5.11). The same planning CT and structure set were used for re-planning on Monaco (v5.40.01). The re-planning for simulated MR-Linac treatment was done by the same dosimetrists following the same institutional protocols.

The impact of magnetic field on dose calculation was taken into account in Monaco (v5.40.01) with the GPUMCD algorithm [14]. The GPUMCD calculation would regress to the results of x-ray voxel Monte Carlo (XVMC) [15] without magnetic field present for the clinical machine for the patients studies. The Unity beam model also accounted for transmission through the cryostat, the couch and receiver coils with a complicated set of attenuation parameters determined at the commissioning. The beam filtration and the nominal beam energy of the MR-Linac also differ from the 6MV photon beams with a Versa HD. Table 1 presents the main parameters of the two Elekta machines (Unity MR-Linac and Versa HD) for comparison.

**Table 1** Differences in irradiation geometry between a conventional Versa HD linac and the MR-Linac

Device specifications	Versa HD	MR-Linac
Static magnetic field	-	1.5 T
Nominal beam energy	6 MV FFF	7 MV FFF
Additional beam filtration	-	Cryostat
MLC leaf width at isocenter	5.0 mm	7.15 mm
MLC leaf travel direction	Arbitrary	Cranio-caudal
Source-to-axis distance	100 cm	143.5 cm
Isocenter position relative to patient	Variable	Fixed at bore center

The prescription dose were 60 Gy in 30 fractions for brain plans, 44 Gy in 20 fractions for esophagus plans, 45 Gy in 20 fractions for lung plans, 36 Gy in 10 fractions for vertebra plans and 50 Gy in 25 fractions for rectum plans. All the plans were designed with 5 coplanar fields except the brain cases, which were planned with 9 fields evenly spaced gantry angles. Since currently Elekta Unity only supports the step and shoot (ss) technique for IMRT, while the clinical plans used dynamic MLC (dMLC), for studying the delivery efficiency and TPS usability, reference ss-IMRT plans with Versa HD was generated for all cases. Based on our experience, the difference in the plan quality between dMLC-IMRT and ss-IMRT is negligible if the same beam setup and optimization parameters are used. The step-and-shoot plans for both MR-Linac and Versa HD were all limited to a maximum of 250 segments, while the plans for dMLC were limited to a maximum of 20 control points per beam. Other key parameters for the three groups plans for example nominal energy, dose calculation algorithm, grid spacing, statistical uncertainty, minimum segment area, minimum segment width, minimum MU per segment were presented in table 2.

**Table 2** Calculation and segmentation parameters for the three plan groups

Plan parameters	MRL-IMRT	ss-IMRT	dMLC-IMRT
Energy	7 MV FFF	6 MV FFF	6 MV FFF
Algorithm	GPUMCD	XVMC	XVMC
IMRT technique	Step-and-shoot	Step-and-shoot	Dynamic MLC
Grid spacing (cm)	0.3	0.3	0.3
Statistical uncertainty (%) Per Control Point	3	3	3
Minimum segment area (cm <sup>2</sup> )	2	2	-
Minimum segment width (cm)	0.5	0.5	0.5
Minimum MU/segment	4	4	-
Maximum # segments per plan	250	250	-
Maximum # of Control Points per beam	-	-	20

### Plan evaluation and comparison

Plan evaluations were conducted by the attending physicians and clinical physicists originally assigned to the cases using the Dose-volume histograms (DVH) metrics based on the same institutional protocols. Parameters such as homogeneity index (HI) and conformity index (CI) were used to evaluate the targets dose homogeneity and conformity, while the mean dose (D<sub>mean</sub>) and maximum point dose (D<sub>max</sub>) were used for OARs evaluation. The HI and CI are defined as[16,17]:

$$HI = (D_{2\%} - D_{98\%}) / D_{50\%} \quad (1)$$

$$CI = (TV_{PV} \times TV_{PV}) / (V_{PTV} \times V_{TV}) \quad (2)$$

where D<sub>2%</sub>, D<sub>98%</sub> and D<sub>50%</sub> represent the minimum dose covering 2%, 98% and 50% of the target volume, respectively. V<sub>TV</sub> is the treatment volume of the body received the prescribed dose, V<sub>PTV</sub> is the volume of PTV, and TV<sub>PV</sub> is the target volume covered by the prescribed dose. The lower the HI value means the better the homogeneity[17]. CI is normally used to quantitatively measure the conformality of the dose distribution relative to the target volume, which denotes the ratio of reference dose received by targets and normal tissue. The CI value closer to 1 means a better conformality[18].

For OARs, the D<sub>max</sub> and D<sub>mean</sub> were used to evaluate for a serial organ, while the D<sub>mean</sub> and/or V<sub>x</sub> (% OARs volume receiving x Gy) were used to evaluate a parallel organ. For the skin dose evaluation, the interested volume is defined as the shell volume with the interior surface as a 4 mm contraction from the body contour. The V<sub>10</sub> of the unspecified normal tissue was calculated to evaluate the volume of the low dose region, which defined as body subtracted target volume. For assessing the impact of ERE to the lung, the maximum dose in a 5 mm thick layer inside of the lung surface was evaluated [11]. Table 3 presents the dosimetric parameters evaluated for the treatment sites studied.

Table 3 DVH metrics and evaluation parameters for various treatment sites plans.

Brain		Esophagus		Lungs		Vertebra		Rectum	
PGTV	HI	PGTV	HI	PGTV	HI	PGTV	HI	PGTV	HI
	CI		CI		CI		CI		CI
PCTV	HI	PCTV	HI	PCTV	HI	PCTV	HI	PCTV	HI
	CI		CI		CI		CI		CI
Brain Stem	Dmax	Lungs	V5	Lungs	V5	Skin	Dmax	Bladder	Dmax
	Dmean		V20		V20		NT		V10
Spinal Cord	Dmax		V30		V30			Small Bowel	Dmax
	Dmean		Dmean		Dmean		colon		Dmax
Optic Chiasm	Dmax	Spinal Cord	Dmax	Esophagus	Dmax			Femoral head	V30
	Dmean		Dmean		V40		V40		
Optic Nerve	Dmax	Heart	V30	SpinalCord	Dmax			Skin	Dmean
	Dmean		V40		Dmean		Dmax		
Eyes	Dmean	Lung surface	Dmax	Heart	V30			NT	V10
Lens	Dmax		Skin		Dmax		V40		
Skin	Dmax	NT	V10	Lung surface	Dmax				
NT	V10		Skin		Dmax				
			NT		V10				

NT: Normal Tissue; Dmax: Maximum dose; Dmean: Mean dose; Vx: % volume receiving x Gy.

The TPS usability is assessed by the time it took for generating an IMRT plan from initiating optimization stage 1 to the end of final dose calculation for each method. Additionally, the total number of MUs for each plan was also recorded to provide an estimate of the deliverability[19].

All analyses were performed using IBM SPSS (v25) statistical software (IBM Corporation, Armonk, NY, USA). Two-sided t tests were carried out and  $P < 0.05$  was considered statistically significant. Blinded reviews by the physicians and physicists were performed to assess the plan quality and delivery efficiency.

## Results

### PTV coverage and dose to OARs

Our institutional criteria for plan acceptance were met with all the three sets of plans (MRL-IMRT, ss-IMRT and dMLC-IMRT) for the 17 patients in this study. The MR-Linac plans were considered equivalent to the conventional linac based plans by the quality metrics. Similar PTV coverage with the prescribed dose was achieved, and the doses to OARs were also within the clinically accept limits. **Fig. 1-5** showed the calculated DVH parameters for the plans of five brain patients, three esophagus patients, three lung patients, three vertebra patients, and three rectum patients respectively. In **Fig. 1-5**, the statistical values for these DVH parameters of various organs were presented for MRL-IMRT, ss-IMRT and dMLC-IMRT plans respectively with the box plot. The dark blue, light blue and green boxes showed the result of MRL-IMRT, ss-IMRT and dMLC-IMRT plans respectively, while the boxes mark the 5th and 95th percentiles, the band marks the median, the dot marks the outlying values. The figure's horizontal axis shows the DVH metrics and evaluation parameters. If the DVHs are the CI and HI, the vertical axis shows absolute value from 0 to 1, and if the DVHs are the Dmean and Dmax, the vertical axis shows absolute dose (Gy), and if the DVHs is Vx, the vertical axis shows percentage value. Furthermore the **Fig. 5** only shows the PTV CI and HI for vertebra patients because no OARs were considered. Most parameters showed with minor differences among the three plan groups. The DVH parameters that showed statistically significant difference (at  $P \leq 0.05$  which was chosen) were denoted in the plots with asterisk.

For brain patients, the mean MRL-IMRT, dMLC-IMRT and ss-IMRT CI were  $0.73 \pm 0.08$ ,  $0.81 \pm 0.06$  and  $0.82 \pm 0.86$ , respectively, and the mean HI were  $0.09 \pm 0.01$ ,  $0.06 \pm 0.01$  and  $0.07 \pm 0.01$ , respectively (**Fig. 1**). The differences between MRL-IMRT and ss-IMRT and between MRL-IMRT and dMLC-IMRT were found to be statistically significant, with  $p=0.013$  and  $p=0.024$  for the CI respectively, and with  $p=0.001$  and  $p=0.003$  for the HI, respectively. The brain MRL-IMRT plans had worse CI and HI, but which was not considered clinically significant. In addition, there was a high point maximum dose in the lens with the MRL-IMRT plans, which was also acceptable. The esophagus, lung, rectum and vertebra plans showed no significant difference between MRL-IMRT and ss-IMRT and between MRL-IMRT and dMLC-IMRT (**Fig. 2-5**).

Table 4 shows the maximum dose of the skin and  $V_{10}$  of the unspecified normal tissue. The MRL-IMRT plans had higher dose to the skin roughly by 6% on average, and greater low dose volumes roughly by 8% on average. The differences in the skin dose maximum were statistically significant, with  $p=0.004$  between MRL-IMRT and ss-IMRT, and  $p=0.010$  between MRL-IMRT and dMLC-IMRT, respectively. Likewise, the low dose volume increases from ss-IMRT and dMLC-IMRT had  $p=0.004$  and  $p=0.019$ , respectively. The subtractions of the dose distributions were also analyzed for assessment of any clinical impact for the increased low dose volume. As seen in **Fig. 6** for a typical esophagus case, a big chunk of the  $V_{10}$  volume was at the cranial and caudal border. This was due to the larger penumbra from the MLC leaf tip than from the main jaws with the conventional linac plan. The dose deviation within the boost volume was marginal.

**Table 4** Comparison of dose to skin and normal tissue in all three radiotherapy plan groups

		MRL-IMRT	ss-IMRT	dMLC-IMRT	$P_{\text{MRL vs SS}}$	$P_{\text{MRL vs dMLC}}$
Skin	Dmax(Gy)	$42.90 \pm 10.04$	$40.67 \pm 10.12$	$40.63 \pm 9.84$	0.004	0.010
NT	$V_{10}$	$0.27 \pm 0.13$	$0.25 \pm 0.12$	$0.25 \pm 0.12$	0.004	0.019

## Optimization time and delivery efficiency

The average MUs and optimization time for each plan group are shown in Table 5. The optimization time for the MRL-IMRT, ss-IMRT and dMLC-IMRT plans were  $6.4 \pm 3.1$  min,  $11.1 \pm 5$  min,  $17.9 \pm 6$  min, respectively. MRL-IMRT reduced the average optimization time by 42.3% and 64.2% compared with ss-IMRT and dMLC-IMRT, with  $p < 0.001$ , respectively. The total MUs for the MRL-IMRT, ss-IMRT and dMLC-IMRT plans were  $714.7 \pm 271.51$ ,  $550.42 \pm 155.58$ ,  $580.42 \pm 116.7$ , respectively. Significant difference of the MUs between MRL-IMRT and ss-IMRT was observed ( $p = 0.001$ ), while the difference between MRL-IMRT and dMLC-IMRT group was not statistically significant ( $p = 0.091$ ).

**Table 5** Comparison of efficiency for all three plan groups

	MRL-IMRT	ss-IMRT	dMLC-IMRT	$P_{\text{MRL vs SS}}$	$P_{\text{MRL vs dMLC}}$
Optimization Time (min)	$6.4 \pm 3.1$	$11.1 \pm 5.0$	$17.9 \pm 6.0$	$< 0.001$	$< 0.001$
MUs	$714.7 \pm 271.51$	$550.42 \pm 155.58$	$580.42 \pm 116.7$	0.001	0.091

## Discussion

This study included five brain, three esophagus, three lung, three vertebra and three rectum patients previously treated with a conventional linear accelerator. The PTV size under the limit was the only inclusion/exclusion criteria for patient selection, since the Elekta 1.5 T MR-Linac allows the maximum field size of 22 cm in the superior-inferior direction at isocenter [20]. For the patient cohort, the longitudinal length of the PTV was  $11.3 \pm 4.0$  cm, and the volume of the PTV was  $485.5 \pm 309.0$  cm<sup>3</sup>. Several published studies have shown that the Monaco is capable of producing clinically acceptable plans for the 1.5 T MR-Linac on a few tumor sites [10, 12, 13, 21]. Others have evaluated the quality of IMRT plans using a <sup>60</sup>Co MRI guided radiation therapy system [22, 23]. Our study shows that it is feasible to use the 1.5 T MR-Linac to treat multiple tumor sites with IMRT based on clinically validated protocols and comparative dosimetry. This means that the MR-Linac can be used to treat future patients with these tumor sites for exploring the potential advantages of more accurate targeting in treatment delivery.

MRL-IMRT plans have been shown to meet the clinical requirements of target coverage and OARs sparing successfully for multiple tumor sites. However, there were small differences in the target dose homogeneity and conformity, and the OAR dose, noticeably in the brain plans. The plan quality reflected by target volume conformity and homogeneity is closely related to the complexity of target volume geometry in relation with adjacent OARs, the delivery equipment and technique, and the optimization algorithm [17]. The worse homogeneity and conformality and higher OAR dose for MR-Linac plans was primarily the result of increased source to isocenter distance, effectively increased MLC leaf width, and increased penumbra. In addition, the MLC leaves can travel only in the cranio-caudal direction and the conventional linac MLC leaf moves in the arbitrary direction, thus the field portals can be less than optimal to conform with target. Apart from that, the

MR-Linac isocenter position relative to patient is fixed at bore center, which might not always be ideal. These MR-Linac features were considered relevant to have an impact to the plan quality.

MR-guided dose delivery is inevitably affected by the presence of the permanent magnetic field. The Lorentz force influences the trajectory of secondary electrons. The produced secondary electrons may return to the tissue surface at the air-tissue interface, as so-called ERE [21]. Due to this effect, hot spots and cold spots can arise around the air cavities. This effect is of major concern where there is air volume present in or near the target volume, such as in a head and neck case, and in lung or pelvic region [21]. However, in our study, the ERE apparently did not induce remarkable dose effects, perhaps the multiple beam directions in IMRT plans largely neutralized the dose perturbation by the magnetic field. The maximum dose at the lung surface, defined as a 5 mm inner layer around the lung contours, was not significantly different with the conventional linac plans. This is consistent with the results reported by previous studies, such as that by Allen Li et al[12]. The irregular shape of air cavity inside the human body can be another reason why the magnetic field effect is not as significant as that seen in the phantom study. Furthermore, the inclusion of the effect of the transverse magnetic field in IMRT plan optimization can significantly reduce, or even completely remove, the dose effects on the air-tissue or lung-tissue interfaces inside the body.

However, the observed increases in skin dose for the MR-Linac plans were expected, and consistent with other published studies[10, 11, 12, 21]. This was clearly the consequence of ERE under the 1.5 T magnetic field. Furthermore, a significant increase of the low dose region in the normal tissues was also observed in our study. The dose-difference maps showed the higher doses in a region of approximately 3 cm at the superior and inferior edges of the target volume with the MR-Linac. This is largely due to the fixed MLC leaf direction and extended distance of the treatment. A small effect could possibly be associated with that transverse magnetic field sweeps the contaminant electrons away from the radiation beam and traveling along the magnetic field direction. Hackett et al[24] observed that for large fields, the spiraling contaminant electrons (SCE) dose was in the same order of magnitude as that from scattered and leakage photons, and the dose for both SCE and scattered photons decreased rapidly with decreasing beam size and increasing distance from the beam edge.

This study also demonstrated that the planning efficiency of MR-Linac IMRT plan was superior to conventional linac based IMRT plans. The average optimization time for MRL-IMRT plan was reduced by 42.3% and 64.2% compared with ss-IMRT and dMLC-IMRT, respectively. This is mainly owing to that the MR-Linac specific TPS Monaco (v5.40.01) employs a much fast dose engine based on a graphic processing unit (GPU)-based Monte Carlo dose calculation platform (GPUMCD)[12, 14].

The number of MUs has been used as a surrogate measure for plan complexity assessment [11]. In this study, the average number of MUs for the MRL-IMRT plans was nearly 30% higher than the ss-IMRT plans, but no statistically significant difference was observed for the dMLC-IMRT plans. The dose rate for Unity MR-Linac is 425–450 MU/min, which is less than that of a conventional linac (generally 600–1400 MU/min). It has been reported that the beam-on time would decrease by 10 to 40 seconds for every 100 MU/min increase of dose rate[25]. Therefore, it is expected that the delivery time for MR-Linac is longer compared with the conventional linac. Currently, only the step-and-shoot delivery technique can be used for MR-Linac system, while the dynamic MLC delivery technique has been used with conventional linacs in our clinical practice. The step-and-

shoot technique delivery time is also longer than dynamic MLC technique. Dynamic MLC delivery in the future will improve the delivery efficiency for Elekta Unity.

## Conclusions

It was feasible to create clinically acceptable IMRT plans with a 1.5 T MR-Linac system for multiple tumor sites. The target coverage, the dose conformity, and the OAR sparing were similar to the plans using a conventional linac. The presence of 1.5 T transversal magnetic field was fully considered throughout the dose calculation and plan optimization process in Monaco system. With the GPUMCD dose engine, the planning efficiency of MRL-IMRT was improved with much reduced optimization time. The delivery time and total MU for the MR-Linac plans were increased. Potential clinically important features were the increased skin dose and increased volume of low dose region, which should warrant special attentions in the clinic.

## Declarations

### Ethics approval and consent to participate

The Ethics Committee of Sun Yat-sen University Cancer Center approved the study protocol.

### Consent for publication

Not applicable

### Availability of data and materials

All data generated or analyzed during the current study are available from the corresponding author upon reasonable request.

### Competing interests

The authors declare that they have no competing interests.

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### Authors' contributions

All authors contributed to the research. SD completed the treatment plans, performed the data analysis, and drafted the manuscript. XH and BW made contribution to the study's conception and design. YL, HL and YC revised and commented on the draft. RL and JZ participated in the data analysis.

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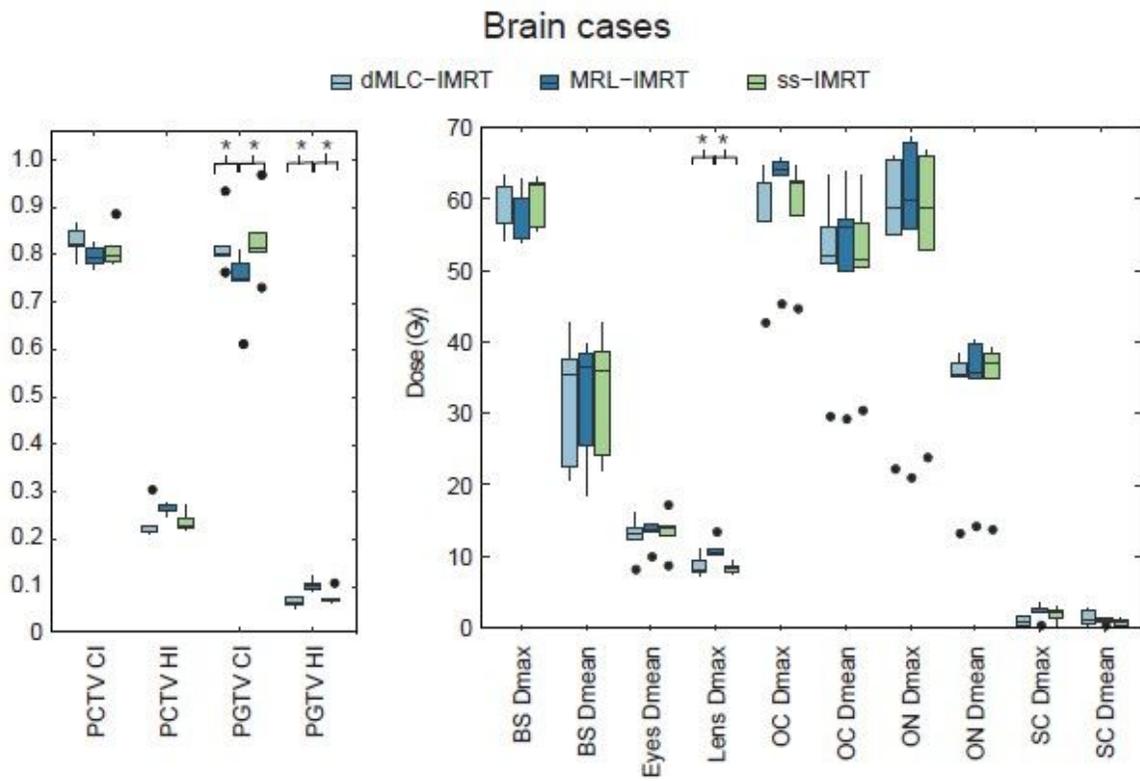
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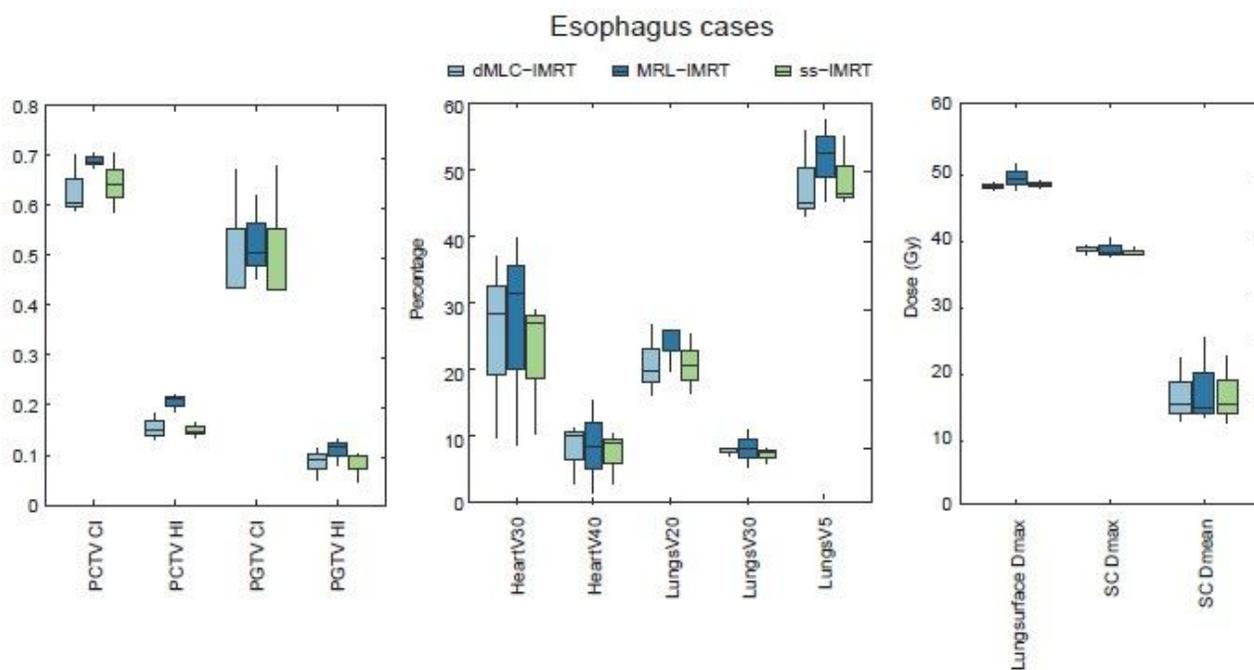
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## Figures



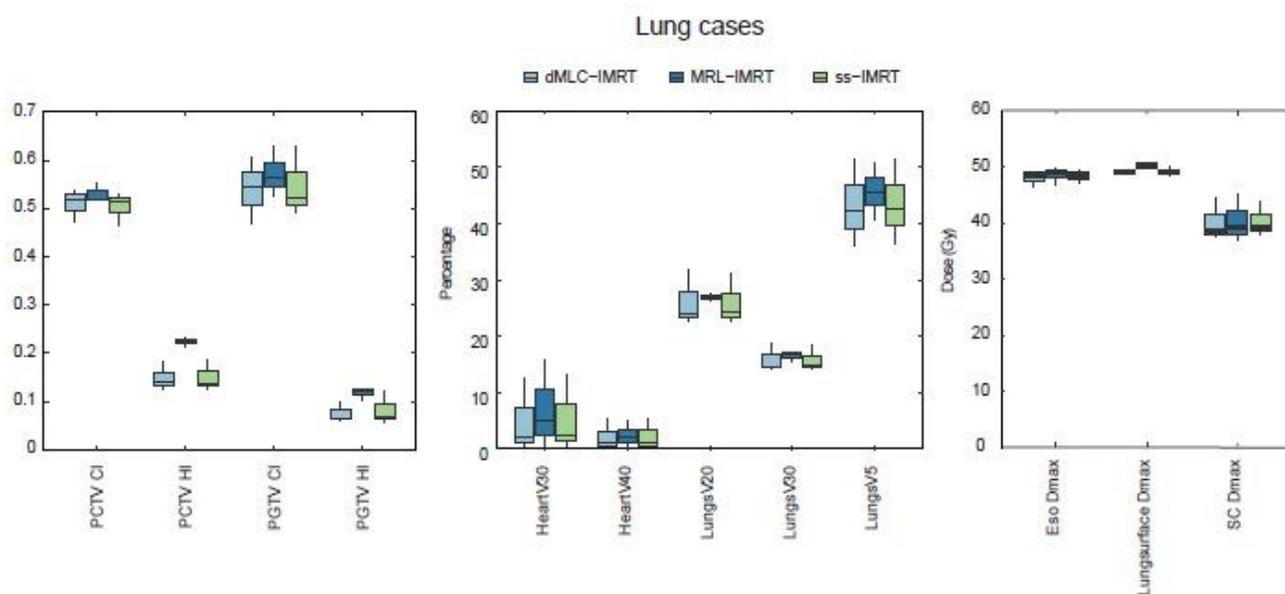
**Figure 1**

DVH parameters for five brain patients with MRL-IMRT, ss-IMRT and dMLC-IMRT plans. The boxes mark the 5th and 95th percentiles, the band marks the median, the dot marks the outlying values. A \* indicates a significance of  $P < 0.05$ .



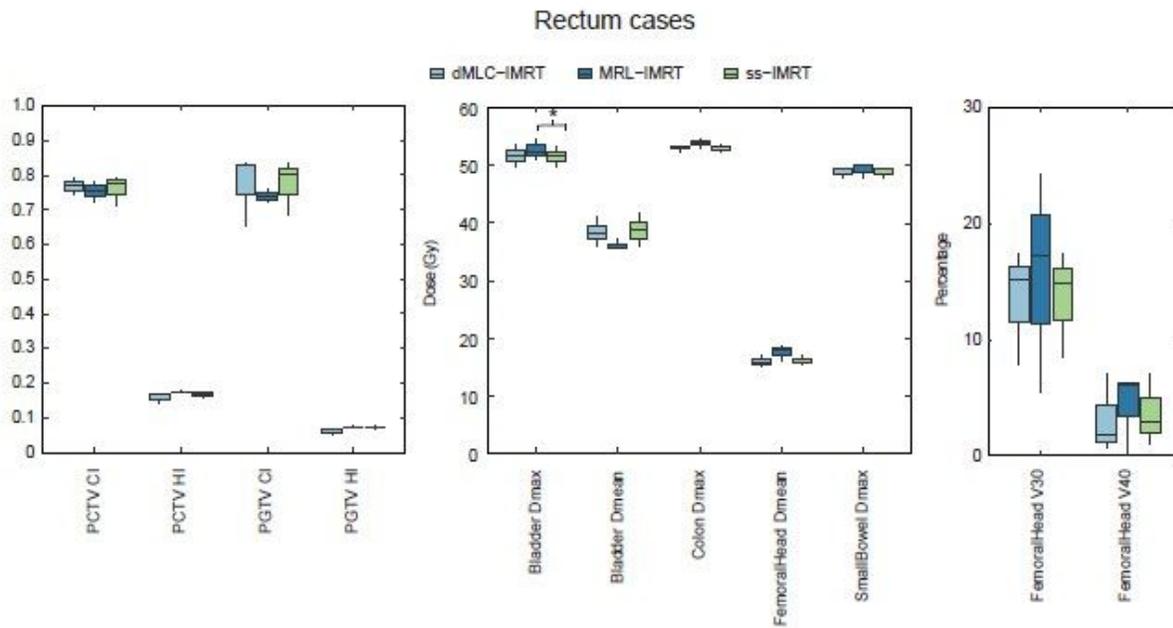
**Figure 2**

DVH parameters for three esophagus patients optimized with MRL-IMRT, ss-IMRT and dMLC-IMRT. The boxes mark the 5th and 95th percentiles, the band marks the median.



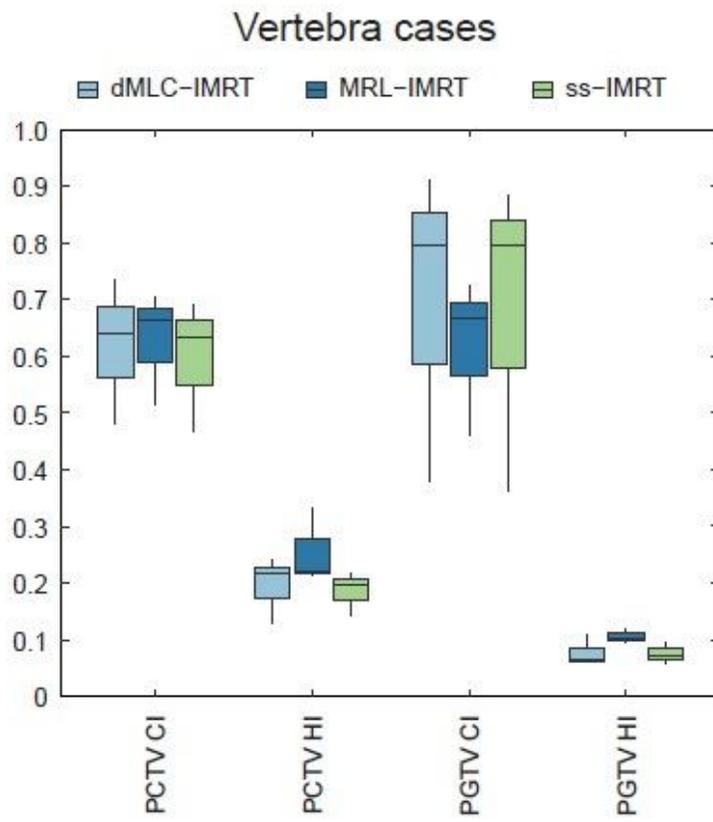
**Figure 3**

DVH parameters for three lung patients optimized with MRL-IMRT, ss-IMRT and dMLC-IMRT. The boxes mark the 5th and 95th percentiles, the band marks the median.



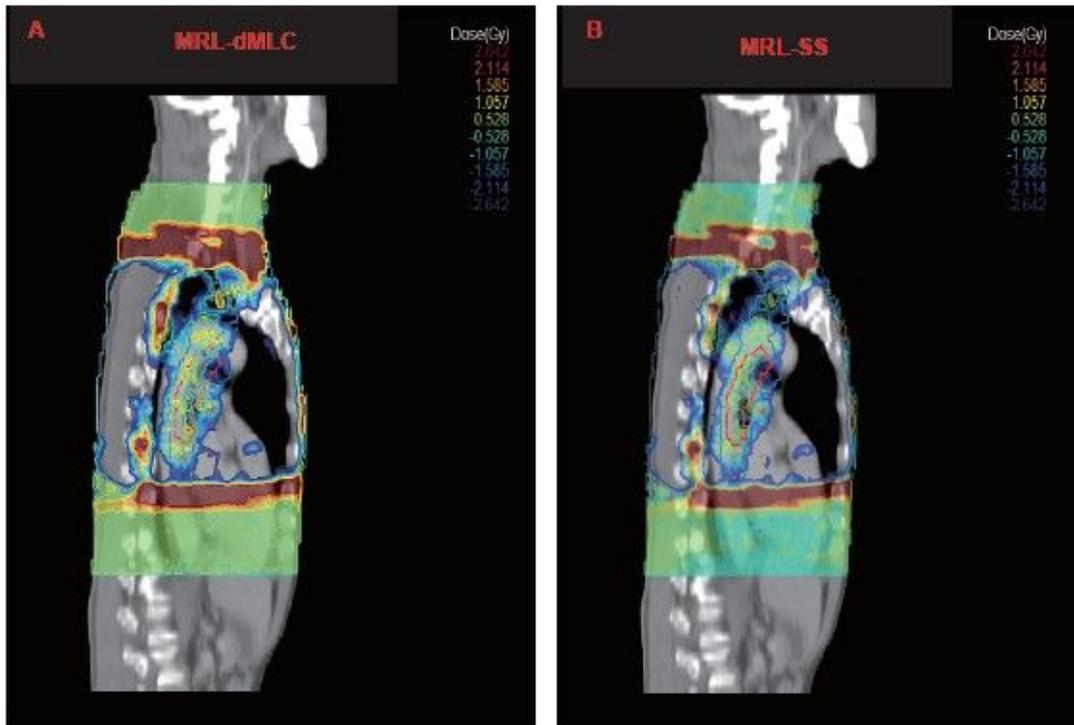
**Figure 4**

DVH parameters for three rectum patients optimized with MRL-IMRT, ss-IMRT and dMLC-IMRT. The boxes mark the 5th and 95th percentiles, the band marks the median.



**Figure 5**

DVH parameters for three vertebra patients optimized with MRL-IMRT, ss-IMRT and dMLC-IMRT. The boxes mark the 5th and 95th percentiles, the band marks the median.



**Figure 6**

The dose-difference maps which are obtained by subtracting the dose distribution of the dMLC-IMRT plan and ss-IMRT plan voxel-by-voxel from the dose distribution in the MRL-IMRT plan for an esophagus case.