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Original research article

Dosimetric comparison of dynamic conformal arc integrated with segment shape optimization and variable dose rate versus volumetric modulated arc therapy for liver SBRT

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ABSTRACT

Aim: The aim is a dosimetric comparison of dynamic conformal arc integrated with the segment shape optimization and variable dose rate (DCA_SSO_VDR) versus VMAT for liver SBRT and interaction of various treatment plan quality indices with PTV and degree of modulation (DoM) for both techniques.
Background: The DCA is the state-of-the-art technique but overall inferior to VMAT, and the DCA_SSO_VDR technique was not studied for liver SBRT.
Materials and methods: Twenty-five patients of liver SBRT treated using the VMAT technique were selected. DCA_SSO_VDR treatment plans were also generated for all patients in Monaco TPS using the same objective constraint template and treatment planning parameters as used for the VMAT technique. For comparison purpose, organs at risk (OARs) doses and treatment plans quality indices, such as maximum dose of PTV (D_{max}%), mean dose of PTV (D_{mean}%), maximum dose at 2 cm in any direction from the PTV (D_{2cm}%), total monitor units (MU's), gradient index $R_{50\%}$, degree of modulation (DoM), conformity index (CI), homogeneity index (HI), and healthy tissue mean dose (HTMD) were compared.
Results: Significant dosimetric differences were observed in several OARs doses and lowered in VMAT plans. The D_{2cm}%, $R_{50\%}$, CI, HI and HTMD are dosimetrically inferior in DCA_SSO_VDR plans. The higher DoM results in poor dose gradient and better dose gradient for DCA_SSO_VDR and VMAT treatment plans, respectively.
Conclusions: For liver SBRT, DCA_SSO_VDR treatment plans are neither dosimetrically superior nor better alternative to the VMAT delivery technique. A reduction of 69.75% MU was observed in DCA_SSO_VDR treatment plans. For the large size of PTV and high DoM, DCA_SSO_VDR treatment plans result in poorer quality.

1. Background

Radiotherapy is emerging as an important treatment modality for liver tumors, either with curative or palliative intent. In recent years, stereotactic body radiation therapy (SBRT) has evolved as a promising technique for the treatment of hepatocellular carcinomas (HCC).[1,2] With the advancement in imaging modalities and delivery techniques, an intense dose of radiation can be focused on small moving tumors. In SBRT, the high fractional ablative dose can be delivered to unresectable liver tumors for better local control.[3,4] SBRT is extensively used for primary and metastatic liver tumors as standard treatment options over conventional fractionation.[4,5] Both SBRT and radiofrequency ablation (RFA) are promising treatment options for patients with intrahepatic oligometastatic disease.[6] Various treatment delivery techniques, such as conventional static field, dynamic conformal arcs (DCA), intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT), are available in SBRT.[7,8] Moreover, SBRT of liver tumors on Cyberknife using a single fiducial marker tracking regime is also encouraged with additional safety margins around the ITV.[9]

The DCA is a state-of-the-art technique and used over the years for stereotactic radiosurgery (SRS) and stereotactic radiotherapy

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(SRT). Further, the DCA approach has been extended to SBRT over the last few years.[10–13] In SBRT, treatment delivery using the DCA technique, the dose prescription is commonly defined at the specific isodose surface that covers 95% of the target volume and is normalized to 100% at the isocenter.[14] Nowadays, the VMAT technique is the standard treatment practice in SBRT to facilitate the sharp dose gradient outside the target volume. Moreover, the conformity index is better in VMAT as compared to the conventional static field.[15,16] In contrast to DCA, VMAT is inverse planning and optimizes the multileaf collimator (MLC) shapes, gantry speed, and dose rate simultaneously, which leads to an increase in treatment plan complexity. In VMAT, a high treatment plan complexity along with a high fractional dose increases the total monitor units (MUs) and treatment duration.[1,2] For moving tumors, the VMAT delivery is always prone to the interplay effect because of movement between linear accelerator parameters (MLC, dose rate and gantry speed) and target.[17–19] In contrast to VMAT, the DCA treatment technique is more simple for moving tumors because of MLC motion. In SBRT, the treatment delivery using DCA is a promising tool for moving tumors because the interplay effect is not very much relevant for it. The field projection is continuously changing to encompass the target at each control point. Furthermore, DCA is superior to VMAT in the context of shorter treatment delivery and a lower interplay effect. In DCA, the gradient index and conformity index are not dosimetrically superior to VMAT plans owing to its lower degree of freedom.[10,20,21]

To increase the efficacy of DCA technique, the Monaco treatment planning system (TPS) (version 5.0, Elekta, Crawley, UK) allows modification in DCA, where segment shape optimization (SSO) (Monaco version 5.10, Elekta CMS, Maryland Heights, MO, USA) and variable dose rate (VDR) is integrated with the DCA. The modified DCA is an inverse planning based delivery technique in which MLC conforms to the target projection and allows the optimization of gantry speed, dose rate, and segment shape to confirm the target.[22,23] There is no sufficient literature available for the dosimetric comparison of modified DCA versus VMAT for SRS/SRT and SBRT. Besides, the modified DCA also allows a partial blockage of a target which overlaps with organs at risk (OARs), if OARs are assigned with higher priority or as avoidance structure.

2. Aim

The main aim of this study is to perform the dosimetric comparison between the VMAT and modified DCA which is integrated with the SSO and VDR (DCA_SSO_VDR) for the liver SBRT. A correlation of various treatment plan quality indices with planning target volume (PTV) and degree of modulation (DoM) were also analyzed for both techniques.

3. Materials and methods

3.1. Patient selection

A total number of twenty-five patients of liver SBRT pretreated using the VMAT technique were included in this study. All the patients underwent the 64 slice CT scan acquisition (GE Discovery 710 PET-CT, Amersham, UK). Out of these, seventeen patient scans were acquired using four-dimensional computed tomography (4DCT) and the remaining eight patients were scanned using a breath-hold technique with the help of a pressure sensor-based load cell device, Anzai gating system (AZ-733V; Anzai Medical System, Tokyo, Japan).[24] In the 4D-CT scans, the gross tumor volume (GTV) was delineated on all ten phases to delimit the internal target volume (ITV). A PTV was generated by taking an isotropic margin of 5 mm around the ITV. The treatment planning conditions viz. size of the PTV, location of PTV, prescribed dose and number of fractions of all the patients are given in Table1.

Table 1
Treatment planning conditions such as the location of the tumor, PTV (cc), prescription dose (cGy) and the number of fractions for all cases are defined in the table below.

Patient	Location	PTV (cc)	Prescribed Dose (cGy)	Fractions
1	RUL	118.5	4000	5
2	RLL	319.2	2500	5
3	RUL	313.5	4800	6
4	RLL	1097.9	4000	5
5	RUL	89.4	5000	5
6	RLL	151.3	5000	5
7	RLL	513.1	4200	6
8	RLL	290.2	4000	5
9	RLL	858.7	4800	6
10	RUL	204.8	4800	6
11	RUL	212.1	4500	5
12	RUL	440.5	4500	6
13	RLL	617.2	3600	5
14	RLL	772.6	4000	5
15	RML	1226.3	4000	15
16	RLL	795.5	4500	15
17	LLL	475.1	4500	15
18	RLL	311.5	5000	5
19	RLL	896.7	4500	15
20	LLL	213.8	5000	5
21	RLL	1217.9	4500	15
22	LLL	523.2	4500	15
23	RML	456.2	4500	15
24	RML	298.1	5000	10
25	RLL	249.3	5000	5

Abbreviations: RUL = Right Upper Lobe; RML = Right Middle Lobe; LLL = Left Lower Lobe; RLL = Right Lower Lobe.

3.2. Treatment planning

The patient treatment planning was done in the Monaco treatment planning system (TPS; Monaco ver. 5.1, Elekta CMS, Maryland Heights, MO, USA). DCA_SSO_VDR treatment plans were also generated corresponding to the VMAT plans for all patients using the same objective constraint's template. Treatment plans were generated for Elekta Versa HD linear accelerator (Elekta, Crawley, England) equipped with an Agility head collimator. The treatment planning parameters viz. gantry start and stop angle, collimator angle, couch angle and beam energy were the same in DCA_SSO_VDR treatment plans as in VMAT. All the treatments were planned using 10 MV beam for both techniques. An isocenter was located in the center of PTV for both types of treatment plans. Both DCA_SSO_VDR and VMAT were optimized using the SSO algorithm (Monaco version 5.10, Elekta CMS, Maryland Heights, MO, USA) and dose calculation was performed using the Monte Carlo algorithm with 2 mm grid size and 3% Monte Carlo statistical variance per dose calculation.[25] For comparison purposes, both kinds of treatment plans were rescaled, so at least 95% of PTV received 100% of the prescription dose.

Furthermore, vulnerable OARs were also considered, while generating the treatment plans, and appropriate constraints were optimized for both techniques as defined by RTOG 1112 protocol. OARs constraints used for evaluation are mean liver dose (MLD), dose to 700 cc (D_{700cc}) of normal liver (liver-ITV), V_{20Gy} of normal liver (absolute normal liver volume receiving 20 Gy), dose to 0.5 cc ($D_{0.5cc}$) of the stomach, esophagus, duodenum, small bowel, large bowel, skin, maximum dose (D_{max}) to planning risk volume (PRV) cord (spinal cord +5 mm margin), mean dose (D_{mean}) to left kidney and right kidney and dose to 30 cc (D_{30cc}) of heart. While analyzing, all the OARs and plan quality metric physical doses were normalized to prescription dose allowing simple comparison and interpretation. All the treatment plans were optimized using two

partial coplanar arcs for both kinds of treatment plans. The complementary collimator angle of 30° and 330° were chosen for both arcs to reduce the tongue and groove effect and accumulative effects of transmission through MLC.

3.3. Plan quality metric

The treatment plans generated using both delivery techniques were compared using dose-volume histogram statistics and various other treatment plans quality indices such as maximum dose of PTV (D_{max} (%): in % of prescription dose), mean dose of PTV (D_{mean} (%): in % of prescription dose), maximum dose at 2 cm in any direction from the PTV (D_{2cm} (%): in % of prescription dose), total monitor units (MUs), gradient index ($R_{50\%}$), Degree of modulation (DoM), Conformity index (CI), Homogeneity Index (HI), healthy tissue mean dose (HTMD), where $R_{50\%}$, DoM, CI, HI are defined as follows:

$R_{50\%}$ is defined as the ratio of the 50% prescription isodose volume to the PTV volume as given in Eq. (1).

$$R_{50\%} = \frac{\text{The 50\% prescription isodose volume}}{\text{PTV volume}} \tag{1}$$

Masi et al. describe the DoM for VMAT plans which determines the treatment plan complexity by considering the effect of leaf sequence variability (LSV) defined in Eq. (3), aperture area variability (AAV) defined in Eq. (4) and MU at each control point, and the final formula to calculate DoM is given in Eq. (5).[26] Park et al. also studied the DoM by incorporating the effect of gantry speed, dose rate and leaf speed for VMAT plans and reported the significant correlation with previously published results of Masi et al.[27] The DICOM-RP files were exported from TPS and the inhouse program was written in the MATLAB (version 2011) to calculate the DoM as defined in Eq. (5). The lower the values, the more treatment plan complexity so the reciprocal of the final values were taken to make the interpretation simpler. Hence, the higher DoM will be reflected in higher treatment plan complexity.

$$\text{pos}_{\max}(\text{CP}) = \left\langle \max(\text{pos}_{n\in N}) - \min(\text{pos}_{n\in N}) \right\rangle_{\text{leftbank}} \tag{2}$$

$$LSV_{CP} = \left(\frac{\sum_{n=1}^{N-1} \left(\text{pos}_{\max} - \left| \left(\text{pos}_n - \text{pos}_{n+1} \right) \right| \right)}{(N-1)^{*}\text{pos}_{\max}} \right)_{\text{leftbank}} * \left(\frac{\sum_{n=1}^{N-1} \left(\text{pos}_{\max} - \left| \left(\text{pos}_n - \text{pos}_{n+1} \right) \right| \right)}{(N-1)^{*}\text{pos}_{\max}} \right)_{\text{rightbank}} \tag{3}$$

$$AAV_{CP} = \left(\frac{\sum_{a=1}^{A} \left(\left\langle \text{pos}_a \right\rangle_{\text{leftbank}} - \left\langle \text{pos}_a \right\rangle_{\text{rightbank}} \right)}{\sum_{a=1}^{A} \left(\left\langle \max(\text{pos}_a) \right\rangle_{\text{leftbank}\in\text{arc}} - \left\langle \max(\text{pos}_a) \right\rangle_{\text{rightbank}\in\text{arc}} \right)} \right) \tag{4}$$

$$DoM_{arc} = 1 \Big/ \sum_{i=1}^{i-1} \left[\frac{\left(AAV_{cp_i} + AAV_{cp_{i+1}} \right)}{2} \right] \tag{5}$$

CI which is the ratio of the square of PTV covered by prescription isodose volume (PIV) to the product of PTV and PIV as defined by Paddick et al. in Eq. (6).[28]

$$\text{CI} = \frac{\text{PTV (PIV)}^{*}\text{PTV (PIV)}}{\text{PTV}^{*}\text{PIV}} \tag{6}$$

where PTV (PIV) — PTV covered by PIV

HI is defined as follows[29]:

$$\text{HI} = \frac{D_2 - D_{98}}{D_{pres}} * 100 \tag{7}$$

where D_{98} is the dose to 98% of the PTV; D_2 is the dose to 2% of the PTV; D_{pres} — Prescribed Dose to the PTV.

HTMD is defined as a mean dose of the spherical shell surrounding the PTV with internal and external radii of 0.5 cm and 1.5 cm from the PTV, respectively.[21]

3.4. Patient-specific QA

For each delivery technique, patient-specific QA plans were generated using the Octavious R series phantom and measurements were performed using Octavius 1500 ion chamber array (PTW, Freiburg, Germany) which consists of 1405 air vented cubic ion chambers of $0.44 \times 0.44 \times 0.30$ cm,[3] each mounted below a 0.5 cm polystyrene build-up layer irradiation.[30] The 2D gamma index was evaluated using Verisoft software (version 6.0.1 PTW, Freiburg, Germany) with a tolerance of 10% dose difference for values below 0.3 Gy and suppress the dose below 10% of maximum dose of calculated volume when normalized at global maximum dose.

3.5. Statistics

A paired sample t-test/Wilcoxon signed ranks test was used, subject to applicability, to check the hypothesis that the difference in the mean value of the parameters for the two methods is significant or not. The Shapiro–Wilk test was used to evaluate the normality of data. A threshold p-value of 0.05 was considered statistically significant between the two techniques. Pearson correlation coefficients were calculated to analyze the significant linear correlation between two variables.

4. Results

The mean value with standard deviation (SD) for various treatment plan quality indices was defined for the normally distributed data, otherwise median with interquartile range (IOR) was defined where the data normality was absent, with their respective p-values as shown in Figs. 1–4.

The results of treatment plan quality indices and various OAR's doses for both kinds of treatment techniques are shown in Figs. 1–4. The black line and red line correspond to VMAT and DCA_SSO_VDR techniques, respectively. The difference in the mean values of D_{max}% (PTV) and D_{mean}% (PTV) for VMAT and DCA_SSO_VDR techniques were statistically insignificant as represented in Fig. 1(a, b), respectively, whereas the difference in mean values of D_{2cm}%, $R_{50\%}$, CI, HI, and HTMD% were statistically significant as demonstrated in Figs. 1(c, d) and 2(a, b, f), respectively. In VMAT plans, the values of D_{2cm}% and $R_{50\%}$ indices were lower and resulted in lower HTMD with better CI (Fig. 2(a) and (f)).

The difference in MUs is statistically significant and results in high DoM for VMAT plans as shown in Fig. 1(e) and (f) for MUs and

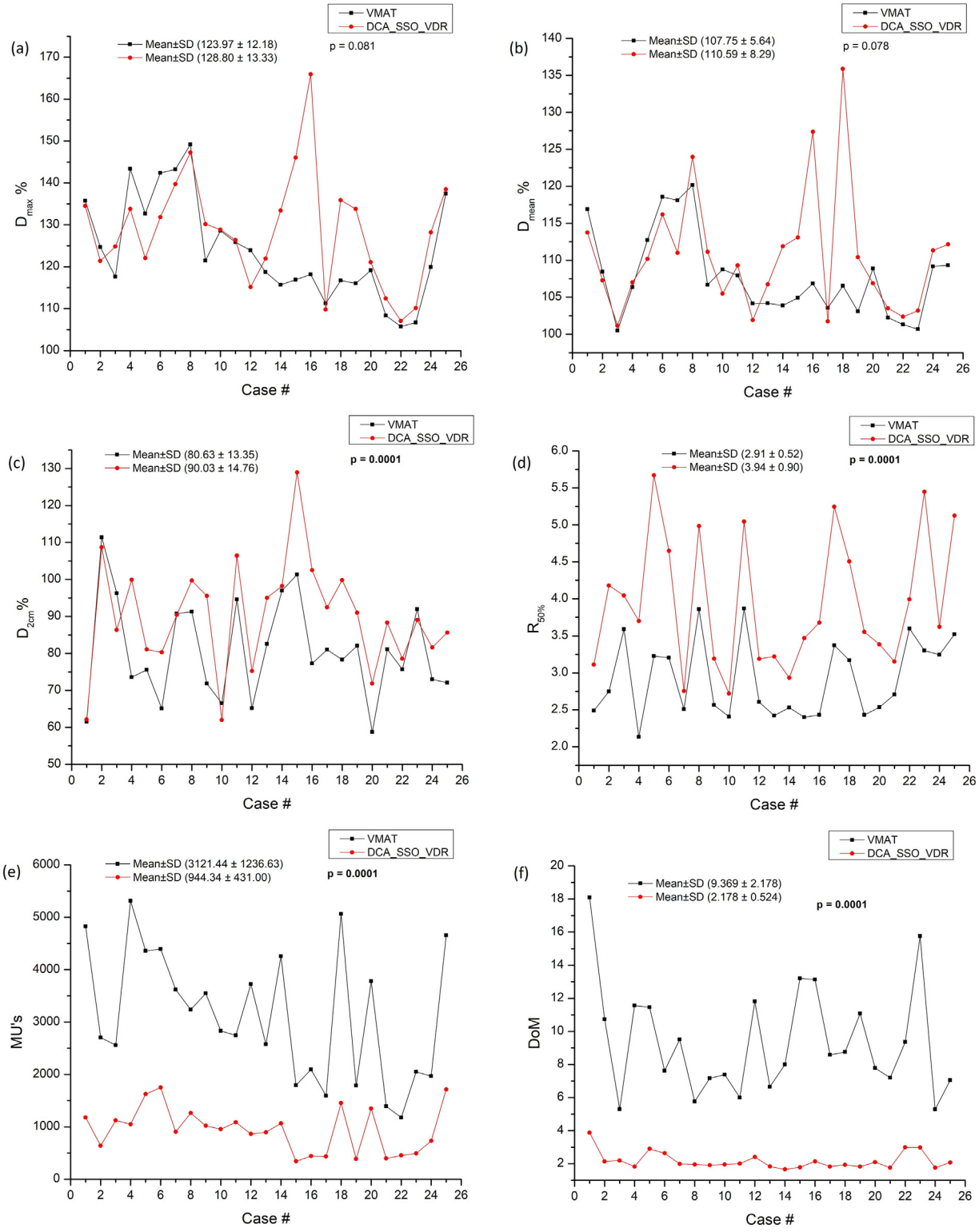

Fig. 1. Comparison of (a) D_{max}% (PTV); (b) D_{mean}% (PTV); (c) D_{2cm}%; (d) $R_{50\%}$; (e) MU's and (f) DoM; values between VMAT and DCA_SSO_VDR treatment techniques with respective p-values for all cases are demonstrated here. The statistical significant p-values are shown in bold text.

DoM, respectively. In contrast to VMAT plans, the number of MUs is considerably lower in DCA_SSO_VDR plans, reducing the beam-on time. As presented in Fig. 2(c), the difference in the MLD is statistically significant. However, in Liver SBRT the MLD is at a higher priority to save normal liver as much as possible, which, consequently, results in lower radiation-induced liver disease (RILD). The differences in D_{700}cc and V_{20}Gy of the normal liver for VMAT and DCA_SSO_VDR treatment techniques are statistically significant as demonstrated in Fig. 2(d) and (e), respectively.

The differences in the mean value of OARs viz. esophagus, stomach and heart doses for VMAT and DCA_SSO_VDR plans are statistically insignificant as represented in Figs. 3(a, b) and 4(c). However, for OARs viz. the duodenum, small bowel, large bowel, PRV cord, left kidney, right kidney and skin the differences in the

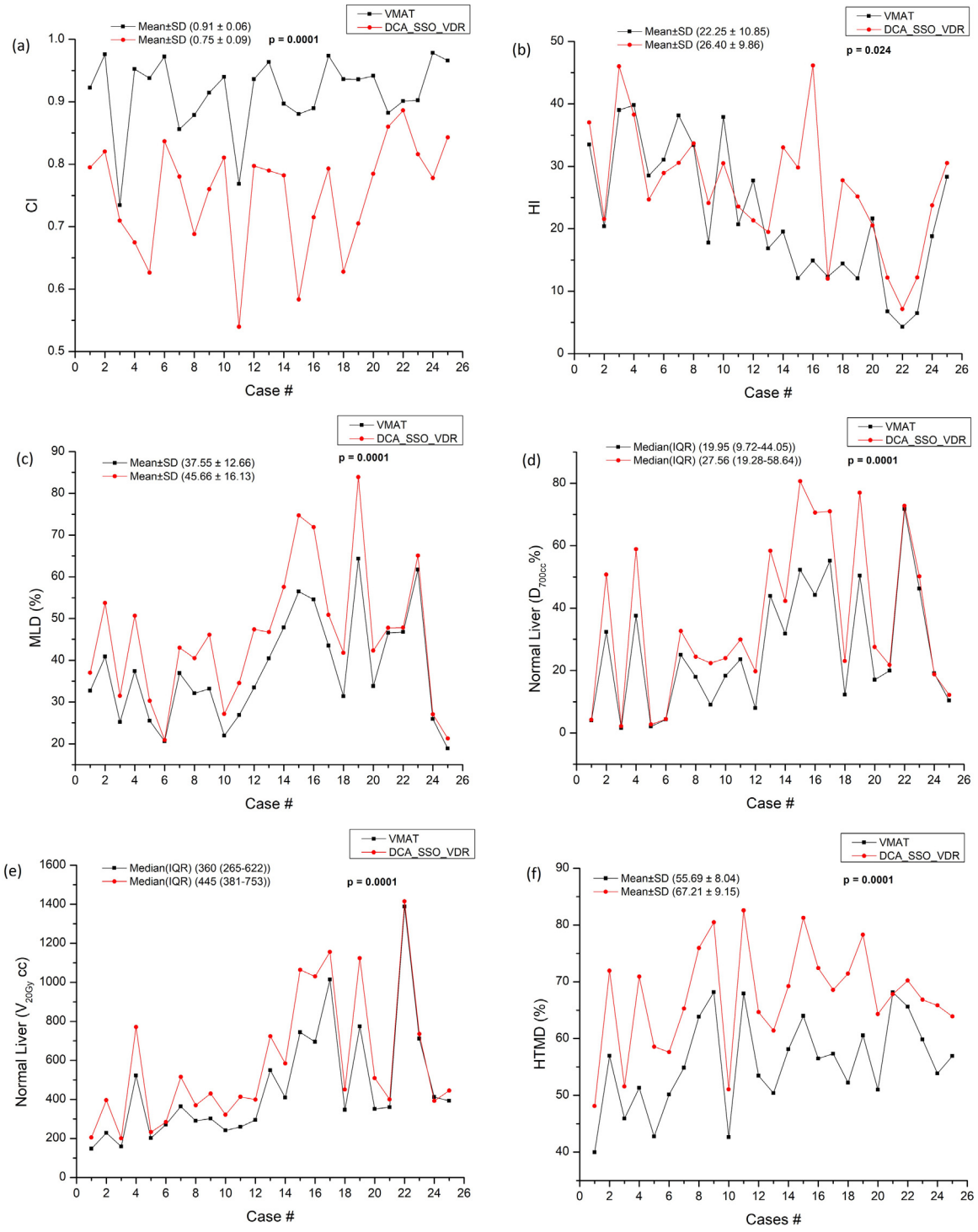

Fig. 2. Comparison of (a) CI; (b) HI; (c) MLD%; (d) Normal Liver (D_{700}cc%); (e) Normal Liver (V_{20}Gy%) and (f) HTMD%; values between VMAT and DCA_SSO_VDR treatment techniques with respective p-values for all cases are demonstrated here. The statistical significant p-values are shown in bold text.

mean value of doses for VMAT and DCA_SSO_VDR plans are statistically significant as represented in Figs. 3(c–f) and 4(a, b, d).

The linear correlation and significance of treatment plan quality indices viz. MUs, HI, CI, $R_{50\%}$, D_{2cm}% and DoM with PTV size were analyzed using the Pearson correlation coefficient for both VMAT and DCA_SSO_VDR treatment plans. The reduction in MUs was noticed with an increase in PTV size for both techniques, but statistically significant for the DCA_SSO_VDR technique only (Fig. 5(a)). For HI, no correlation was observed with PTV size in DCA_SSO_VDR plans, whereas for VMAT, the correlation between HI and PTV is on the verge of statistical significance threshold level as shown in Fig. 5(b). In VMAT, HI is decreasing with an increase in the size of PTV.

Similarly, for CI, no statistically significant correlation was observed with the change in the size of the PTV for both techniques as demonstrated in Fig. 5(c). As represented in Fig. 5(d), the $R_{50\%}$ continuously decreases with an increase in PTV size and correlation is statistically significant for both treatment techniques. The positive correlation was observed between D_{2cm}% and PTV as shown in Fig. 5(e), but this trend is statistically significant only for

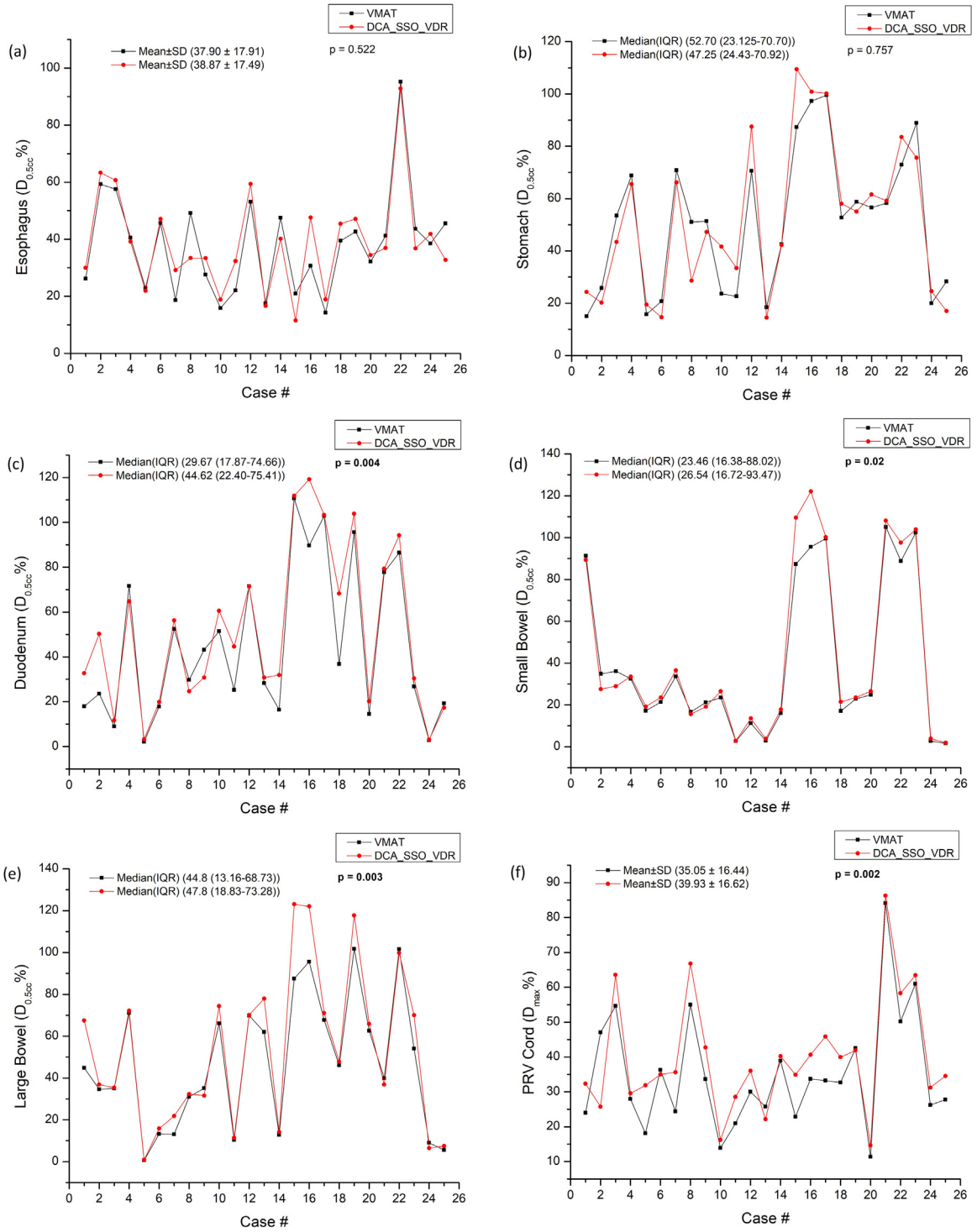

Fig. 3. Comparison of OARs doses in percentage viz. (a) esophagus; (b) stomach; (c) duodenum; (d) small bowel; (e) large bowel and (f) PRV cord; values between VMAT and DCA_SSO_VDR treatment techniques with respective p-values for all cases are demonstrated here.

the DCA_SSO_VDR technique and statistically insignificant for the VMAT technique. The treatment plan complexity (DoM) increases with the PTV size in VMAT plans and correlation is statistically insignificant. However, in DCA_SSO_VDR treatment plans the negative correlation between DoM and PTV was observed as represented in Fig. 5(f).

The correlation between the MU ratio of VMAT and DCA_SSO_VDR treatment plans with PTV size was also analyzed and the statistically significant increasing trend was observed with an increase in PTV size as shown in Fig. 6(a). In addition to all, correlation of DoM ratio (DoM_VMAT and DoM_DCA_SSO_VDR) with HI, CI, and D_{2cm}% was also studied for both treatment techniques as shown in Fig. 6(b–d). An insignificant correlation was found with CI and HI for both techniques and, hence, it may be inferred that an increase in plan modulation does not make any change in CI and HI. For D_{2cm}%, the statistically significant correlation was observed with the DoM ratio for the DCA_SSO_VDR technique, whereas in VMAT, the correlation was statistically insignificant.

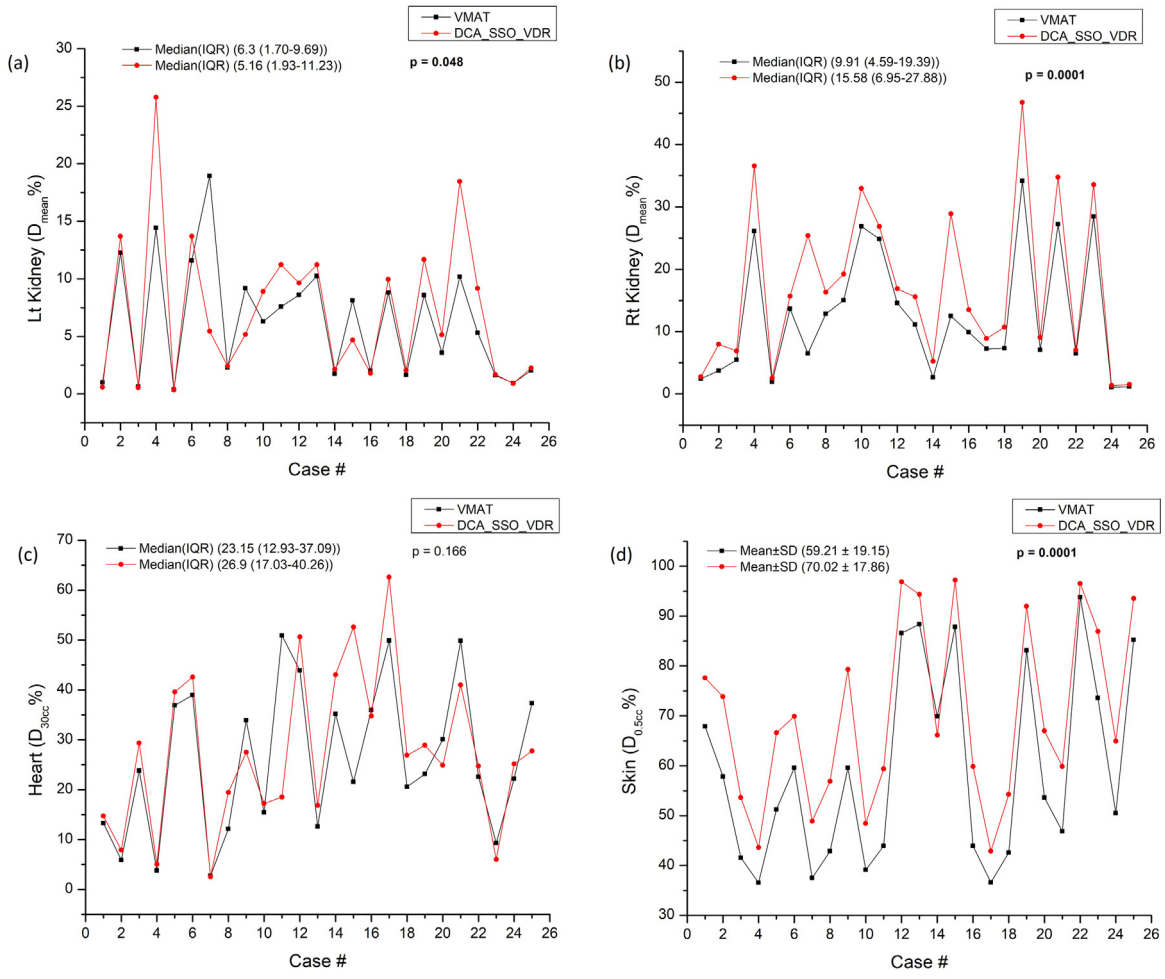

Fig. 4. Comparison of OARs doses in percentage viz. (a) left kidney; (b) right kidney; (c) heart; (d) skin; values between VMAT and DCA_SSO_VDR treatment techniques with respective p-values for all cases are demonstrated here. The statistical significant p-values are shown in bold text.

The correlation between $R_{50\%}$ and DoM was also analyzed for both techniques and results in a significant correlation for both methods. In VMAT, the trend is decreasing whereas in DCA_SSO_VDR the trend is increasing in nature. Therefore, increasing the plan modulation results in decreasing the $R_{50\%}$ and increasing the $R_{50\%}$ for VMAT and DCA_SSO_VDR treatment plans, respectively, as illustrated in Fig. 6(e, f).

4.1. Patient-specific QA

All the VMAT treatment plans were passing with more than 95% gamma index with gamma criteria of 3% and 3 mm for dose difference (DD) and distance agreement (DTA), respectively. In the DCA_SSO_VDR technique, all the treatment plans were passing with more than 95% gamma index with gamma criteria of 2% and 2 mm for DD and DTA, respectively.

5. Discussion

As evident from Fig. 1(a) and (b), the differences in the maximum dose and mean dose of the PTV for two different techniques are statistically insignificant. The mean values of the D_{2cm}% are 80.63% and 90.03% for VMAT and DCA_SSO_VDR techniques, respectively. Therefore, the dose spillage beyond 2 cm from the PTV is more in DCA_SSO_VDR treatment plans in comparison to VMAT treatment plans as shown in Fig. 1(c). This finding is consistent with $R_{50\%}$ values as well, the higher value of D_{2cm}% leads to a lower dose gradient and vice versa, therefore results in a higher $R_{50\%}$ value. The dose gradients in DCA_SSO_VDR treatment plans are not so sharp as compared to VMAT treatment plans. The mean values of D_{2cm}% and $R_{50\%}$ are much lower in VMAT plans and results are statistically significant as represented in Fig. 1(c) and (d), respectively. Dose fall-off is much sharper in the VMAT delivery which is the primary concern of liver SBRT treatment and, consequently, results in better normal liver sparing. Mostly in HCC cases, liver tumors are embedded in the normal liver; therefore, a better $R_{50\%}$ index leads to lower MLD. As plotted in Fig. 2(c), the MLD value is lower in VMAT treatment plans and, consequently, will result in a lower normal tissue complication probability of a normal liver. A lower $R_{50\%}$ will ultimately lead to lower HTMD; the difference in the mean value of HTMD is statistically significant for two different techniques. Therefore, high dose volume (HTMD) spillage around the PTV is also lower in VMAT treatment plans in comparison to DCA_SSO_VDR treatment plans as presented in Fig. 2(f).

MUs are significantly lower in DCA_SSO_VDR treatment plans (Fig. 1(e)) and will result in shorter beam-on time. Hence, the DCA_SSO_VDR delivery method can be more comfortable for patients, especially in breath-hold treatments. Although in the DCA_SSO_VDR technique, the gantry speed and dose rate are continuously changing but average aperture size is opened for a large part of treatment to cover the PTV. The large aperture size results in fewer MUs as compared to small aperture size and may be less susceptible to the interplay effect. Many studies are available for conventional DCA techniques in support of viable delivery options

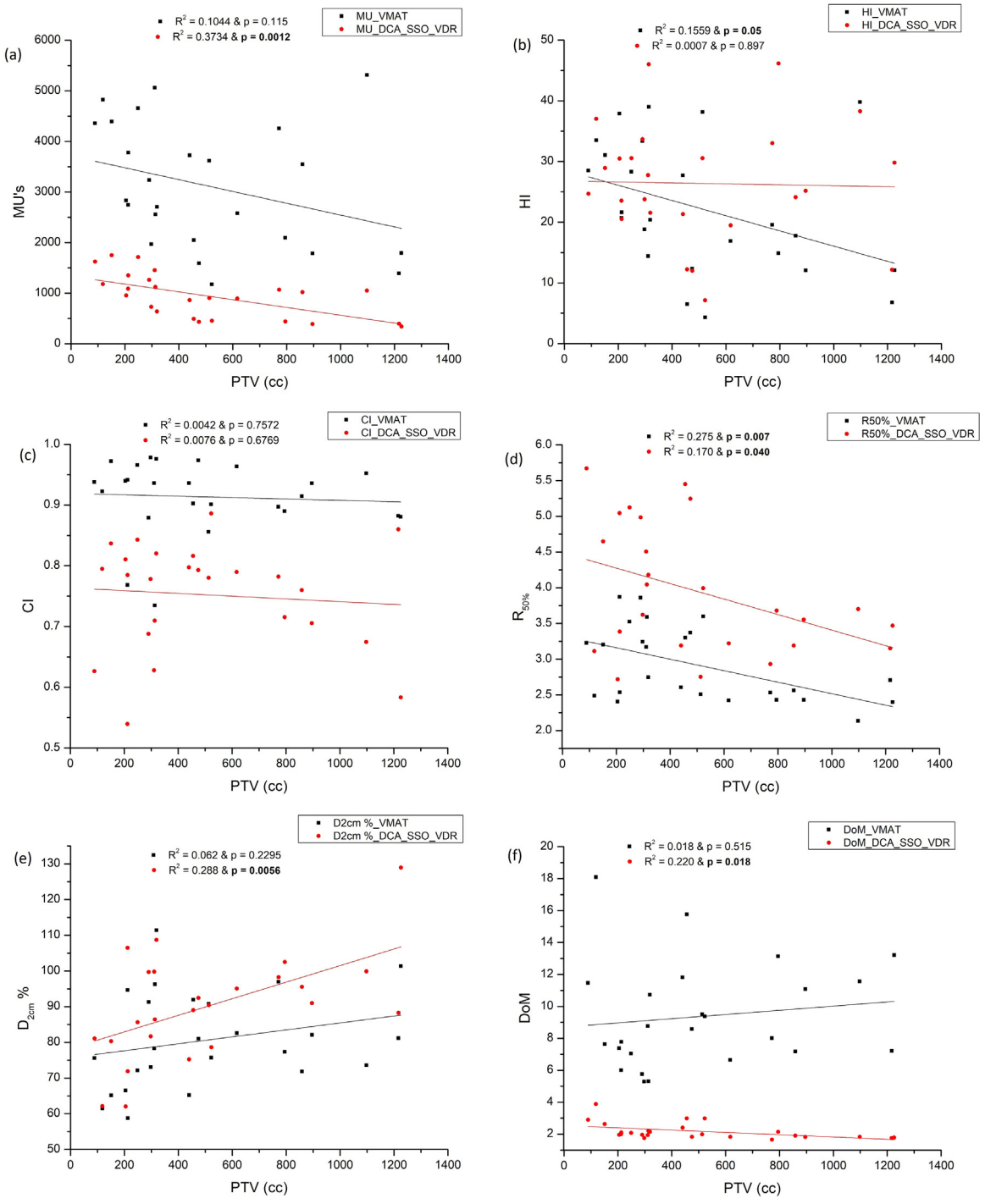

Fig. 5. Pearson correlation coefficient between PTV and (a) MUs; (b) HI; (c) CI; (d) $R_{50\%}$; (e) D_{2cm}% and (f) DoM was shown here with respective R^2 and p-values for both VMAT and DCA_SSO_VDR treatment techniques. The statistically significant p-values are shown in bold text.

for SBRT and result in a lower interplay effect.[1,2,10,13,15] In our study, the treatment plan complexity (DoM) was calculated for both techniques and the value of DoM for DCA_SSO_VDR treatment plans was found to be significantly lower than VMAT treatment plans as presented in Fig. 1(f).

The CI was also found to be better for VMAT treatment plans (Fig. 2a) and the results obtained are consistent with various other studies, although the comparison was performed for the conventional DCA technique in all the studies.[10,20,21,31] Even for the modified DCA (DCA_SSO_VDR) technique, CI was not found superior in comparison to the VMAT technique in this study. Similarly, for HI the significant difference in HI was observed between the two techniques (Fig. 2b). Because of normal liver dosage, a significant difference was seen in MLD along with the other two parameters D_{700cc}% and V_{20}Gy. Further, for OARs doses, $D_{0.5cc}$% of the esophagus, stomach and D_{30cc}% of the heart were observed to be dosimetrically equivalent for both techniques (Figs. 3(a, b) and 4(c)). $D_{0.5cc}$% of the duodenum, small bowel, large bowel, skin and D_{max}% of PRV cord, D_{mean}% of both kidneys were also observed and the significant difference was noticed for both techniques (Figs. 3(c–e), and 4(a, b, d)).

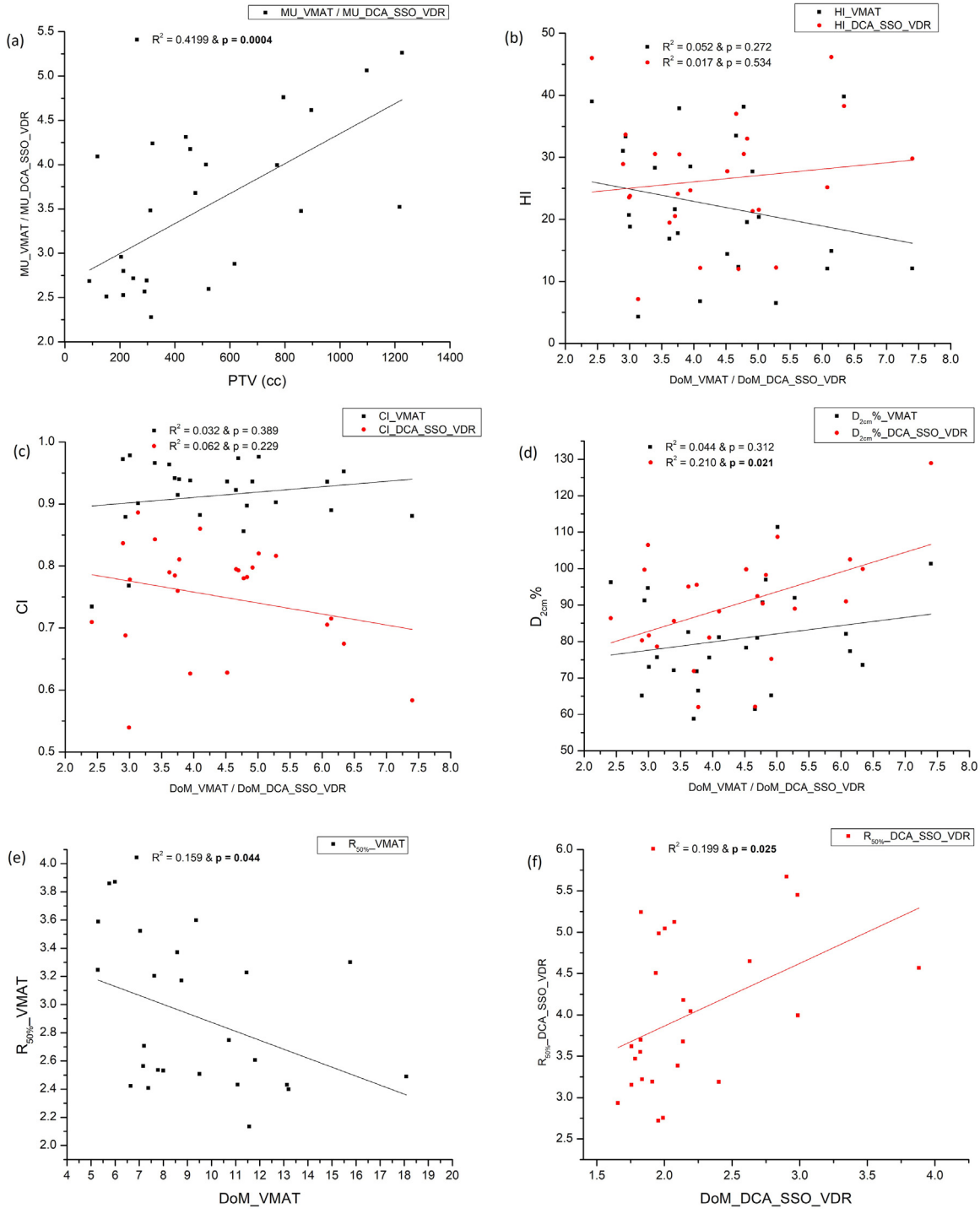

Fig. 6. Pearson correlation coefficient between PTV and MU ratio (MU_VMAT/MU_DCA_SSO_VDR) was shown in (a) with respective R2 and p-values and correlation between DoM ratio s(DoM_VMAT / DoM_DCA_SSO_VDR) and HI, CI and D_{2cm}% shown in (b–d). The correlation between $R_{50\%}$ and DoM was illustrated for VMAT and DCA_SSO_VDR techniques in (e) and (f), respectively. The statistically significant p-values are shown in bold text.

The correlation of various plan quality indices with PTV was also studied for both delivery techniques as presented in Fig. 5(a–f). From Fig. 5(a), it is clear that the trend of MUs is continuously decreasing with PTV size for both techniques, but the negative correlation is significant only for DCA_SSO_VDR plans. MUs also depend upon the dose per fraction, so MUs dependency on fraction size is taken care of by another parameter (DoM). With the increase in the size of PTV, collimator opening will be increased which further results in the large collimator and phantom scattering (S_{cp}) and, consequently, fewer MUs required to deliver the same dose for a large PTV in comparison to a small PTV. The S_{cp} factor is predominant only for DCA_SSO_VDR techniques but not for VMAT. In the VMAT technique, the treatment plan complexity (DoM) increases with PTV size (Fig. 5(f)); hence, more MUs per cGy in a single fraction is required to deliver for a large PTV in comparison to a small PTV. The higher treatment plan complexity in the VMAT plan can lead to a small average aperture size opening because of high modulation and, consequently, results in more MUs. Although,

the correlation between DoM and PTV is not significant for VMAT plans.

In VMAT, the treatment plans are less homogeneous for small lesions, as an increase in the PTV size caused a decrease in the HI (Fig. 5(b)). However, the HI never plays a major role in the treatment planning of SBRT and is generally deemed to be acceptable.[14] In the DCA_SSO_VDR technique, no significant correlation was seen between HI and PTV. For CI, no significant correlation was observed with PTV for both techniques. The CI is independent of PTV size for both techniques. As demonstrated in Fig. 5(d), a strong negative correlation was observed between $R_{50\%}$ and PTV for both methods. With an increase in PTV size, the ratio of the 50% isodose volume to PTV decreases for both techniques. The D_{2cm}% is more in DCA_SSO_VDR plans because of a lower degree of freedom in comparison to VMAT plans. The trend of D_{2cm}% is increasing with PTV size for both techniques but the correlation is significant for the DCA_SSO_VDR method only. Therefore, D_{2cm}% is manageable even for large size of PTV in VMAT plans, whereas, for the DCA_SSO_VDR method, it becomes a challenge to control large size tumors (Fig. 5(e)). As the PTV size increases, the high dose kinks start increasing outside the PTV which is difficult to control in the DCA_SSO_VDR technique.

DoM is higher for VMAT treatment plans as compared to DCA_SSO_VDR treatment plans (Fig. 5(f)). The DoM is continuously increasing with the PTV size in the VMAT technique but not significant, whereas, in the DCA_SSO_VDR technique, a decreasing trend was observed because S_{cp} is a more predominating factor for DCA_SSO_VDR treatment plans due to the aperture size opening for the large part of the treatment to encompass the whole target. The treatment plan complexity is decreasing with PTV size in DCA_SSO_VDR treatment plans and increasing with PTV in VMAT treatment plans. Therefore, in the DCA_SSO_VDR delivery technique, the DoM and MUs are lower but D_{2cm}% and $R_{50\%}$ are higher in comparison to the VMAT treatment plans.

The association of the MUs ratio (MU_VMAT/MU_DCA_SSO_VDR) with different PTV sizes was also analyzed and a significant positive correlation was noticed as represented in Fig. 6(a). Therefore, the MUs are relatively increasing more in VMAT treatment plans as compared to DCA_SSO_VDR treatment plans with an increase in PTV size. So as the PTV increases, the treatment plan complexity is increasing more for the VMAT technique in comparison to the DCA_SSO_VDR technique. The linear correlation between the DoM ratio (DoM_VMAT/DoM_DCA_SSO_VDR) and various other parameters (HI, CI, and D_{2cm}%) was also studied for both techniques to analyze the impact of a relative increase in plan modulation on these parameters using the VMAT technique. As demonstrated in Fig. 6(b–d), no significant correlation was observed for CI and HI. However, D_{2cm}% was found to significantly increase with the DoM ratio for DCA_SSO_VDR treatment plans. Therefore, it could be interpreted that a DoM increase will help to control the D_{2cm}%. But as the PTV size increases D_{2cm}% is difficult to control as shown in Fig. 5(e). So DCA_SSO_VDR treatment plans can be done for small size PTV with adequate DoM to control the D_{2cm}% and $R_{50\%}$.

A strong interaction between $R_{50\%}$ and DoM was also seen in their respective techniques. The $R_{50\%}$ is decreasing with DoM for VMAT treatment plans whereas in DCA_SSO_VDR treatment plans the $R_{50\%}$ is increasing with DoM (Fig. 6(e–f)). Therefore, the dose fall-off around the target will be larger as the treatment plan complexity increases in VMAT plans whereas the same relation is reversed in DCA_SSO_VDR treatment plans. The dose gradient around the target was found to be lower which results in a higher 50% volume as DoM increases in DCA_SSO_VDR plans. The large beam size opening in DCA_SSO_VDR treatment plans results in poor dose fall as DoM increases whereas, in VMAT plans, the average aperture size opening decreases with an increase in DoM and leads to more MUs and better control of dose gradient around the target.

The forward DCA plans become more challenging for the large size of PTV along with poor CI in comparison to VMAT plans as suggested by Vieillevigne et al.[21] Morales et al. also reported that DCA treatment plans are a good alternative to modulated beam plans in those cases where dose constraints leverages are available for OARs.[13] In our study, it was also observed that DCA_SSO_VDR treatment plans are better in terms of MUs if the dose constraint for a normal liver and other OARs is clinically acceptable, but dosimetrically inferior especially for large size of PTV. Fewer MUs in DCA_SSO_VDR treatment plans result in shorter beam-on time, which could be more beneficial for breath-hold treatments.

6. Conclusion

DCA_SSO_VDR delivery technique is not a better alternative to the VMAT delivery technique for liver SBRT treatment. Significant dosimetric differences were observed for several OARs doses and OARs doses are lower in VMAT plans. But other treatment plan quality indices, like D_{2cm}%, $R_{50\%}$, CI, HI, and HTMD, are dosimetrically inferior in DCA_SSO_VDR treatment plans and the difference is statistically significant from VMAT treatment plans. The reduction of 69.75% in MUs was observed in DCA_SSO_VDR plans in comparison to VMAT plans and plan delivery can be very simple for moving tumors due to a lower interplay effect and treatment plan complexity. In DCA_SSO_VDR plans, D_{2cm}% is difficult to manage for large size PTV due to an increase in high dose kinks outside the PTV. Moreover, in DCA_SSO_VDR plans, the higher DoM results in poor dose gradient and leads to an increase in high dose spillage volume ($R_{50\%}$) around the target.

Conflict of interest

None declared.

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