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1 Treatment planning study for irradiation of pulmonary veins under influence of heartbeat motion in human data

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The PVs move on one hand due to the heartbeat and on the other hand due to respiration of the patient. Both motion types are independent from each other and can hence be studied individually. While the influence of respiration is analyzed in chapter XXX, the effect of heartbeat motion will be discussed in this chapter. CTs gated to the complete cardiac cycle in end-expiration of five AF patients were acquired at Mayo Clinic (Minnesota, USA). The motion direction as well as motion amplitude of LPV and RPV were studied for all cases. Motion influences on accuracy and homogeneity of the dose delivery in the PVs were studied. The resulting interplay pattern for all patients as well as rescanning as possible motion mitigation technique have been studied and the results will be presented in this chapter.

1.1 Material and methods

Details on the used input data as well as the used treatment planning parameters will be given. Afterwards an overview over all studies will be given. Finally, the analysis proceeding will be described.

1.1.1 Treatment planning input data

For treatment planning studies with the in-house treatment planning software TRiP4D [Ric13], 4DCT data sets, target and OAR contours as well as a deformable image registration for motion assessment in-between the different motion phases are needed.

4DCT

In order to assess the motion of the PV under influence of heartbeat motion ECG gated 4DCTs in end exhale (breath hold) were studied. Five AF patient data sets (four male patients and one female) were recorded and anonymized at Mayo Clinic (Minnesota, USA). The CT scans were acquired on a Sensation 64 CT scanner (Siemens). The 4DCT data set each consisted of twenty cardiac motion phases, the reference phase was motion phase zero. In order to distinguish structures within the heart the CT scans were contrast enhanced. The radiopaque material was administered intravenously (150cc Omnipaque 350 at 4cc/sec).

Segmentation

Segmentation of the target volumes as well as the OAR were carried out by a collaborating cardiologist at Mayo Clinic with Eclipse™ (Varian Medical Systems). The volumes of the contours for the ablation sited for LPV and RPV are presented for each patient in table 1.1.

Table 1.1: Target volume for LPV and RPV for all investigated patients.

patient no	LPV [cm ³]	RPV [cm ³]
1	2.03	2.39
2	2.62	5.16
3	1.45	4.16
4	1.66	2.07
5	2.06	1.90

Image registration

Non-rigid image registration have been performed with Plastimatch [Sharp07] [Shack10]. The quality of registration was validated with visualization techniques: false color images [Bro07], checker board images [Bro07] as well as a qualitative check of the vector field regularization. These tests were carried out between motion phase 3 (which is the motion phase of the maximal displacement of the ventricle) and the reference phase (motion phase zero) or motion phase 18 (the motion phase of the maximal displacement of the atria) and the reference phase.

1.1.2 Treatment planning parameters

Treatment plans without motion (3D, static) as well as with motion (4D) were generated. For the dose optimization process, 3D treatment plans were generated to homogenously cover the CTVs, 4D treatment plans covered the ITV [Gra12]. Both CTV and ITV were studied with additional safety margins (see section “Margin”). The grid spacing was chosen to 1 mm in x and y direction, respectively. The spacing between the IESs were chosen to 3 mm_{H2O}. A maximal contour extension of 1.1 times the focal spot size of 4mm was chosen as well as a distal contour fall off of 4 mm_{H2O}. TRiP’s ‘all points divergent beam’ algorithm was used to calculate the absorbed dose. Intensity modulated particle therapy (IMPT) including the esophagus as critical structure have been used in part of the study. Thereby the optimization included dose restrictions to this OAR, so that the esophagus should not receive more than 70% of the physical dose. The strength of this restriction was furthermore determined by a weightfactor, which was set to 75%. All other treatment plans were generated as single field uniform dose (SFUD). In all simulations a physical dose of 25 Gy was applied in one fraction.

The generation of treatment plans is furthermore also dependent on the theoretically possible beam application. Spill lenght, shape and particle density are thus important factors. For the here presented simulations GSI accelerator parameters have been used. Thereby a spill length of 2.2s is assumed. The pause in between spills is either 2.2s, when no energy change is required afterwards, or 3.2s when a energy change is needed. The spill shape is approximated by a Gaussian function. The particle intensities feasible at GSI vary between 2×10^6 particles per spill and 2×10^8 particles per spill. Inbetween these two extreme intensity levels, fifteen different intensity levels can be used. In the resulting treatment plan, the intensity steps are automatically chosen.

Field number and beam directions

The field number and directions were systematically investigated and are listed in table 1.2. Four different field numbers (one to four) were studied. While for one field the gantry angle was kept constant to 0° and only the couch angle was changed, for higher field numbers different gantry angles were used. These angles are illustrated in figure 1.1.

Table 1.2: Studied field number and beam channel directions

Field number	Couch angle [°]	Gantry angle [°]
1 field	-90	0
	-45	0
	-135	0
2 fields	90	-60/120
	90	-60/135
	90	-60/0
	90	-45/135
	90	-45/150
	90	-45/0
3 fields	90	-60/120/150
	90	-60/120/0
	90	-45/135/150
	90	-45/135/0
4 fields	90	-60/120/-45/135
	90	-60/120/0/180
	90	-45/135/0/180
	90	-160/90/-60/145

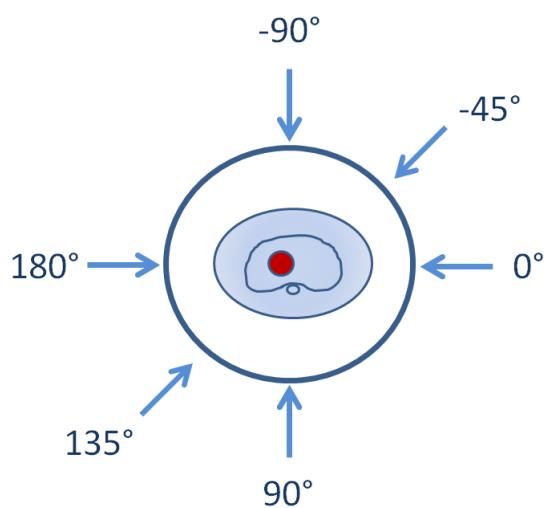


Figure 1.1: Entry channels for different gantry directions for a couch angle of 90° .

Motion trajectories

As the reconstruction of the 4DCTs was based on the time scale a phase-based motion state detection was employed. A sinus motion was chosen for the motion trajectories. In order to consider possible divergence in the heartbeat motion pattern of patients, different periods (1 s and 0.7 s) as well as different starting phases (0° and 90°) were used.

Margins

Besides the original volume of the CTV safety margins have been added to the volumes of the treatment planning study. These margins were applied in order to account for theoretically possible deviations in between treatment planning and delivery, like slight positioning errors, changes between CT acquisition and treatment delivery etc. Isotropic safety margins of 3mm, 5mm and 7mm have been chosen. The ITV volumes used as the final target were generated from the original CTV contour as well as the CTVs with margin, so that potential range variations were considered in the margins.

1.1.3 Treatment planning studies

3D treatment plans were produced on one hand as reference values to the 4D cases, as it represents the ideal but not deliverable dose distribution. On the other hand they were also generated in order to study the best suited combinations of beam entry channels as well as to study possible safety margin limitations. In order to find a suitable field number and beam direction for the treatment planning studies, static simulations on the original CTV volume (LPV together with RPV) with the above mentioned treatment planning parameters were carried out for all five patients. 17 different beam channel combinations were studied (see table 1.2). As a criteria for the best possible solution the dose to OAR were assessed. Furthermore, different ITV margins (original, an increased with 3mm, 5mm and 7mm margin) were studied in 3D treatment plans for all patients. The resulting dose depositions were compared to IMPT dose deliveries (where the esophagus was included in the optimization process). Possible limitations were again analyzed according to the dose deposition in the OARs. In order to prepare for the 4D simulations, the motion of the PVs due to heartbeat was than assessed. 4D plans were distinguished between an underlying motion without any compensation, resulting in interplay patterns, and with the application of rescanning as motion mitigation technique. For rescanning different rescan numbers (5, 10, 15 and 20) were compared. Static, interplay as well as rescanning treatment plans for all patients where carried out with one beam channel combination, all four safety margins, the stated treatment planning parameters and the four stated motion trajectories.

1.1.4 Analysis

Both the dose deposition in OAR as well as dose homogeneity in the target volume were studied. For the OAR dose-volume restriction in esophagus, trachea, aorta and the whole heart were compared to values from RTOG study protocols (see next paragraph). As further OAR cardiac substructures (ventricles and coronary arteries) were studied. Here the mean dose into the structures as well as the maximum point dose and the maximal irradiated volume (thus sum over all voxels of the organ which receive dose) were analyzed. In general, the median values of these parameters over all patients were further calculated. Besides the second quartile (median, 50th percentile) also the third quartile (75th percentile) was assessed. For comparison of the resulting dose coverage in the target region dose-volume-histograms (DVHs) were studied. Furthermore motion-volume-histograms (MVHs) [Ric13] were generated displaying the relative displacement of every voxel of the investigated volume to the reference phase in all three motion directions. With these the resulting motion of the PV due to heartbeat could be assessed.

Dose-volume constraints for organs at risk

The dose deposition in the OAR is an important limitation and selection criteria when studying the field number and beam channel direction as well as the possible safety margin limitations. Since a single fraction of 25 Gy or higher is assumed to be used in the presented, non-invasive treatment modality, dose tolerance limits used in stereotactic body radiotherapy (SBRT) are highly related. An extensive collection of dose-volume-limits for SBRT are presented in Grimm et al. [Gri11] and the AAPM Task Group Report [AAPM10]. Both are literature reviews of limits utilized and reported in existing publications. For the OAR in the here presented treatment planning study (esophagus, trachea, heart and aorta) the dose-volume-limits in both literature reviews were taken from the Radiation Therapy Oncology Group (RTOG). The RTOG is a national clinical cooperative group of over 360 institutions across the United States and Canada, which was funded by the National Cancer Institute (NCI) [RTOG]. In their study protocols RTOG 0631 (a phase II/III trial of SBRT for localized spine metastasis) [RTOG0631] and RTOG 0915 (a randomized phase II trial of SBRT for medically inoperable patients with stage I peripheral non-small cell lung cancer) [RTOG0915] the following dose-volume-limits were stated (see table 1.3).

Table 1.3: Dose-volume limits for OAR.

OAR	Volume [cc]	Dose [Gy]	endpoint
Aorta / great vessels	10	31	Aneurysm
Esophagus	5	11.9	Stenosis / fistula
Heart	15	16	Pericarditis
Trachea	4	10.5	Stenosis / fistula

Since the heart is not only a critical organ but also the target site in this treatment modality, further differentiation of limits depending on the substructures of the heart are needed. Unfortunately, data herefore is scarce and literature on cardiac disease resulting from radiation exposure mostly reliant on patient data treated with cancer radiotherapy (in particular breast cancer and Hodgkin's lymphoma) or atomic bomb survivors. Besides the stated dose-volume limitation, the mean dose and maximum point dose to the whole heart was studied. Furthermore the maximal irradiated heart volume (each voxel which received a dose deposition) was examined. Concerning substructures the left and right ventricle as well as the coronary arteries were analyzed for mean and maximum dose deposition and maximal irradiated volume contribution.

Dose deposition in target volume and motion of PVs

The V95 (measure of dose coverage) and V107 (measure of over dosage) of the CTVs were analyzed. As an indicator for the dose homogeneity, the width of the dose fall off was determined by analyzing the difference D5-D95. The stated values have been evaluated for all beam applications (static, interplay, rescanning). Static thereby means that no motion was included, resulting in a 3D case. This is only used as a reference value for the 4D cases interplay and rescanning, as the static case represents the ideal, but not deliverable dose distribution.

1.2 Results

In the following the results of the beam direction and safety margin study, PV motion assessment as well as the treatment planning studies will be discussed. As a criteria for an adequate field number and beam channel direction as well as safety margin limitation the dose to OAR will be presented in detail. The motion is shown as the relative displacement to the reference motion phase. For the treatment planning study different dose analysis parameters will be presented and compared for different cases (static, interplay and rescanning).

1.2.1 Beam direction

In figure 1.2 the resulting dose to the pertinent OARs is shown for all studied beam directions and patients. The corresponding volumes result from the dose volume limits (e.g. 5 cm³ for esophagus, see table 1.3). The stated, recommended dose limit is represented by a dashed line in the plots. In all studied cases, the difference between different beam directions for a certain patient is rather small, resulting in no obvious preferable beam direction for the five studied patient. For the four studied OAR it becomes furthermore obvious, that while some organs, like trachea and aorta, are well spared for almost all beam directions in all patients, esophagus and in particular the heart are much more critical.

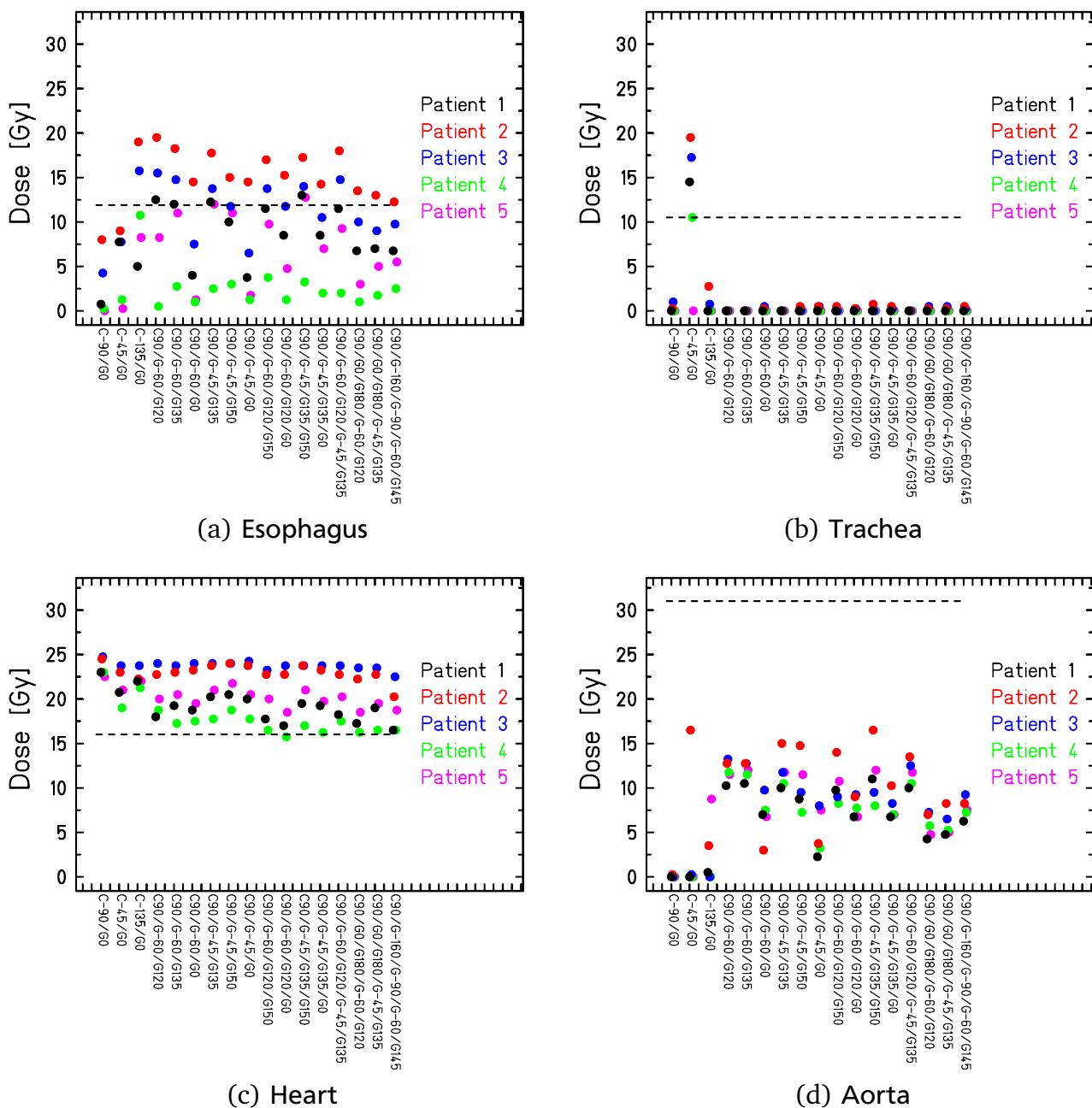


Figure 1.2: Dose-volume data of different OAR when irradiating the LPV and RPV as SFUD in the five patient data sets with different field numbers (1 field, 2 fields, 3 fields, 4 fields) and different beam directions. The dose-volume-limit for each critical organ is indicated with a dashed line in each plot, respectively.

In the esophagus the median dose over all patients is 7.8Gy (75th percentile: 9.0Gy) for one field, 10.5Gy (13.9Gy) for two fields, 11.0Gy (13.9Gy) for three fields and 9.1Gy (12.8Gy) for four fields. The result is dependent on the underlying patient anatomy. While the majority of the beam directions for patient 1, 4 and 5 remain under the respective dose-volume limit, patient 2 and 3 result in many dose-volume exceeding depositions. For these patients a dose deposition of 11.9 Gy or less are achieved in only about 2% and 65% of studied cases, for patient 2 and 3,

respectively. While a single field yields very small dose deposition in the esophagus, these beam channels result in higher dose depositions in the heart and cardiac substructures like the coronary arteries (see figure 1.7) and are thus inapplicable. For patient 2 higher field numbers and thus more beam directions result in dose limit exceeding depositions. Due to this result a different treatment delivery (intensity modulated particle therapy, IMPT) was additionally studied in comparison to a simple SFUD irradiation in further dose deposition studies (see section 1.2.2).

The dose volume limit for the heart is exceeded in all patients for all beam directions. As the heart is not only an OAR in this treatment modality, but some of its substructure are also the target itself, a closer analysis of the dose deposition in the heart is required. In figure 1.3 the mean and maximal dose deposition in the whole heart as well as the maximal irradiated volume are shown. The mean dose over all patients and beam directions is found to have a median of 1.3Gy (75th percentile: 1.5Gy). The median over the maximum point dose is found to 26.6Gy (27.1Gy). Concerning the maximal irradiated volume it can be seen that expect of one result less than 30% of the heart is irradiated in all other cases. In the case of couch position 90° and gantry angles of -160°, -90°, -60° and 145° these maximal volume is drastically increased, and reaches up to 49.9% for patient 2. Hence this beam channel case (beam channel case 17) will be stated separately in the following analysis. The median of the maximal irradiated volume over all patients results to 17.4% (20.8%), excluding beam channel case 17 and to 16.8% (20.5%) including this case.

For results for the dose deposition in the cardiac substructures are presented in figure 1.4 - figure 1.6. For the ventricles, the mean dose to both LV and RV is negligible. The maximal point dose on the other hand varies dependent on beam direction and patient. Single beam directions yield a high maximal dose deposition in the LV as in the case of a couch angle of -90° or -135° the beam traverses the LV. Thus for these beam directions the maximal dose to the RV is smaller. The overall maximal dose deposition results to a median of 1.4Gy (75th percentile: 7.4Gy) for LV and 1.3Gy (5.0Gy) for RV. Besides the single beam direction no maximal point dose exceeds 11.2Gy in case of LV and in case of RV all maximal point doses are smaller than 10.1Gy. Concerning the maximal irradiated volume of the ventricles, it can be stated that the results differ depending on the studied patient. In case of the LV patient 2 has a higher irradiated volume compared to the other patients, while for this patient on the contrary the RV is better spared than in other patients. Over all patients the LV is irradiated to a higher extend than the RV. The maximal irradiated volume over all beam directions and patients results to a median of 1.2% (6.0%) for LV, excluding the case of beam channel 17 and to 1.9% (6.4%) including this case. For RV it results to 0.2% (7.6%) excluding the beam channel case and to 0.2% (8.3%) including it. For the coronary arteries the beam channel 17 also results in the highest irradiated volume. Even though the coronary arteries are found on the surface of the

whole heart and hence also on the ventricles, the irradiated volume of these structures differ from the result of the ventricles. Here the RCA are irradiated to a higher extend than the LCA. The median maximal value for the LCA results to 15.7% (28.0%) including the stated beam channel case 17 and to 15.2% (27.4%) excluding it. For the RCA the median over the maximal value is much higher and found to 27.9% (42.4%) including the beam channel case and to 24.8% (42.1%) excluding it. For the mean dose deposited in the LCA one and four beam directions result in an increased dose deposition, while three fields yield in general a low mean dose for all studied beam directions and patients. The same is true for the maximum point dose in the LCA. In the case of RCA, the result seem to be independent of field number and beam direction. Overall the median over the mean dose results to 0.4Gy (1.0Gy) for LCA and 0.6Gy (1.6Gy) for RCA. For the maximal point dose the median dose deposition over all beam directions and patients results to 6.8Gy (10.9Gy) for LCA. For the RCA it is found to 5.4Gy (7.9Gy).

While it was not expected to find one beam direction feasible for all five patients, it is striking that no beam position results in a clear benefit for the OAR of the individual patients. This is due to the challenging position of the PV target site, which is in direct proximity to the esophagus and due to the fact that the heart is not only an OAR in this treatment modality, but also the target site itself. Nevertheless for the analyzed cardiac substructure, especially the radiosensitive LCA, it can be concluded that three beam channels seem to be beneficial for all patients. Regarding the mean dose deposition in the LCA as well as the maximal irradiated heart volume, combined with the requirement of a robust treatment and hence the benefit of large gantry angles in between different beam channels, a couch angle of -90° was chosen together with gantry angles of -45°, 135° and 0°. These beam channel directions were used for a closer analysis of safety margin limitation as well as for the treatment planning studies for all patients.

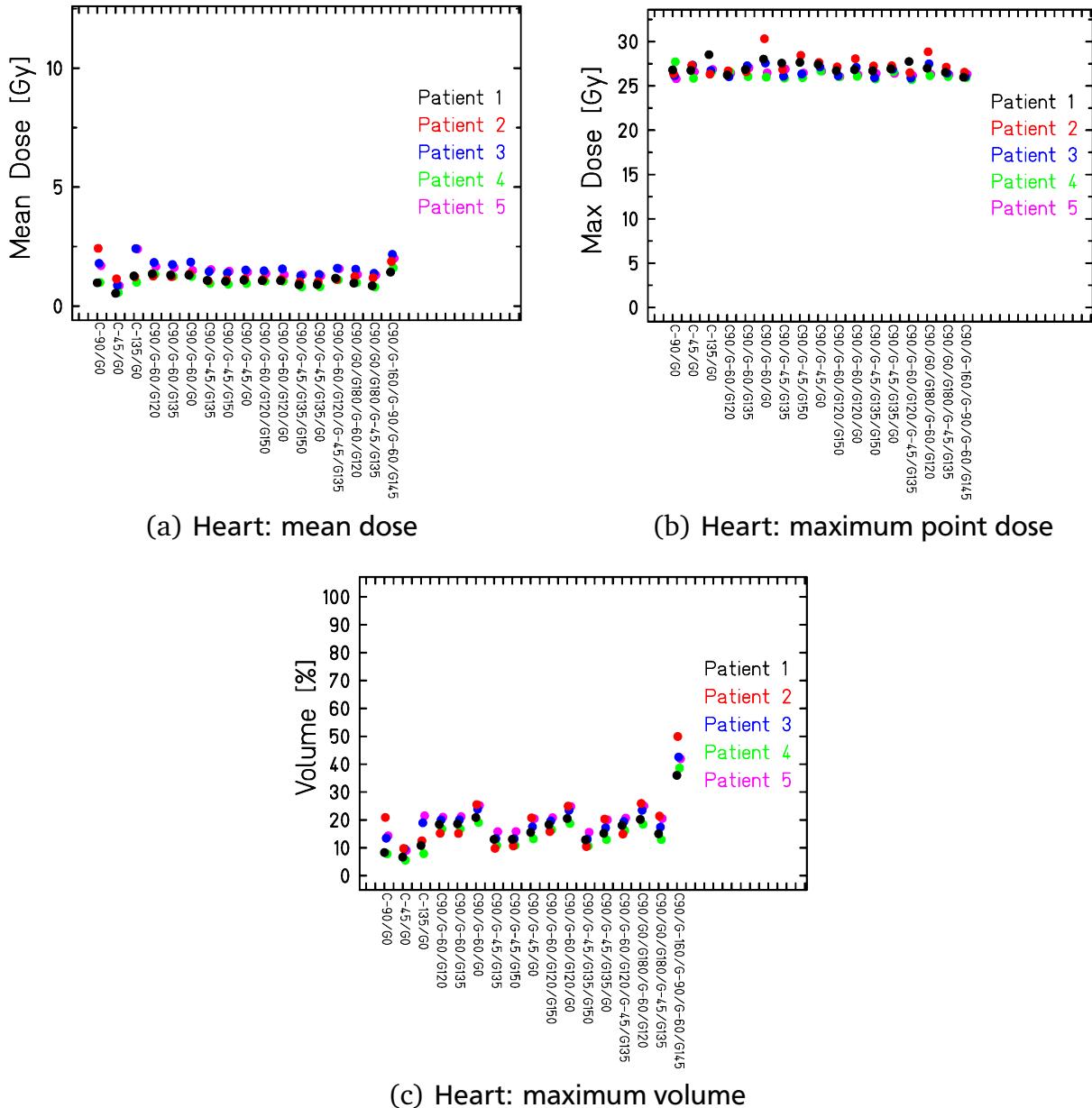
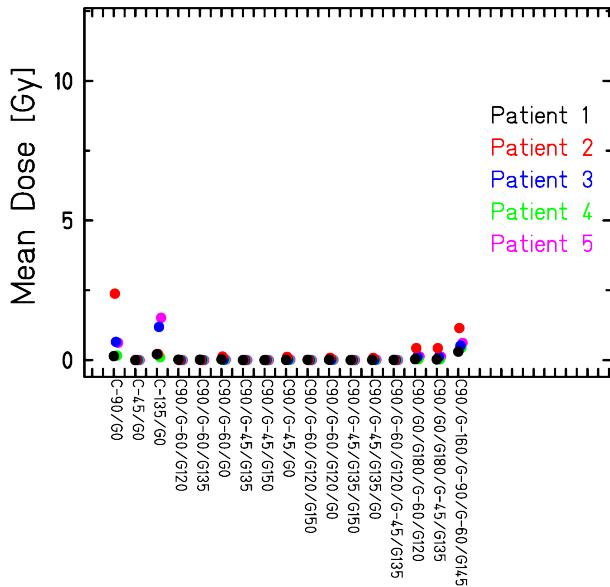
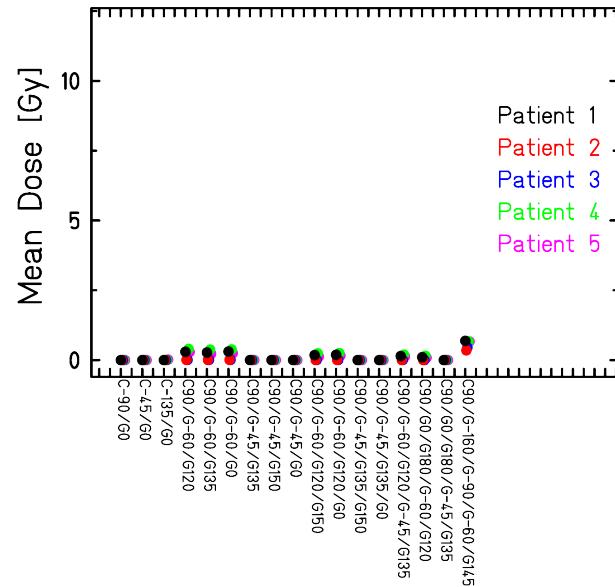


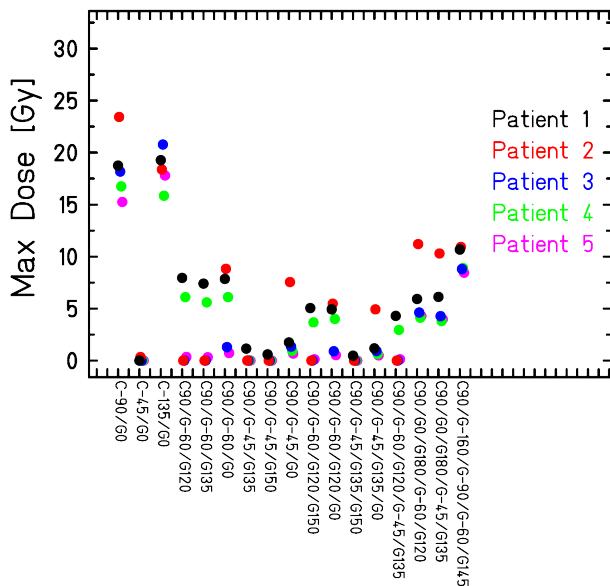
Figure 1.3: Mean and maximum dose to the heart and maximal irradiated heart volume when irradiating the LPV and RPV in the five patient data sets with different field numbers and beam directions.



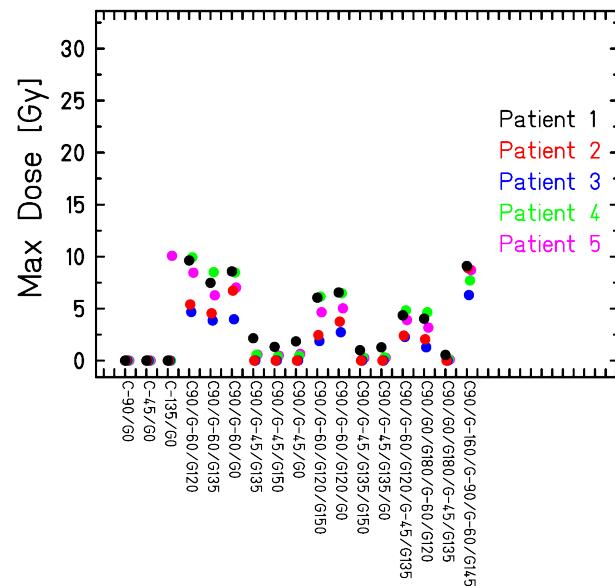
(a) Mean dose: LV



(b) Mean dose: RV



(c) Maximum point dose: LV



(d) Maximum point dose: RV

Figure 1.4: Mean dose with standard deviation and maximal point dose of left ventricle (LV) and right ventricle (RV), respectively, when irradiating the LPV and RPV in the five patient data sets with different field numbers and beam directions.

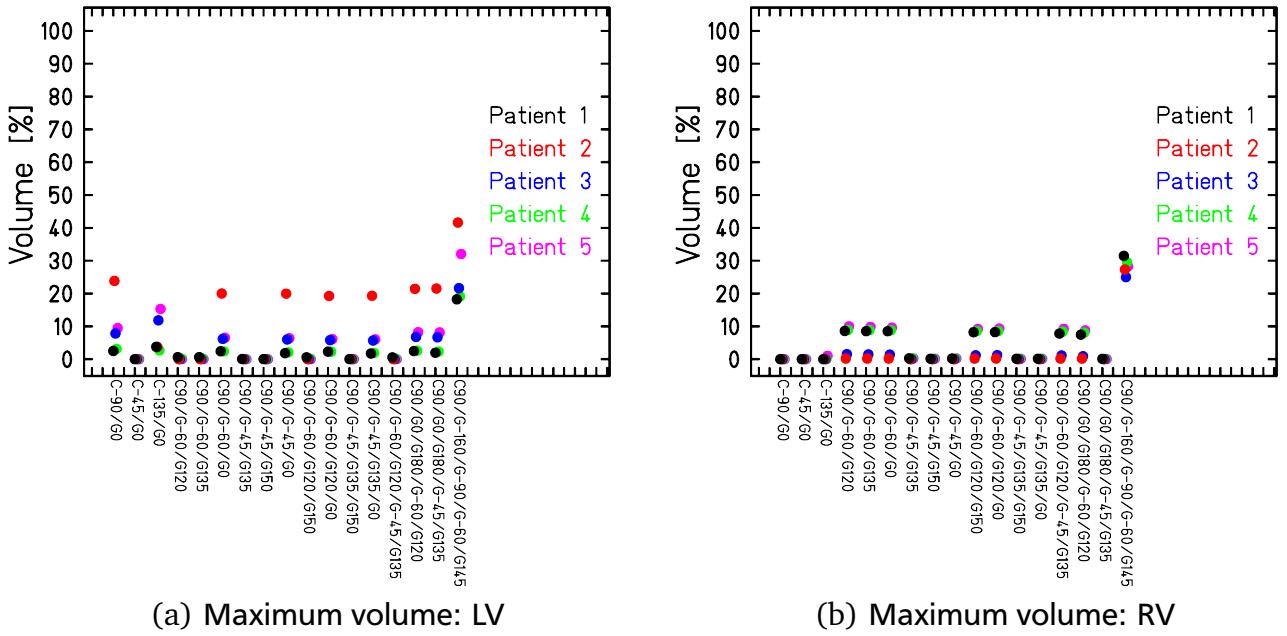


Figure 1.5: Maximal irradiated volume of left ventricle (LV) and right ventricle (RV), respectively, when irradiating the LPV and RPV in the five patient data sets with different field numbers and beam directions.

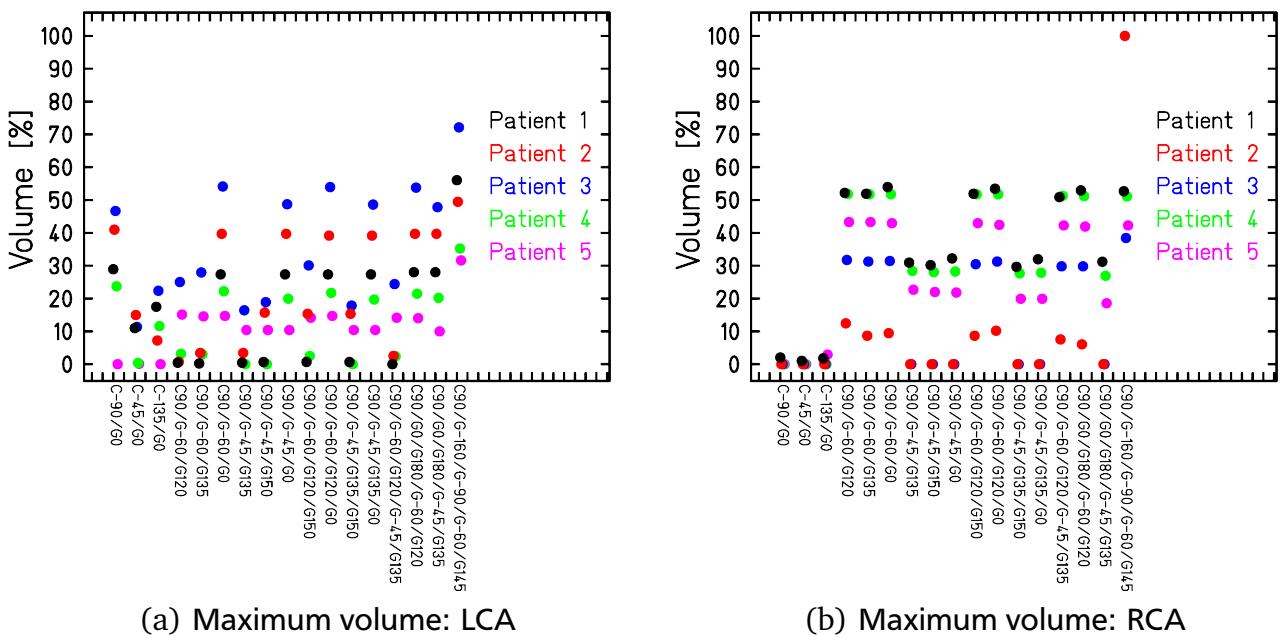


Figure 1.6: Maximal irradiated volume of left coronary artery (LCA) and right coronary artery (RCA), respectively, when irradiating the LPV and RPV in the five patient data sets with different field numbers and beam directions.

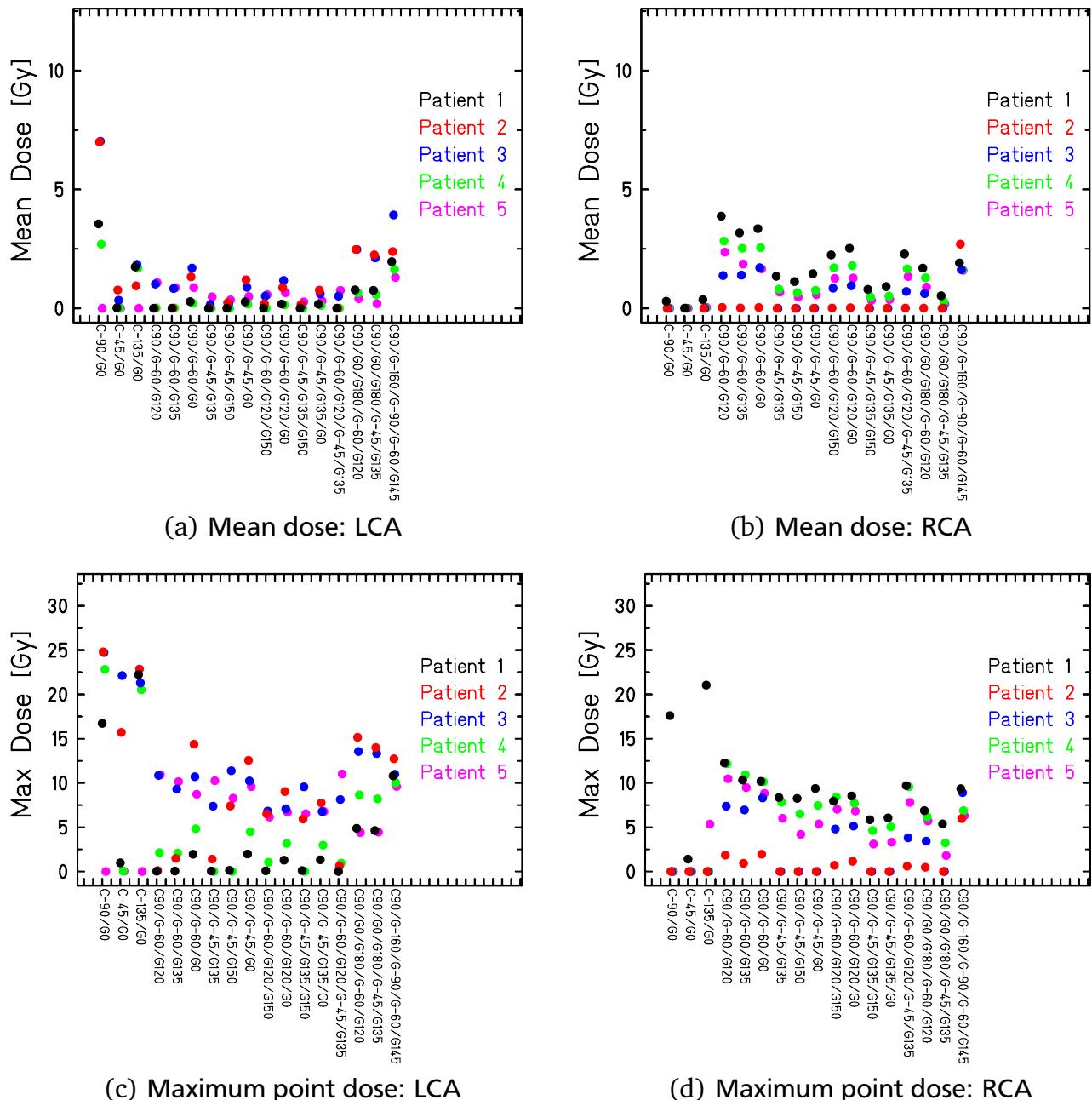


Figure 1.7: Mean dose with standard deviation and maximal point dose of left coronary artery (LCA) and right coronary artery (RCA), respectively, when irradiating the LPV and RPV in the five patient data sets with different field numbers and beam directions.

1.2.2 Safety margin limitations

Figure 1.8 shows the dose results for the main OAR when irradiating the PVs with no safety margin (0mm) and different additional, isotropic safety margins (3mm, 5mm or 7mm). The dose-volume-limits were studied according to the recommendation of RTOG (see table 1.3) and the limit for each organ is indicated by a dashed line in the plots. Besides an SFUD treatment, IMPT deliveries were also studied. Thereby the esophagus was implemented as a critical structure in the optimization process and it was stated that this structure should not receive more than 70% of the physical dose of 25Gy. The results of these two treatment delivery techniques, SFUD irradiation and IMPT, are both shown in each plot.

As expected, the dose to the enclosed OAR increases with increasing safety margin for all patients. This is the case both for SFUD and IMPT delivery. Nevertheless the IMPT delivery does lead to a reduced dose deposition in the esophagus. For no safety margin, the median dose over all patients is found to 8.5Gy (75th percentile: 12.4Gy), which decreases to 7.0Gy (9.0Gy) with IMPT delivery. For 3mm safety margin an SFUD irradiation results to 13.0Gy (18.6Gy) and reduces to 9.3Gy (12.1Gy) for IMPT. With 5mm safety margin the RTOG limit of 11.9Gy starts to be exceeded even for IMPT deliveries as it results to 11.8Gy (15.1Gy) (compared to 19.0Gy (22.8Gy) with SFUD). For 7mm margin this result further increases to 14.3Gy (17.1Gy) (SFUD irradiation: 23.3Gy (24.6Gy)). Even though only the esophagus is included in the IMPT optimization process, also other OAR profit from this irradiation mode. This can be understood as the beam stopping in front of the esophagus (gantry angle of -45°) is optimized into having less raster points in the IMPT delivery compared to an SFUD irradiation and hence a reduced dose contribution to the total dose delivery. The other beam channels (gantry angles of 135° and 0°) are hence optimized into having more raster points compared to the SFUD delivery, contributing more to the dose deposition. Adjacent OAR to the esophagus, like trachea and aorta, are thus also receiving a smaller dose deposition from the beam channel stopping in proximity to them. As only an IMPT treatment leads to acceptable dose depositions in the esophagus, the median dose to the other organs will only be stated for this delivery type. Over all patients the trachea is receiving a median dose of 0Gy in all cases, since only patient 2 and 3 are yielding a dose in this critical structure. The 75th percentile is found to 0.4Gy with no safety margin and 1.1Gy, 3.0Gy, 6.6Gy for 3mm, 5mm and 7mm, respectively. All of these dose deposition are under the recommended dose-volume-limit for the trachea (10.5Gy for 4cm³). For the aorta an irradiation with no safety margin leads to a median dose deposition of 6.5Gy (8.5Gy), while 8.3Gy (10.6Gy), 9.8Gy (12.3Gy) and 11.3Gy (14.0Gy) are deposited with 3mm, 5mm and 7mm margin. All these results are far under the critical dose-volume limit of 31Gy for 10cm³. It can thus be concluded that trachea and aorta do not receive a critical dose deposition while treating the PVs with a dose of 25Gy. For the heart the dose-volume limits are much more

critical. A mean of 18.3Gy (22.8Gy) was yielded for no safety margin and 23.0Gy (24.9Gy), 24.3Gy (25.0Gy) and 24.8Gy (25.0Gy) for 3mm, 5mm and 7mm margin, respectively. Hence all studied irradiations by far exceed the dose-volume limit of 16Gy for 15cm³. A close analysis of the radiosensitive cardiac substructures is presented in figure 1.9 - figure 1.11.

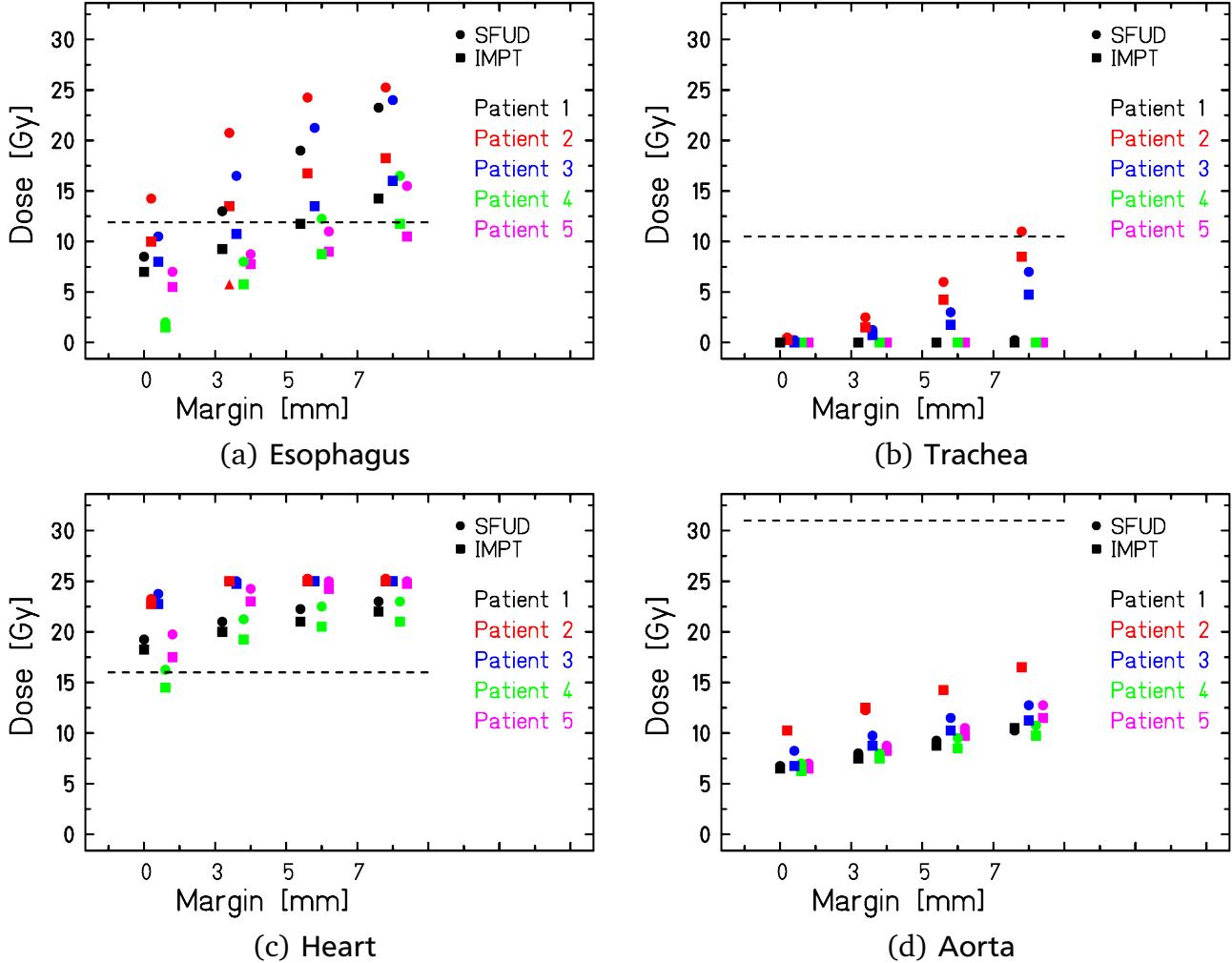


Figure 1.8: Dose-volume data of different OAR when irradiating the PVs in five patient data sets with different margins and two different delivery techniques (SFUD and IMPT). The dose-volume-limit for each critical organ is indicated with a dashed line in each plot, respectively.

It should further be noted that another IMPT parameter set was studied for the esophagus of patient 2 with 3mm Margin. While the other four patients are within the dose-volume limit with this safety margin this patient exceeds the limit by 1.6Gy. The result could be improved by using another parameter set (maximum dose fraction of 30% and a weighting factor of two), which is represented as a triangle in plot 1.8. The dose can be drastically reduced to 5.8Gy for 5cm³ esophagus. It can thus be concluded that patient individual optimization can further improve the stated results. However, as the majority of the patients did not exceed the limit for 3mm margin, the previously stated parameters for IMPT treatment were used in further analysis.

Closer analysis of the dose deposition in the heart can be seen in figure 1.9. The mean deposited dose in the heart does not increase with the size of the safety margins. Furthermore only a small difference in between SFUD and IMPT irradiation can be observed. The median value of the mean dose over all patients for an IMPT irradiation with no safety margin is found to 1.0Gy (75th percentile: 1.1Gy). For the irradiation of the PVs with safety margin it results to 1.3Gy (1.5Gy) for 3mm, 1.4Gy (1.6Gy) for 5mm and 1.5Gy (1.6Gy) for 7mm, respectively. While also the maximum point dose does not increase with added safety margin, it can be seen that IMPT treatment does lead to a higher point dose compared to an SFUD irradiation. A comparison of the median maximum point dose and the 75th percentile over all patients and for all margin cases is presented in table 1.4.

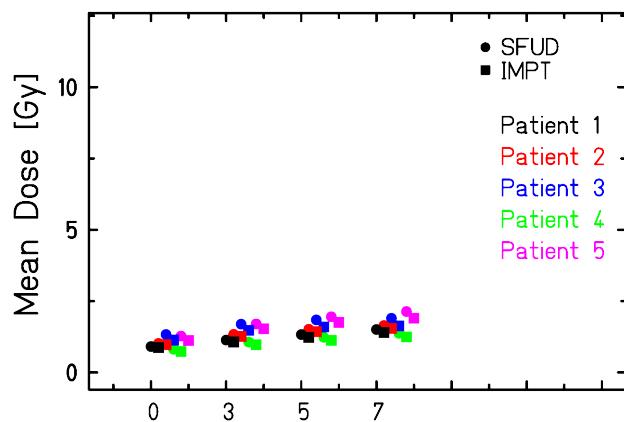
Table 1.4: Median and 75th percentile of maximum point dose to the heart.

Margin	SFUD: median (75th percentile) [Gy]	IMPT: median (75th percentile) [Gy]
0 mm	26.9 (26.9)	27.58 (29.4)
3 mm	26.2 (26.6)	28.35 (29.0)
5 mm	26.5 (26.6)	28.00 (28.8)
7 mm	26.2 (27.7)	26.80 (27.7)

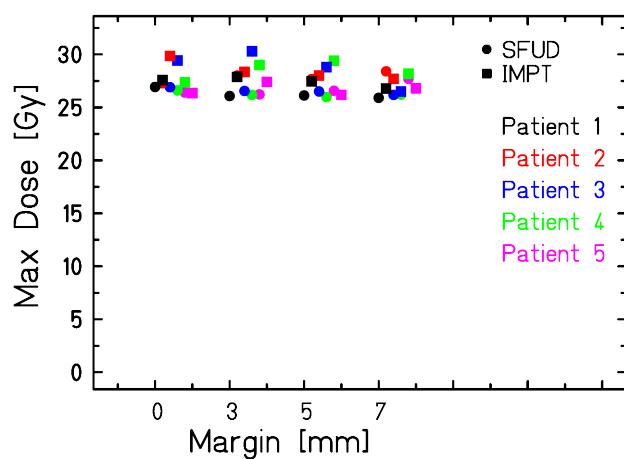
The highest maximum point dose (30.3Gy) was deposited in the heart of patient 3 with a margin of 3mm. In comparison, the SFUD result for this case is 26.6Gy. As esophagus and the other adjacent OAR (trachea, aorta) receive in general less dose with IMPT due to the intensity reduction in one beam channel direction, the other beam channels have to deposit more particles. Especially gantry angle 0°, which traverses the heart, is hence leading to an increased dose deposition in the heart. Since this beam channel direction has to penetrate only a small volume of the heart, the maximal irradiated volume shows a slight improvement in IMPT delivery compared to SFUD irradiation. The results are presented in table 1.5.

Table 1.5: Median and 75th percentile of maximum irradiated volume of the heart.

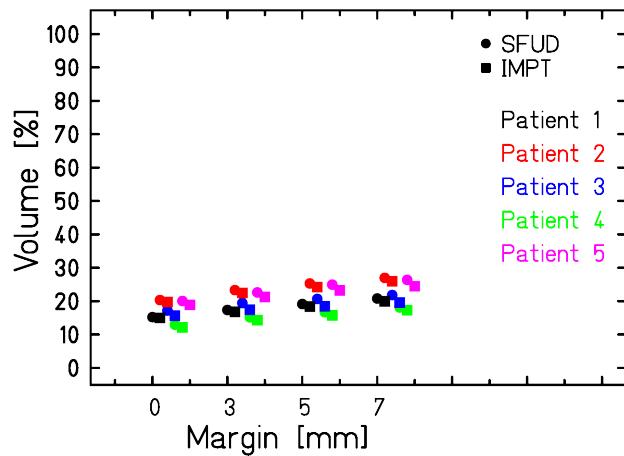
Margin	SFUD: median (75th percentile) [%]	IMPT: median (75th percentile) [%]
0 mm	17.2 (20.0)	15.7 (18.9)
3 mm	19.4 (22.6)	17.4 (21.2)
5 mm	20.7 (24.9)	18.5 (23.2)
7 mm	21.8 (26.4)	19.9 (24.4)



(a) Heart: mean dose



(b) Heart: maximum point dose



(c) Heart: maximum volume

Figure 1.9: Mean and maximum dose to the heart and maximal irradiated heart volume when irradiating the LPV and RPV in the five patient data sets with different margins (0 mm, 3 mm, 5 mm, 7mm) and two different delivery techniques (SFUD irradiation and IMPT).

The results for the analysis of the affected cardiac substructures can be found in figures 1.10 and 1.11. Concerning the ventricles it can be seen that the mean dose is negligible (see figure 1.10). The result for the maximal point dose is patient anatomy dependent. While patient 2 receives a higher LV maximal point dose than all the other patients (about 5Gy), no dose is deposited in the RV of this patient for any added margin. For an IMPT irradiation the median and 75th percentile of the maximal dose to the LV and RV over all patients and for all safety margin cases is shown in table 1.6. For both ventricles the dose is increasing with the size of the safety margin. The left ventricle is receiving a higher maximum point dose than the right ventricle in all cases. Concerning the maximal irradiated volume it can also be stated that the LV is irradiated to a higher extend than the RV, and that also the affected volume is increasing with the underlying safety margin size (see table 1.10).

Table 1.6: Median and 75th percentile of maximum point dose to the ventricles.

Margin	LV: Median (75th percentile) [Gy]	RV: Median (75th percentile) [Gy]
0 mm	0.9 (1.3)	0.0 (0.1)
3 mm	1.5 (2.4)	0.9 (1.3)
5 mm	1.8 (4.5)	2.5 (3.2)
7 mm	3.2 (6.0)	4.1 (4.8)

Table 1.7: Median and 75th percentile of maximum irradiated volume of ventricles.

Margin	LV: Median (75th percentile) [%]	RV: Median (75th percentile) [%]
0 mm	4.7 (5.1)	0.00 (0.1)
3 mm	6.1 (7.3)	0.5 (0.6)
5 mm	7.3 (9.1)	1.1 (1.2)
7 mm	8.9 (10.8)	1.8 (2.1)

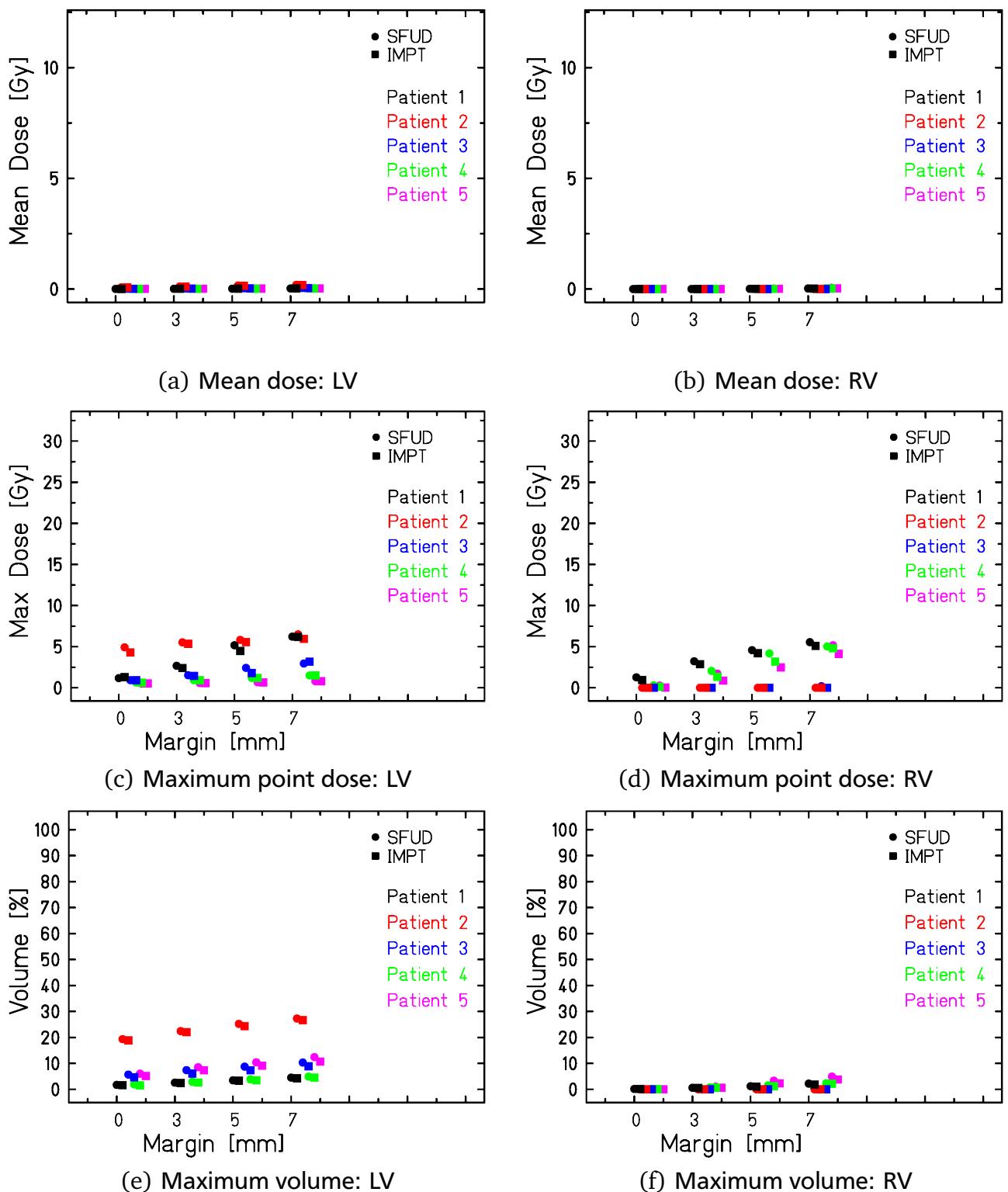


Figure 1.10: Mean dose, maximal point dose and maximal irradiated volume of left ventricle (LV) and right ventricle (RV), respectively, when irradiating the LPV and RPV in the five patient data sets with different margins (0 mm, 3 mm, 5 mm, 7mm) and two different delivery techniques (SFUD irradiation and IMPT).

Concerning the coronary arteries, it can be seen that the LCA and RCA are receiving a comparable mean dose. The maximum point dose on the other hand is higher for the LCA. The same is valid for the maximum irradiated volume. This is due to the proximity of the upper LCA branches to the LPV target site. Due to the small vessel size of the coronary arteries this also results in a relatively high maximal irradiated volume.

Table 1.8: Median and 75th percentile of mean dose to the coronary arteries.

Margin	LCA: median (75th percentile) [Gy]	RCA: median (75th percentile) [Gy]
0 mm	0.2 (0.5)	0.3 (0.4)
3 mm	0.5 (0.9)	0.5 (0.8)
5 mm	0.7 (1.1)	0.7 (1.3)
7 mm	1.5 (1.6)	1.0 (1.7)

Table 1.9: Median and 75th percentile of maximum point dose to the coronary arteries.

Margin	LCA: median (75th percentile) [Gy]	RCA: median (75th percentile) [Gy]
0 mm	6.0 (6.3)	3.1 (4.7)
3 mm	7.4 (7.6)	3.8 (6.5)
5 mm	8.7 (13.2)	4.3 (7.2)
7 mm	20.1 (21.3)	5.9 (7.9)

Table 1.10: Median and 75th percentile of maximum irradiated volume of coronary arteries.

Margin	LCA: median (75th percentile) [%]	RCA: median (75th percentile) [%]
0 mm	26.7 (39.2)	19.2 (26.5)
3 mm	28.5 (41.5)	25.1 (29.8)
5 mm	29.6 (44.6)	33.2 (35.6)
7 mm	31.4 (49.6)	39.6 (39.7)

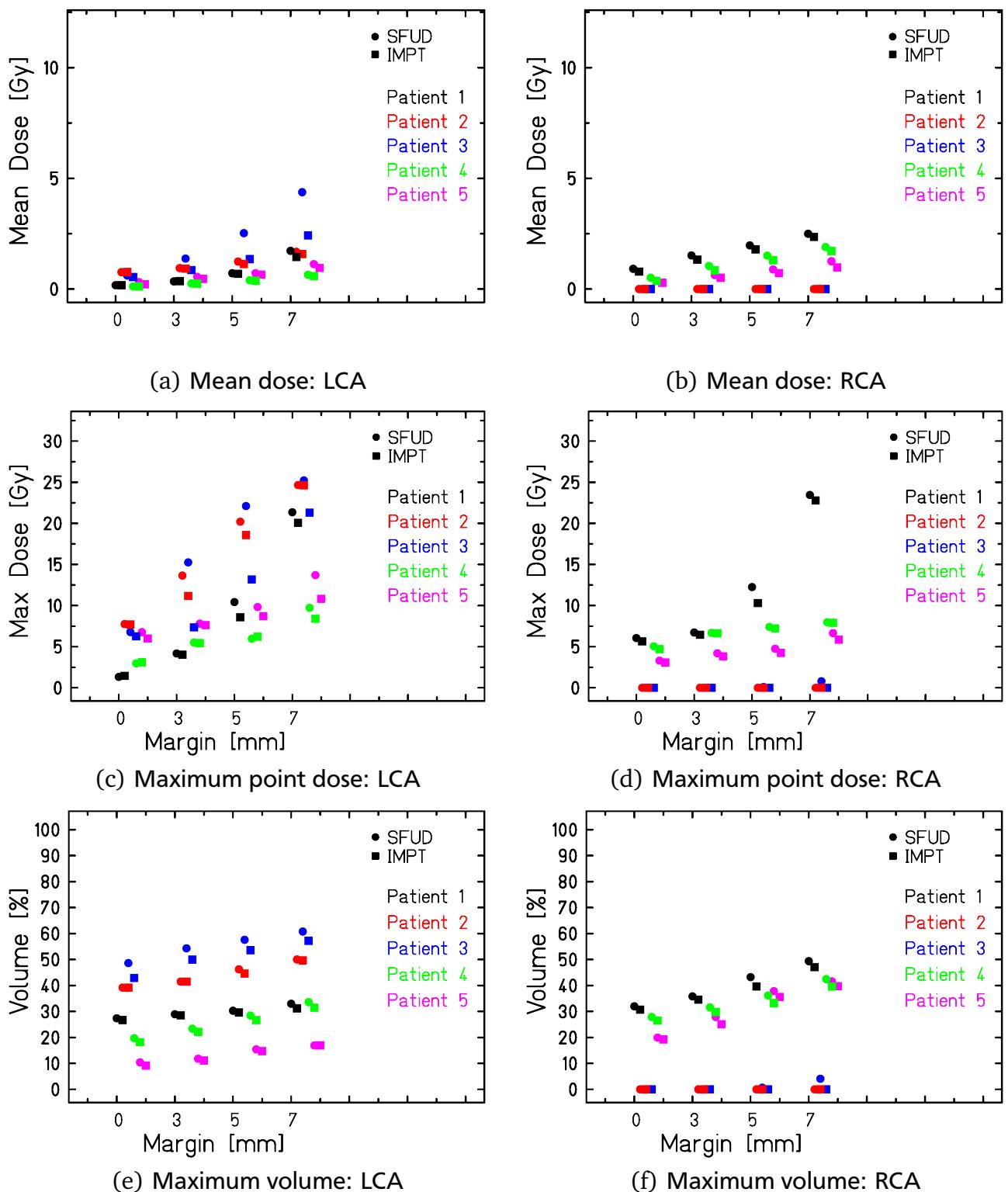


Figure 1.11: Mean dose, maximal point dose and maximal irradiated volume of left coronary artery (LCA) and right coronary artery (RCA), respectively, when irradiating the LPV and RPV in the five patient data sets with different margins (0 mm, 3 mm, 5 mm, 7mm) and two different delivery techniques (SFUD irradiation and IMPT).

1.2.3 Motion assessment of heartbeat

Using the resulting deformation maps from deformable image registration the motion of the ablation sites of LPV and RPV was assessed. Motion volume histograms (MVHs) [Ric13] displaying the relative displacement of every voxel of the investigated volume to the reference phase in all three motion directions were generated. The mean and standard deviation of these displacement values in each motion phase of LPV and RPV are plotted for all patients and motion directions in figure 1.12 and 1.13, respectively.

The mean and standard deviation of each patient over all motion phases are stated in table 1.11. From the five studied patients patient 4 is displaying the highest absolute displacement, both in LPV and RPV. Furthermore it can be seen that none of the motion directions can be determined as the largest contribution to the absolute displacement, neither in LPV or RPV motion. In table 1.12 the maximal absolute displacement for each patient is presented together with the corresponding motion phase. While motion phase six is the motion phase with the biggest displacement in 30% of all cases, no evident maximal motion phase can be assessed. On average, the absolute amplitude over all motion phases and patients is found to $(2.71 \pm 1.57)\text{mm}$ for LPV and $(2.62 \pm 1.41)\text{mm}$ for RPV. In SI direction, the mean amplitude is $(-0.60 \pm 1.36)\text{mm}$ for LPV and $(-0.17 \pm 1.57)\text{mm}$ for RPV. In AP direction it is $(0.77 \pm 0.96)\text{mm}$ for LPV and $(1.00 \pm 1.58)\text{mm}$ for RPV, while in LR direction it is found to $(0.36 \pm 0.92)\text{mm}$ for LPV and $(-1.00 \pm 1.48)\text{mm}$ for RPV. Hence, averaged over all patients it can be stated that the PVs are moving mostly in AP direction. Nevertheless the contribution of the other motion directions are in the same order of magnitude.

The motion phases of the heartbeat gated CT scan are based on the ECG trace and result in a division of a single heartbeat. The motion phases can hence be directly assigned to the contraction (systole) and dilatation (diastole) of both atria and ventricles. Contraction of the atria (atrial systole) is occurring in between motion phase four and nineteen, in the same time as the ventricular relaxation (ventricular diastole). The ventricular systole and at the same time atria diastole are hence much shorter, occurring in the remaining motion phases twenty to three. The maximal displacement of the atria should thus be observed in motion phase eighteen, while the maximal amplitude of the ventricle should be observed in motion phase three. The motion of the PVs on the other hand result in a much more chaotic displacement. No motion phase can be assessed to a maximal displacement in all patient cases and no dominant motion direction is observed. The underlying heartbeat motion which causes the PVs to move should hence be much more complex.

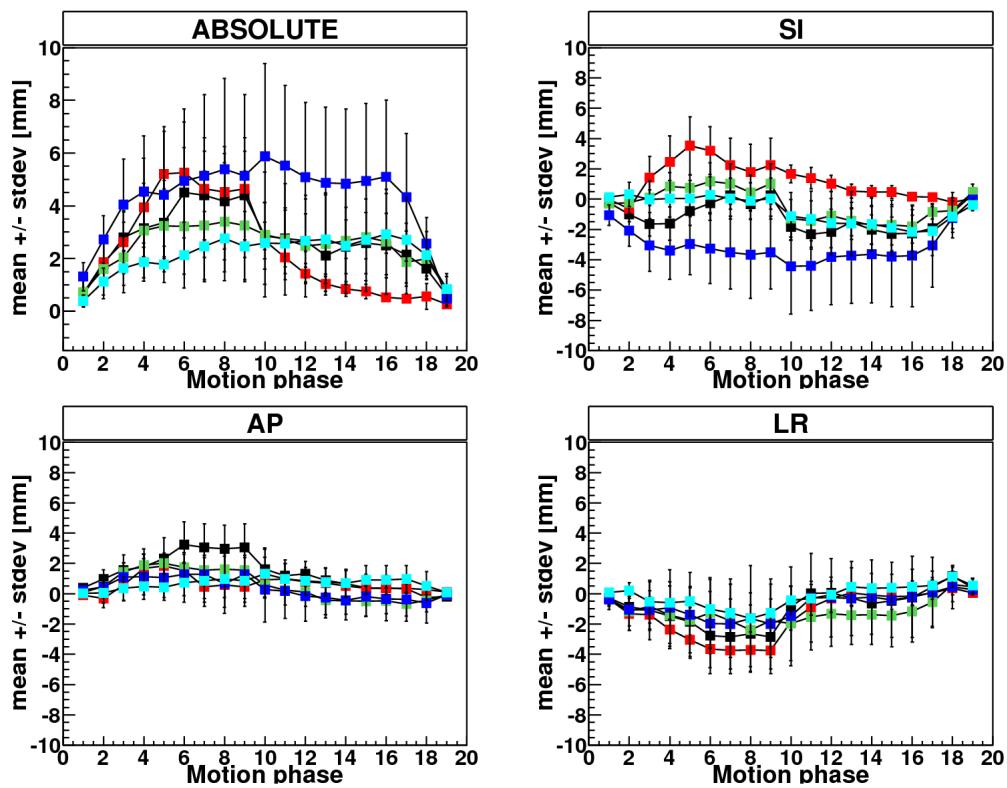


Figure 1.12: Motion amplitude of LPV under influence of heartbeat for all patients. (Patient 1: black, Patient 2: red, Patient 3: green, Patient 4: blue, Patient 5: turquoise)

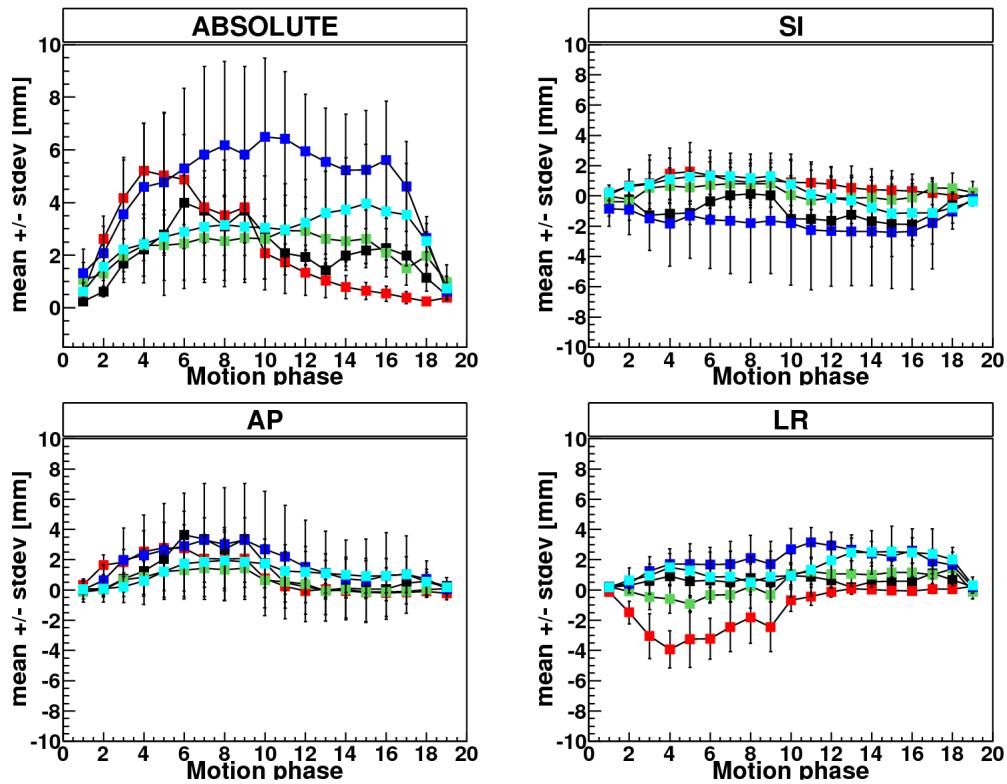


Figure 1.13: Motion amplitude of RPV under influence of heartbeat for all patients. (Patient 1: black, Patient 2: red, Patient 3: green, Patient 4: blue, Patient 5: turquoise)

Table 1.11: Mean displacement of PVs over all motion phases (MP) in all patients and motion directions.

Patient	LPV: ABS [mm]	LPV: SI [mm]	LPV: AP [mm]	LPV: LR [mm]
1	2.71 ± 1.18	-1.17 ± 0.91	1.35 ± 1.08	-0.89 ± 0.75
2	2.31 ± 1.14	1.16 ± 1.10	0.63 ± 0.53	-1.38 ± 0.90
3	2.48 ± 1.75	-0.36 ± 1.07	0.54 ± 0.78	-1.18 ± 1.95
4	4.27 ± 2.54	-3.07 ± 2.49	0.34 ± 1.43	-0.78 ± 2.47
5	2.15 ± 1.23	-0.75 ± 1.44	0.67 ± 1.10	-0.18 ± 0.94
Patient	RPV: ABS [mm]	RPV: SI [mm]	RPV: AP [mm]	RPV: LR [mm]
1	2.12 ± 0.71	-0.88 ± 0.65	1.11 ± 0.87	0.60 ± 0.60
2	2.25 ± 1.28	0.70 ± 1.15	0.96 ± 1.07	-1.19 ± 1.01
3	2.22 ± 1.19	0.23 ± 1.25	0.50 ± 1.77	0.39 ± 0.70
4	4.62 ± 2.33	-1.68 ± 3.12	1.67 ± 2.82	1.84 ± 0.94
5	2.77 ± 1.72	0.22 ± 1.77	1.03 ± 1.25	1.40 ± 1.40

Table 1.12: Biggest absolute displacement of PVs with corresponding motion phase (MP) in all patients.

Patient	LPV: max. ABS [mm]	MP
1	4.50 ± 1.72	06
2	5.26 ± 1.92	06
3	3.39 ± 2.24	08
4	5.52 ± 3.06	11
5	2.92 ± 1.54	16
Patient	RPV: max. ABS [mm]	MP
1	3.99 ± 1.40	06
2	5.20 ± 1.80	04
3	2.93 ± 1.35	11
4	6.49 ± 3.00	10
5	3.95 ± 3.95	15

The overall displacement field between the extreme states of the ventricular displacement (motion phase three) and atrial displacement (motion phase eighteen) for two exemplary patients with a small motion amplitude (patient 5) and a large motion amplitude (patient 4) are shown in figure 1.14. In order to visualize the location of the displacement, an axial cut of the reference state CT is underlaid. The absolute values of the displacement vectors are shown as contour plots.

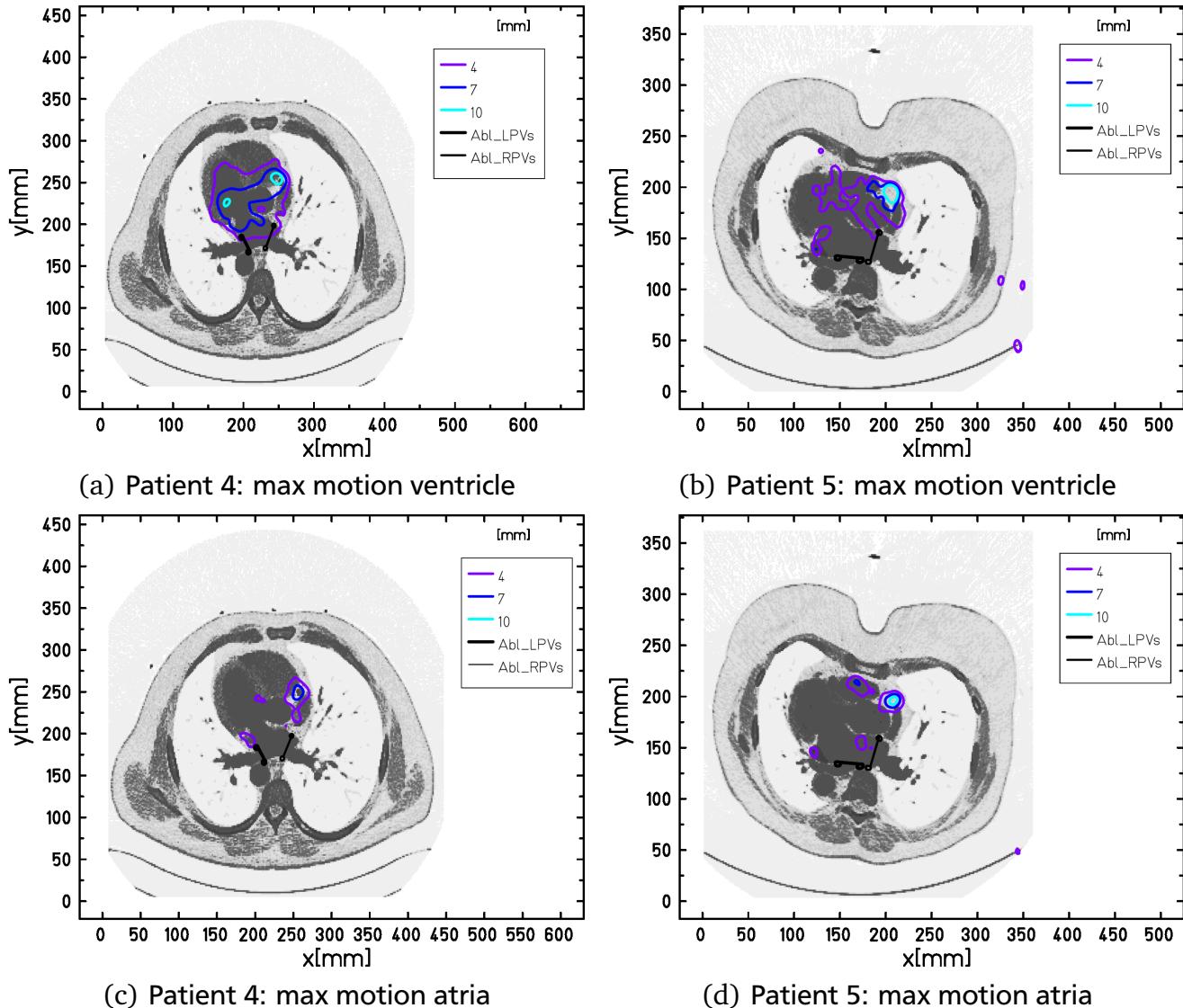


Figure 1.14: Axial slices of the reference state of the CT overlaid with the absolute values of the displacement field (obtained from deformable image registration) in the corresponding slice for heartbeat motion. In the top row the displacement from the motion phase with the maximal ventricle motion to the reference phase is shown, in the lower row the displacement from the motion phase with the maximal atrial motion, for Patient 4 and Patient 5, respectively.

1.2.4 Motion mitigation techniques for heartbeat

The absolute motion amplitudes of up to 5mm due to heartbeat are expected to yield dose inhomogeneities when not compensated for. The resulting Interplay effect and dose deposition was studied for every patient for different motion patterns and different margins to the target volumes. The dose analysis values V95, V107 and D5-D95 were assessed and plotted. For comparison also the corresponding values for the 3D case (static) are shown. Due to the small motion amplitude, rescanning was studied as motion mitigation technique. The results of the stated dose values in case of rescanning with different rescan numbers will also be presented.

Dose deposition

A representative dose deposition for all studied techniques (static, interplay and rescanning with ten rescans) is shown exemplary for patient 4 (as this is the patient with the largest PV motion amplitude both in LPV and RPV) in figure 1.16. Rescanning and interplay are shown for a sinus motion with a period of 0.7s and a starting phase of 0°. The target volumes LPV and RPV were irradiated simultaneously and a margin of 3mm was added. It can already been seen from this dose cut figures that rescanning with only ten rescans drastically improves the outcome compared to interplay and yields a result which is comparable to the static case.

For patient 4, the different motion patterns DVHs of ten rescans compared to the interplay results as well as a static irradiation are displayed in figure 1.15 for 3mm safety margin. In order to assess the dose information of all patients the DVHs were analyzed and compared for dose steepness, dose coverage as well as over dosage. The average results over all patients with the resulting standard deviation can be seen in figure 1.17. A more detailed analysis can be found in appendix XXX, where the values are plotted for each patient (figures ?? - ??) and all corresponding numerical values are shown (tables 1.24 - 1.33).

For interplay it can be seen that the results are dependent on the used motion period and starting phase. This can be seen in the mean values of dose parameter value results for different, underlying motion patterns. E.g. for the RPV, the mean value of the dose coverage parameter over all patients is $V95 = (88.8 \pm 12.8)\%$ for a sinus motion with 1s period and a starting phase of 90° and $(98.01 \pm 1.36)\%$ for a sinus motion with 0.7s period and a starting phase of 90°, while for a sinus motion with 0.7s period and a starting phase of 0° the dose coverage is found to $(92.1 \pm 12.7)\%$. The resulting high standard deviation over all patient cases shows that the result is also dependent on the studied patient case. Furthermore the result is also dependent on the studied safety margin, so that e.g. the dose coverage for a sinus motion with 1s period and a starting phase of 90° results to $(95.9 \pm 2.4)\%$ with 3mm safety margin. All these dependencies

are also valid for the other studied dose analysis parameters, dose homogeneity and over dosage.

The underlying deformation map with its motion amplitude does not enable a prediction of the magnitude of the interplay effect. This was studied in more detail for the dose coverage parameter V95. Here, the correlation between the maximal absolute motion amplitude of the left and right PV (see table 1.12) and the resulting V95 value for 3 mm Margin were assessed for all studied motion patterns (sinus motion with period of 1s or 0.7s and starting phase of 0° and 90°) and patients. The results can be seen in figure 1.18. A moderate correlation between the dose coverage and maximal amplitude resulted only in the case of RPV where a motion period of 0.7s with a starting phase of 90° was chosen ($r=0.49$; $p<0.05$). Nevertheless these results could not be verified in the other motion cases and in the irradiation of the LPV and hence no dependence between target volume displacement and dose coverage in case of interplay was found.

As can be seen in figure 1.17 (as well as in more detail for all patients in appendix XXX) rescanning yields improved results compared to interplay in all studied cases. This is valid for dose steepness, dose coverage as well as over dosage. Especially dose coverage and over dosage are comparable to the static results for all patient and motion patterns. Exemplary, the dose coverage of patient 4 (with the largest absolute displacement) will be discussed. V95 for a static irradiation of the LPV of patient 4 with 3mm safety margin is found to 99.8%. With a motion of 0.7s period length and a starting phase of 0° the value decreases to 90.0%. With rescanning, V95 can be improved to 99.75% with only five rescans. Also for RPV the static dose coverage with 3mm margin is found to 100% for this patient. With the stated motion and safety margin the dose coverage decreases to 97.0% in the case of interplay. With five rescans the value improves again to 100.0%. The improvement of dose coverage and over dosage compared to interplay is valid for all studied rescan numbers, starting from the smallest studied rescan number of five, as shown here. Nevertheless, in some studied cases five rescans is not enough to yield results comparable to the static irradiation. For example for the LPV irradiation with five rescans in patient 1 with a motion period of 1s and 90° starting phase (3mm safety margin) V95 results in a smaller dose coverage (93.2%) than the static case (100%). Even though this result is improved compared to interplay (86.9%), a much better result can be gained with higher rescan numbers, starting with ten rescans (99.2%). Also the results for dose homogeneity improves with higher rescan numbers. For a motion pattern of 0.7s period and 0° starting phase (3mm safety margin) in patient 4, the dose homogeneity in case of interplay is found to 9.9%. With five rescans a dose homogeneity of 5.5% is yielded, which further decreases to 4.6% with ten rescans, 4.4% with fifteen rescans and 3.9% with twenty rescans (compared to 3.9% in the static irradiation). It can thus be concluded that rescan numbers higher than five yield better slightly results, while ten rescans show results comparable to the static irradiation in all studied

patient cases, for all studied safety margins and for all underlying motion patterns. As can be furthermore seen in figure 1.17, the standard deviation of the dose analysis parameters over all patients is rather small for ten and higher rescan numbers, proving the robustness of rescanning as a motion mitigation technique for a displacement of the PVs due to heartbeat.

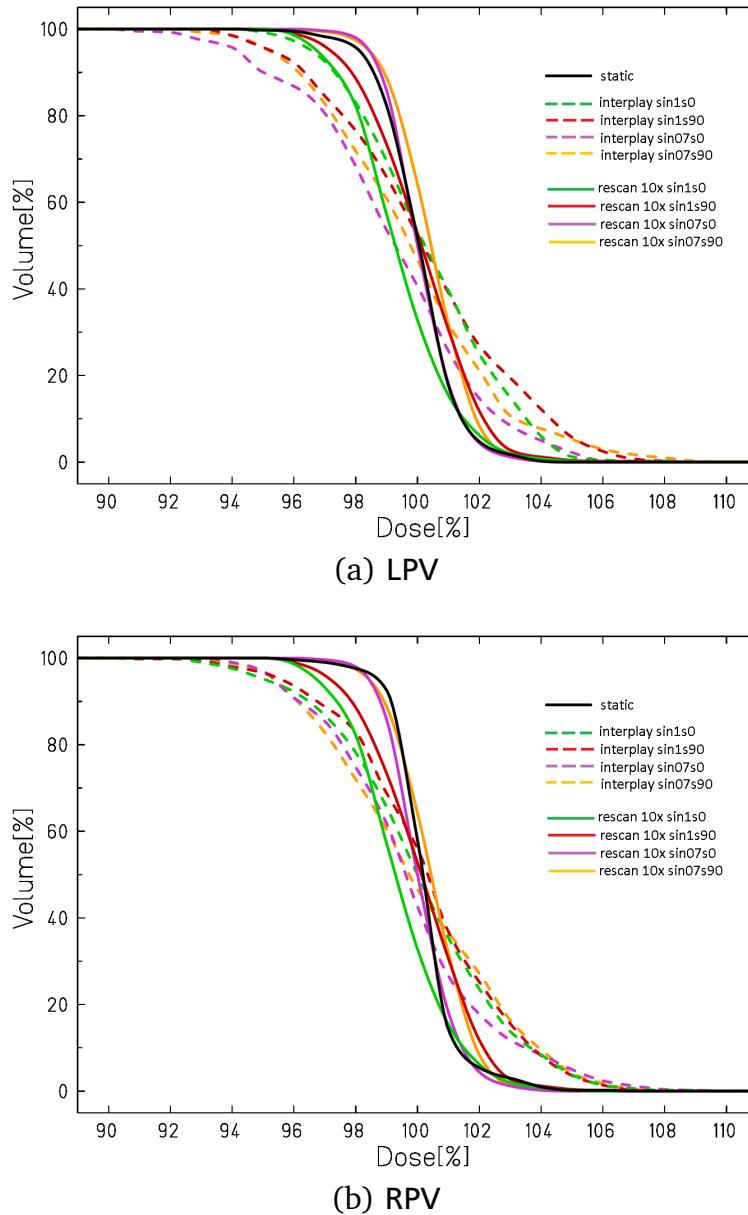
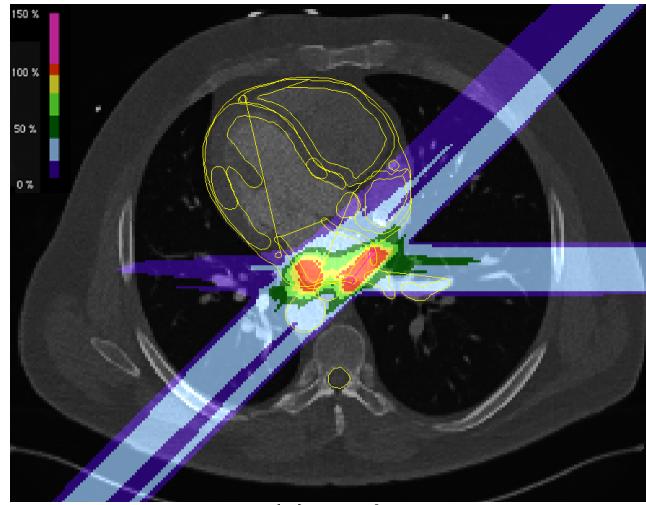
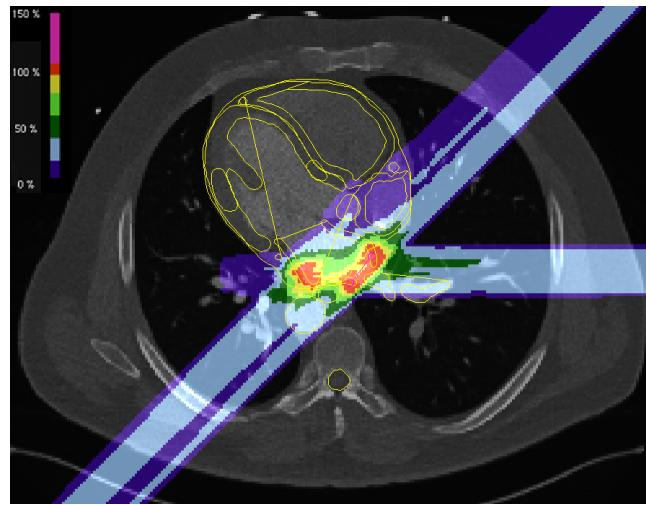


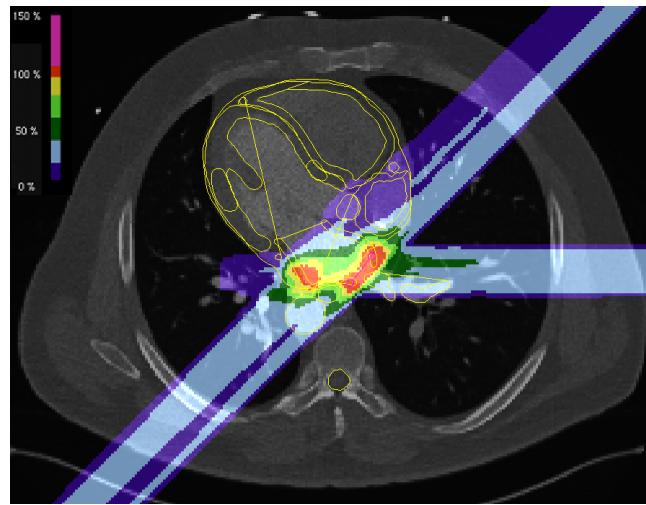
Figure 1.15: Dose volume histograms for CTV of patient 4 for 3mm safety margin irradiation (LPV (a) as well as RPV (b)) in case of static irradiation (black), interplay (dashed) and rescanning with ten rescans (solid). The motion patterns are shown in colors (sin1s0: sinus with motion period of 1s and starting phase 0°, sin1s90: sinus with motion period of 1s and starting phase 90°, sin07s0: sinus with motion period of 0.7s and starting phase 0°, sin07s90: sinus with motion period of 0.7s and starting phase 90°).



(a) static



(b) interplay



(c) rescanning (10x)

Figure 1.16: Dose distribution of patient 4 for static (a) as well as interplay (b) and ten rescans (c) at motion period of 0.7s and a motion starting phase of 0°. The target volume has an added margin of 3mm. The improved outcome of rescanning compared to interplay can already be seen in these dose cuts.

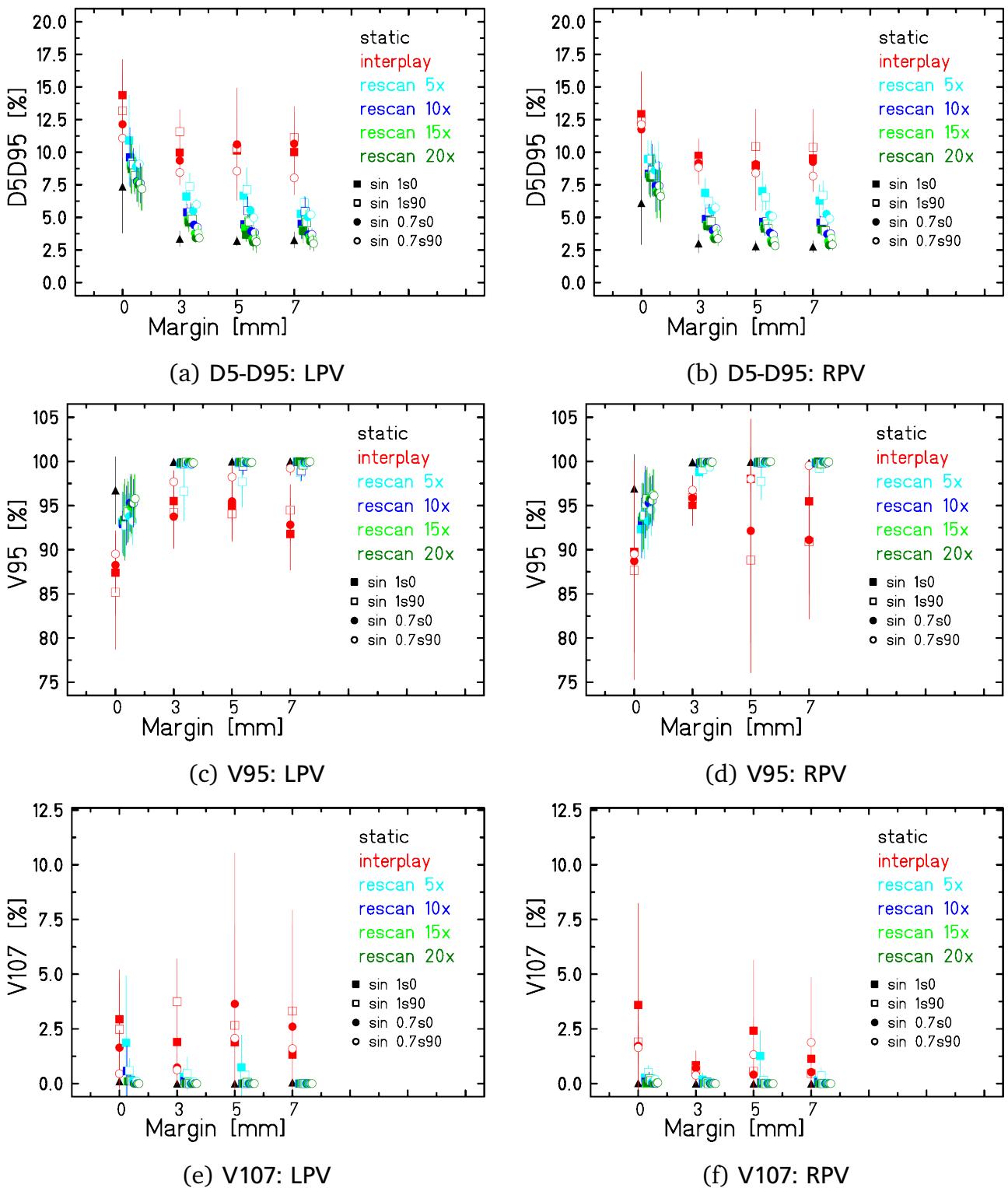


Figure 1.17: Mean and standard deviation of dose analysis parameters D5-D95 (first row), V95 (middle row) and V107 (last row) over all patients. The LPV (left column) and RPV (right column) were studied separately. Static (black) as well as interplay (red) and different rescanning numbers (5 times: turquoise, 10 times: blue, 15 times: light green, 20 times: dark green) were compared for different motion patterns and safety margins. For a better visualization the rescanning data points for each motion pattern are shifted.

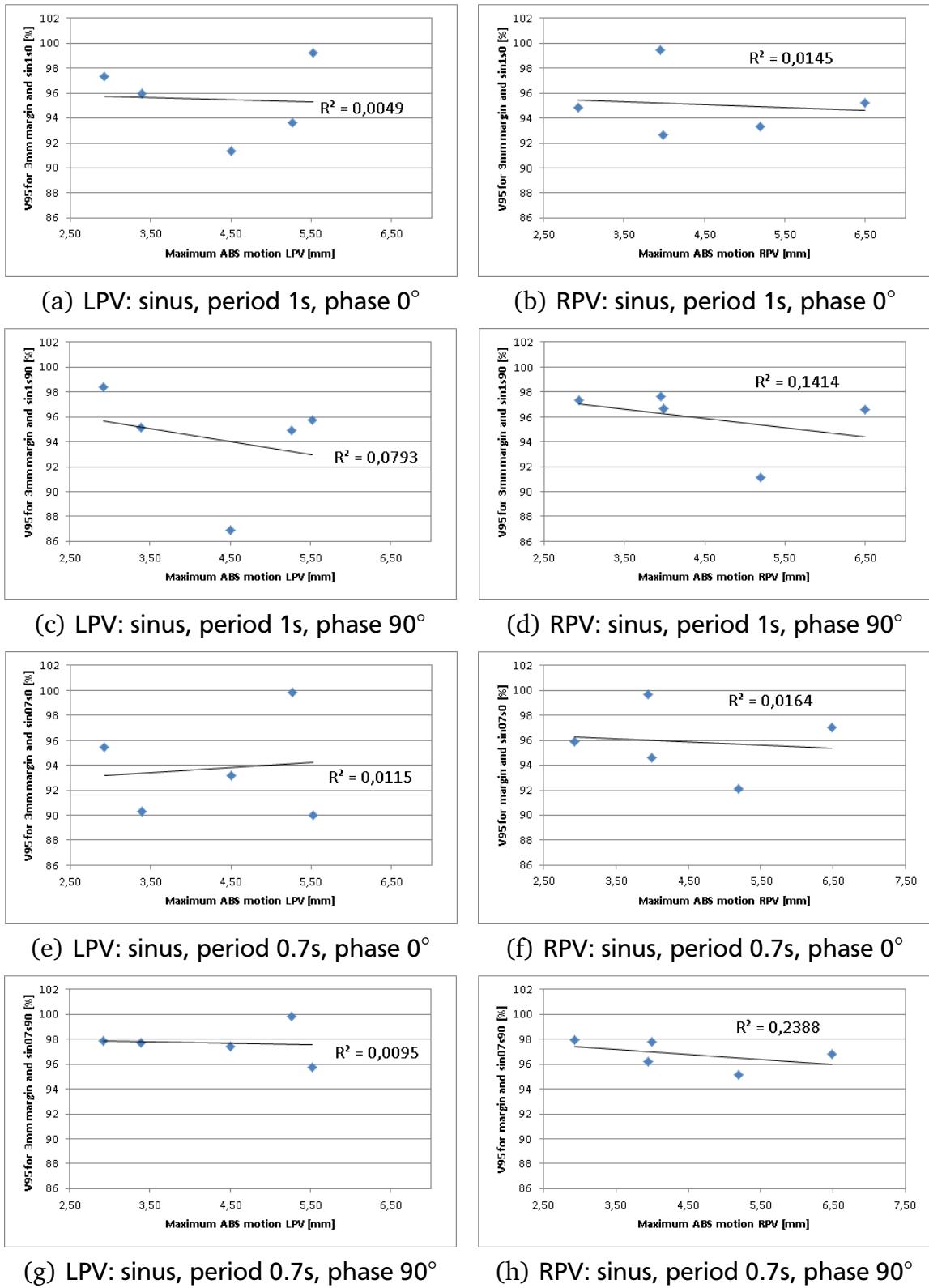


Figure 1.18: Interplay dose homogeneity of LPV (left column) and RPV (right column) in all patients in relation to the maximal absolute displacement of the PVs and for different underlying motion patterns (first row: sinus with 1s period and starting phase of 0°, second row: 1s period and starting phase of 90°, third row: 0.7s period and starting phase of 0°, last row: 0.7s period and starting phase of 90°).

Irradiation time

In figure 1.19 the mean irradiation time over all patients for different rescanning irradiations of LPV and RPV are shown for different safety margins and motion patterns. The duration for each beam entry channel (gantry angle of -45° , 135° and 0°) is plotted individually. It can be seen that the needed irradiation time increases with the used safety margin as the to irradiated volume increases. The irradiation time is independent of the motion pattern but varies depending on the used beam entry channel. Concerning the used rescan number it can be seen that no treatment prolongation is expected for higher rescan numbers. This can be understood as with higher rescans the intensity of each raster point in one iteration is reduced by a factor which is equal to the rescanning number. Hence the time the beam has to spend in one raster position, depositing the predetermined intensity, is reduced resulting in an overall treatment time which is constant for all rescan cases. The stated results were achieved with a low intensity irradiation (minimal particle number of 5.000). For an irradiation with 3mm margin around LPV and RPV the overall treatment time results to (13.71 ± 0.94) min (see table 1.13) with rescanning as motion mitigation technique for heartbeat motion.

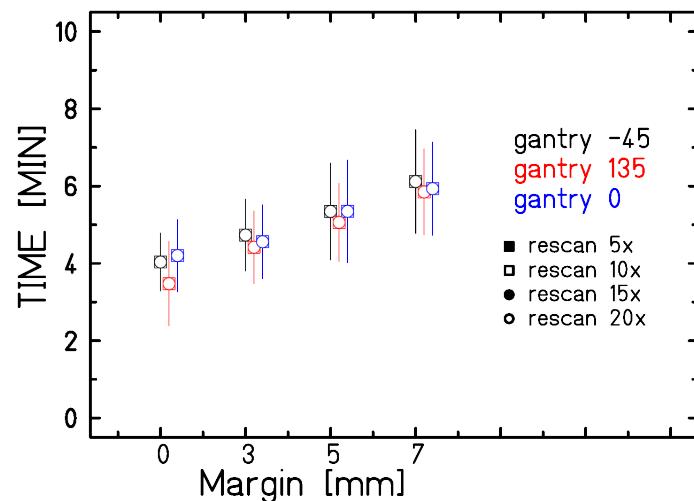


Figure 1.19: Mean and standard deviation of the irradiation time over all patients for different rescan numbers, underlying motion patterns and beam entry channels.

Table 1.13: Mean irradiation time for LPV and RPV with a safety margin of 3mm over all patients.

Gantry angle [°]	time [min]	total [min]
-45	4.73 ± 0.93	
135	4.42 ± 0.94	
0	4.56 ± 0.96	13.71 ± 0.94

1.3 Discussion

In this chapter the influence of heartbeat motion on the PVs was studied and treatment planning studies with rescanning as motion mitigation technique were carried out. A detailed analysis of the dose depositions to the OAR was performed, with special emphasis on the irradiation of cardiac substructures. Beforehand, a study of the best suited field number and beam directions was conducted as well as an analysis of possible safety margin limitations.

1.3.1 Dose to critical structures

Concerning the dose deposition in OAR (esophagus, trachea, aorta and heart) dose-volume limits from SBRT were used. In SBRT treatment a high dose is also applied in a single fraction and hence comparable to the here stated dose delivery of 25Gy physical dose in one treatment session. An extensive collection of dose-volume-limits for SBRT are presented in the study protocols of the Radiation Therapy Oncology Group (RTOG). The there stated dose-volume limits for trachea (10.5Gy in 4cm³) and aorta (31Gy in 10cm³) were not exceeded for any of the studied field numbers and beam channel combinations. The same is valid while keeping the chosen three fields (couch angle of 90° and gantry angles of -45°, 135° and 0°) constant and changing the studied safety margins (0mm, 3mm, 5mm and 7mm). For the esophagus on the other hand, the dose-volume limits were much more critical. Most of the studied beam directions yielded a dose which exceeded the stated dose-volume limit (11.9Gy for 5cm³). Hence an IMPT delivery, including the esophagus in the optimization process, was necessary. With this delivery technique and the above stated beam direction, the dose to the esophagus could be drastically reduced,. Nevertheless only an irradiation of the PVs with 3mm safety margin resulted in a dose deposition into the esophagus which met the dose volume limit (median of 9.3Gy, 75th percentile: 12.1Gy). This result could be drastically improved with different IMPT parameters, enabling a safe irradiation when patient specific IMPT parameters were used. Thus also safety margins higher then 3mm should result in a uncritical dose deposition. For the heart all beam channels, safety margins and delivery types (SFUD or IMPT) exceeded the stated dose-volume limit (16Gy for 15cm³). This is due to the fact that the heart is not only an OAR in the here presented, non-invasive treatment modality for PV isolation, but part of the cardiac structures are also the target itself. Hence a closer look on the affected cardiac substructures and the relevance of these dose depositions on cardiac toxicity and late effects were given.

QUANTEC (quantitative analysis of normal tissue effects in the clinic) [QUANTEC10] offers an comprehensive literature review on the available data of the last 20 years and is meant as an update of the extensively used dose-limits proposed by Emami et al. [Ema91]. In the QUANTEC publication by Gagliardi et al. [Gag10] radiation dose-volume effects in the heart are presented.

It is stated that radiation-induced cardiac diseases are distinguished between acute injuries like pericarditis¹, which can turn into a chronic disease, and late injuries which manifest months or even years after radiation exposure. Typical late injuries are congestive heart failure², ischemia³, coronary artery disease and myocardial infarction⁴. It was summarized that it remains uncertain which region of the heart is most important for radiation induced tissue toxicities. But it is stated that the risk of cardiac events is probably related to both dose and irradiated volume. Pericarditis seems to be related to left ventricle (LV) irradiation, and it was found that LV shielding was able to drastically reduce the incidence rate [Carm76]. It was stated that a mean cardiac dose of 27.1Gy and maximum dose of 47Gy seem to act as predictors for pericarditis [Mar98]. Wei et al. [Wei08] stated another discriminator for pericarditis which was found to be V30 < 46%, which translates in a mean pericardial dose of less than 26Gy. For coronary and ischemic events relevant structures are assumed to be coronary arteries on the left ventricle (LCA) [Nie07] [Tay07] [Tay08]. Furthermore it is stated that excess deaths from heart disease are observed in patients receiving more than 42Gy [Han93] and that aortic and mitral stenosis incidences increased above a threshold dose of 30Gy [Tay07]. For long term cardiac mortality an increased rate was only observed at whole heart doses above 30Gy [Han93].

Hooning et al. [Hoo07] studied the cardiovascular disease incidence in more than 4000 breast cancer survivors after a follow-up period of more than 10 years as patients were treated from 1970 through 1986. It was the first study to examine the effects of cardiovascular risk factors in combination to radiotherapy. They found that the risk of congestive heart failure was significantly increased when the patients had received chemotherapy (95% confidence interval of 1.25 to 2.73) and that smoking drastically increased the risk of the patients to suffer a myocardial infarction (95% confidence interval of 2.03 to 4.55). Concerning radiotherapy they stated that a higher mean dose to the whole heart resulted in an increased risk of congestive heart failure and that an irradiation of the left vs right chest wall (thus more heart volume and in particular including the LV and apex) led to an increased risk of myocardial infarction.

A recent study by Darby et al. [Dar13] investigated more than 2000 breast cancer patients treated in between 1958 and 2001 for coronary events like myocardial infarction, coronary revascularization or death from ischemic heart disease. They found a mean heart dose of 4.9Gy (0.03Gy to 27.72Gy) and that the rates of major coronary events increased linearly with the mean heart dose. They stated an increase of incidences by 7.4% per Gy (95% confidence interval of 2.9 to 14.5) after five years post radiotherapy.

¹ inflammation of the sac containing the heart

² heart is unable to maintain sufficient blood flow

³ deficient blood supply

⁴ heart attack

For the here studied seventeen beam channel combinations, applying a physical dose of 25Gy, the mean dose over all five studied patients was found to have a median of 1.26Gy (75th percentile: 1.48Gy). The median over the maximal point dose was 26.6Gy (75th percentile: 27.1Gy), while in general less than 30% of the heart was irradiated. With the chosen field number of three beam channels with directions of a couch angle of 90° and gantry angles of -45°, 135° and 0°, the mean dose was found to less than 2Gy in all studied patient cases. For different added safety margins to the PVs it was found that the median mean dose over all patients was 1.0Gy (75th percentile: 1.1Gy) with no margin, 1.3Gy (75th percentile: 1.5Gy) for 3mm, 1.4Gy (75th percentile: 1.6Gy) for 5mm and 1.5Gy (75th percentile: 1.6Gy) for 7mm margin. Hence, all these results are in good agreement to the dose and volume limitations stated in the above studies and thus no pericarditis should be expected when irradiating the PVs with an IMPT delivery of carbon ions. As the LV, and with it especially the LCA, are assumed to be radiosensitive structures within the heart the dose depositions to these structures were analyzed in more detail. It was found that three beam channel directions were best suited to yield a lower mean dose deposition in the LCA. Due to robustness criteria of the treatment delivery the above stated beam channel combination was chosen. With this delivery direction it was found that the mean dose to the LCA was, dependent on the used safety margin, 0.2Gy(75th percentile: 0.5Gy) with no margin, 0.5Gy (75th percentile: 0.5Gy) for 3mm margin, 0.7Gy (75th percentile: 1.1Gy) for 5mm and 1.5Gy (75th percentile: 1.6Gy) for 7mm. The maximum point dose to the LCA with these beam channels nevertheless led to an increased dose in the left chamber compared to the right site. This is due to the proximity of the upper LCA branches to the LPV target site.

1.3.2 Beam channel directions and safety margins

In general, it can be stated that field number and beam direction always result in a trade-off between dose to the OAR, irradiation time and robustness. While less fields and hence beam directions shorten the treatment time, it does lead to a less robust treatment. In case OAR are displaced during the treatment (intrafractional motion, see Introduction) or move in between CT image acquisition and irradiation (interfractional motion) beam channels with a large angle in between them are more robust, as not all fields are affected by this displacement and hence only a small dosis would be shifted. Furthermore, opposite fields (like -45° and 135° (see figure 1.1) are more robust against potential range uncertainties and should hence be favored. Due to this reason, combined with the smaller LCA dose deposition in case of three field numbers, a couch angle of 90° and gantry angles of -45°, 135° and 0° was selected for the safety margin limitation studies as well as the motion mitigation treatment plans. Concerning safety margins, which need to be applied in order to account for possible deviations in between treatment planning and dose delivery, it can be stated that only a small margin tolerance was observed. This is due to the difficult position of the PVs close to radiosensitive structures like the esophagus

and especially the heart. With IMPT treatment a delivery with 3mm safety margin was found to fulfill all the needed requirements. A more realistic safety margin of 5mm could be achieved with more restricted parameters in the IMPT optimization.

1.3.3 Movement of PVs in cardiac cycle

Lickfett et al. [Lic05] analyzed the volume changes and displacement of the PVs in 25 healthy volunteers with MRI images. They studied the posterior edge of the PV orifice and observed that the size and location changed considerably during the cardiac cycle. Displacements of up to 7.2 mm were found and it could be concluded that the motion amplitudes were bigger in the coronal (left-right) than in the sagittal (anterior-posterior) direction. In more detail this largest coronal movement was found in the left superior PV, while the largest sagittal motion was observed in the right superior PV with 3.9 mm. The smallest sagittal displacement was 2.5 mm in the left anterior PV. They suspected that the reason for movement is not resulting from a single influence, but is rather a mix of PV contraction, atrial contraction and ventricular force. The movement of PV due to heartbeat is also relevant for catheter ablation. Based on the stated finding Lickfett et al. recommended to keep a 5 mm distance from the PV orifice during PV encircling ablation in order to reduce the risk for PV stenosis. Patel et al. [Pat08] on the other hand, who studied the MRI images of 30 patients in sinus rhythm with paroxysmal atrial fibrillation, stated that the displacement of the pulmonary veins was small. The left lower PV was found to move (2.7 ± 1.2) mm, the left upper PV (2.1 ± 1.1) mm, the right lower PV (1.9 ± 1.1) mm and the right upper PV (2.3 ± 1.0) mm.

In the here studied patient cohort of five AF patients no differentiation between the upper and lower PVs was carried out. The motion was assessed for the whole potential ablation site of LPV and RPV, respectively. Similar to the study by Patel et al. only a small displacement was found, resulting to an average absolute displacement of less than 3mm (LPV: (2.71 ± 1.57) mm, RPV: (2.62 ± 1.41) mm). Even though a tendency to a higher motion in AP direction could be observed, the contributions of the other motion directions were in the same order of magnitude (up to 1mm). Hence no dominant motion direction could be determined. The motion phases of the heartbeat gated CT scan were based on the ECG trace and resulted in a division of a single heartbeat. Thus the motion phases could be directly assigned to the contraction (systole) and dilatation (diastole) of both atria and ventricles. Nevertheless no motion phase could be assessed to yield the maximum displacement. This reinforces the thesis by Lickfett et al. that the underlying heartbeat motion, which causes the PVs to move, is much more complex.

1.3.4 Rescanning as motion mitigation technique

Concerning dose deposition with rescanning compared to interplay it can be concluded that rescanning yields good result. Regarding dose coverage V95 values were higher than 99% in 96.3% of all studied cases with a safety margin of 3mm or higher. The minimum dose coverage over all studied cases with safety margin was found in patient 1, in the irradiation of the LPV with a margin of 3mm and an underlying motion of 1s period and 90° starting phase ($V95=93.2\%$). This result was obtained with five rescans. With higher rescans the dose coverage could be improved, so that only 1.5% of the studied cases with ten or more rescans had a dose coverage smaller than 99% (minimum: 97.1%; 10 rescans in patient 1, 7mm safety margin and motion of 1s period and 90° starting phase). The dose coverage for rescans without safety margin was worse, resulting in 93.1% cases under 99%. V107 values higher than 0% were obtained in 7.3% of all cases with safety margin (maximum of $V107=3.7\%$ in the LPV of patient 3 with safety margin of 5mm, 5 rescans and motion of 1s period and 0° starting phase) compared to 28.8% of cases without safety margin (maximum: $V107=8.0\%$ for the LPV of patient 2 with 5 rescans and motion of 1s period and 0° starting phase. This could be reduced to $V107=2.9\%$ with 10 rescans). With safety margin, the dose homogeneity D5-D95 did not exceed 8.9%. Without safety margin D5-D95 did not exceed 10.2%. Both of these values were achieved with 5 rescans and could be improved with 10 rescans (with safety margin to less than 7% and without to less than 9%). It can hence be concluded that additional safety margins enable a more robust and successful treatment delivery. However, if possible, these margins should be kept as small as technical feasible, as it increases the dose deposition in OARs. Regarding rescan numbers ten rescans yield improved results compared to five rescans. These results are not significantly improved with higher rescan numbers.

1.4 Conclusion

The PVs were found to move due to heartbeat with an amplitude of up to 6mm. This displacement creates interplay effects when irradiated with carbon ions. Rescanning as motion mitigation technique was studied. It yields improved dose coverage and dose homogeneity compared to interplay in all studied patient cases, motion patterns and for all safety margins. It is thus an adequate motion mitigation technique for the irradiation of PVs under influence of heartbeat motion. A rescan number of ten is sufficient to obtain results comparable to the static irradiation. For the treatment delivery, IMPT dose optimization together with a rather small safety margin (of e.g. 3mm) results in dose depositions in the OARs (like esophagus as well as in the cardiac substructures) which are considered tolerable.

for APPENDIX

Motion of PV due to heartbeat

Table 1.14: Patient 1, LPV: Mean and standard deviation of target motion in all phases of the heartbeat, relative to the reference phase.

motion phase	ABS [mm]	SI [mm]	AP [mm]	LR [mm]
01	0.62 ± 0.27	-0.22 ± 0.15	0.39 ± 0.26	-0.28 ± 0.30
02	1.78 ± 0.81	-1.00 ± 0.48	0.97 ± 0.62	-0.86 ± 0.71
03	2.79 ± 0.98	-1.65 ± 0.78	1.55 ± 1.03	-1.08 ± 0.87
04	3.15 ± 1.22	-1.61 ± 1.11	1.78 ± 1.19	-1.48 ± 0.91
05	3.36 ± 1.28	-0.79 ± 0.93	2.32 ± 1.39	-1.83 ± 0.90
06	4.50 ± 1.72	-0.27 ± 1.13	3.25 ± 1.49	-2.76 ± 1.19
07	4.39 ± 1.68	0.26 ± 0.93	3.05 ± 1.56	-2.84 ± 1.15
08	4.17 ± 1.82	-0.32 ± 1.02	2.95 ± 1.58	-2.64 ± 1.19
09	4.39 ± 1.68	0.26 ± 0.93	3.05 ± 1.56	-2.84 ± 1.15
10	2.85 ± 1.26	-1.81 ± 0.88	1.61 ± 1.42	-0.82 ± 0.61
11	2.76 ± 1.08	-2.30 ± 0.98	1.18 ± 1.04	0.02 ± 0.24
12	2.68 ± 1.02	-2.16 ± 1.05	1.31 ± 0.82	0.06 ± 0.29
13	2.11 ± 0.71	-1.53 ± 0.89	0.88 ± 0.82	-0.28 ± 0.56
14	2.44 ± 1.02	-2.01 ± 0.99	0.66 ± 0.86	-0.65 ± 0.61
15	2.58 ± 1.16	-2.29 ± 1.12	0.39 ± 0.88	-0.46 ± 0.59
16	2.49 ± 1.23	-2.25 ± 1.18	0.36 ± 0.85	-0.24 ± 0.57
17	2.15 ± 1.20	-1.91 ± 1.06	0.33 ± 0.85	0.44 ± 0.48
18	1.61 ± 0.41	-0.88 ± 0.38	-0.26 ± 0.60	1.15 ± 0.33
19	0.60 ± 0.20	0.32 ± 0.19	-0.18 ± 0.21	0.39 ± 0.20

Table 1.15: Patient 1, RPV: Mean and standard deviation of target motion in all phases of the heartbeat, relative to the reference phase.

motion phase	ABS [mm]	SI [mm]	AP [mm]	LR [mm]
01	0.25 ± 0.13	-0.03 ± 0.12	-0.02 ± 0.14	0.18 ± 0.11
02	0.62 ± 0.20	-0.23 ± 0.33	0.06 ± 0.37	0.31 ± 0.17
03	1.68 ± 0.31	-1.28 ± 0.42	0.73 ± 0.40	0.61 ± 0.24
04	2.22 ± 0.42	-1.18 ± 0.73	1.26 ± 0.65	0.91 ± 0.54
05	2.77 ± 0.76	-1.11 ± 0.77	2.05 ± 1.02	0.57 ± 0.94
06	3.99 ± 1.40	-0.35 ± 0.90	3.63 ± 1.57	0.65 ± 0.93
07	3.70 ± 1.24	0.04 ± 0.80	3.36 ± 1.41	0.51 ± 1.02
08	3.10 ± 1.12	0.12 ± 0.72	2.68 ± 1.31	0.79 ± 0.92
09	3.70 ± 1.24	0.04 ± 0.80	3.36 ± 1.41	0.51 ± 1.02
10	2.77 ± 0.71	-1.52 ± 0.52	1.77 ± 1.01	0.95 ± 0.74
11	2.08 ± 0.34	-1.51 ± 0.61	0.49 ± 0.77	0.87 ± 0.47
12	1.93 ± 0.45	-1.64 ± 0.62	0.20 ± 0.53	0.64 ± 0.31
13	1.42 ± 0.44	-1.25 ± 0.57	-0.02 ± 0.45	0.18 ± 0.31
14	1.99 ± 0.41	-1.68 ± 0.63	0.13 ± 0.64	0.55 ± 0.45
15	2.18 ± 0.49	-1.87 ± 0.72	0.05 ± 0.62	0.59 ± 0.49
16	2.27 ± 0.74	-1.90 ± 1.00	0.04 ± 0.75	0.57 ± 0.45
17	1.98 ± 0.40	-1.25 ± 0.69	0.46 ± 0.73	1.11 ± 0.26
18	1.14 ± 0.51	-0.27 ± 0.38	0.58 ± 0.59	0.68 ± 0.42
19	0.48 ± 0.21	0.18 ± 0.24	0.28 ± 0.23	0.20 ± 0.13

Table 1.16: Patient 2, LPV: Mean and standard deviation of target motion in all phases of the heartbeat, relative to the reference phase.

motion phase	ABS [mm]	SI [mm]	AP [mm]	LR [mm]
01	0.67 ± 0.48	-0.03 ± 0.21	-0.10 ± 0.17	-0.38 ± 0.67
02	1.86 ± 0.88	-0.62 ± 0.66	-0.32 ± 0.59	-1.31 ± 1.12
03	2.62 ± 1.20	1.43 ± 1.41	0.59 ± 1.06	-1.39 ± 0.94
04	3.94 ± 1.86	2.46 ± 1.71	1.68 ± 0.92	-2.35 ± 0.92
05	5.21 ± 1.80	3.52 ± 1.90	1.82 ± 0.61	-3.03 ± 1.23
06	5.26 ± 1.92	3.21 ± 1.58	1.51 ± 0.58	-3.65 ± 1.62
07	4.64 ± 1.94	2.25 ± 1.77	0.44 ± 0.76	-3.74 ± 1.53
08	4.52 ± 1.72	1.78 ± 1.84	0.57 ± 0.82	-3.71 ± 1.47
09	4.64 ± 1.94	2.25 ± 1.77	0.44 ± 0.76	-3.74 ± 1.53
10	2.68 ± 0.70	1.66 ± 0.59	0.90 ± 0.27	-1.84 ± 0.56
11	2.03 ± 0.61	1.39 ± 0.70	0.96 ± 0.28	-0.89 ± 0.51
12	1.43 ± 0.38	1.03 ± 0.53	0.78 ± 0.24	-0.32 ± 0.28
13	1.03 ± 0.28	0.53 ± 0.47	0.70 ± 0.25	0.06 ± 0.27
14	0.84 ± 0.28	0.48 ± 0.42	0.52 ± 0.12	-0.09 ± 0.28
15	0.75 ± 0.27	0.47 ± 0.42	0.37 ± 0.09	-0.19 ± 0.23
16	0.52 ± 0.10	0.18 ± 0.27	0.35 ± 0.07	-0.16 ± 0.15
17	0.47 ± 0.13	0.13 ± 0.23	0.35 ± 0.11	0.07 ± 0.16
18	0.56 ± 0.49	-0.19 ± 0.29	0.28 ± 0.23	0.36 ± 0.42
19	0.26 ± 0.09	0.05 ± 0.15	0.11 ± 0.12	0.07 ± 0.13

Table 1.17: Patient 2, RPV: Mean and standard deviation of target motion in all phases of the heartbeat, relative to the reference phase.

motion phase	ABS [mm]	SI [mm]	AP [mm]	LR [mm]
01	0.56 ± 0.32	0.07 ± 0.25	0.34 ± 0.40	-0.12 ± 0.23
02	2.62 ± 0.87	0.69 ± 1.07	1.66 ± 0.66	-1.49 ± 0.76
03	4.17 ± 1.55	0.83 ± 1.87	1.84 ± 0.84	-3.05 ± 1.48
04	5.20 ± 1.80	1.48 ± 1.70	2.55 ± 1.36	-3.92 ± 1.22
05	5.04 ± 2.35	1.61 ± 1.93	2.77 ± 1.69	-3.25 ± 1.87
06	4.88 ± 1.71	1.36 ± 1.64	2.76 ± 1.54	-3.22 ± 1.35
07	3.82 ± 1.83	1.02 ± 1.17	2.09 ± 1.57	-2.45 ± 1.64
08	3.52 ± 2.09	0.89 ± 1.11	2.04 ± 2.08	-1.80 ± 1.74
09	3.82 ± 1.83	1.02 ± 1.17	2.09 ± 1.57	-2.45 ± 1.64
10	2.08 ± 1.40	0.89 ± 1.53	0.76 ± 1.27	-0.67 ± 0.74
11	1.72 ± 1.17	0.86 ± 1.40	0.24 ± 1.03	-0.42 ± 0.59
12	1.34 ± 0.86	0.77 ± 1.11	-0.07 ± 0.76	-0.14 ± 0.34
13	1.04 ± 0.66	0.53 ± 0.83	0.05 ± 0.65	0.09 ± 0.36
14	0.79 ± 0.44	0.42 ± 0.59	-0.08 ± 0.46	0.01 ± 0.26
15	0.64 ± 0.33	0.37 ± 0.41	-0.15 ± 0.36	-0.05 ± 0.26
16	0.54 ± 0.29	0.31 ± 0.36	-0.18 ± 0.25	-0.06 ± 0.22
17	0.38 ± 0.23	0.19 ± 0.25	-0.17 ± 0.21	0.04 ± 0.15
18	0.24 ± 0.14	0.04 ± 0.13	-0.10 ± 0.18	0.07 ± 0.10
19	0.39 ± 0.15	-0.06 ± 0.15	-0.23 ± 0.14	0.23 ± 0.14

Table 1.18: Patient 3, LPV: Mean and standard deviation of target motion in all phases of the heartbeat, relative to the reference phase.

motion phase	ABS [mm]	SI [mm]	AP [mm]	LR [mm]
01	0.72 ± 0.48	-0.29 ± 0.51	0.09 ± 0.19	-0.33 ± 0.50
02	1.59 ± 1.12	-0.24 ± 0.70	0.48 ± 0.32	-1.17 ± 1.25
03	2.04 ± 1.34	0.09 ± 0.52	1.43 ± 0.61	-0.82 ± 1.61
04	3.06 ± 1.79	0.83 ± 0.92	1.89 ± 0.75	-1.42 ± 2.21
05	3.23 ± 1.73	0.74 ± 0.88	2.02 ± 0.67	-1.75 ± 2.13
06	3.22 ± 1.82	1.17 ± 1.24	1.73 ± 0.88	-1.26 ± 2.32
07	3.26 ± 2.06	1.01 ± 1.32	1.55 ± 0.82	-1.79 ± 2.42
08	3.39 ± 2.24	0.44 ± 1.17	1.62 ± 0.84	-2.38 ± 2.44
09	3.26 ± 2.06	1.01 ± 1.32	1.55 ± 0.82	-1.79 ± 2.42
10	2.91 ± 2.37	-1.26 ± 1.25	0.58 ± 0.80	-1.98 ± 2.45
11	2.73 ± 2.11	-1.43 ± 1.32	0.25 ± 0.98	-1.54 ± 2.16
12	2.47 ± 1.92	-1.09 ± 1.12	0.12 ± 0.95	-1.33 ± 2.15
13	2.55 ± 1.94	-1.43 ± 1.22	-0.42 ± 0.96	-1.42 ± 1.91
14	2.68 ± 2.02	-1.72 ± 1.25	-0.46 ± 0.88	-1.37 ± 1.96
15	2.82 ± 2.07	-1.70 ± 1.33	-0.50 ± 1.01	-1.46 ± 2.05
16	2.63 ± 1.99	-1.80 ± 1.11	-0.47 ± 0.86	-1.18 ± 2.02
17	1.86 ± 1.19	-0.83 ± 0.47	-0.67 ± 0.80	-0.55 ± 1.61
18	1.99 ± 0.66	-0.76 ± 1.20	-0.45 ± 0.75	0.60 ± 1.13
19	0.80 ± 0.62	0.48 ± 0.50	-0.06 ± 0.28	0.45 ± 0.51

Table 1.19: Patient 3, RPV: Mean and standard deviation of target motion in all phases of the heartbeat, relative to the reference phase.

motion phase	ABS [mm]	SI [mm]	AP [mm]	LR [mm]
01	1.06 ± 0.66	-0.40 ± 0.92	0.12 ± 0.67	0.21 ± 0.25
02	1.30 ± 0.85	-0.39 ± 1.21	0.01 ± 0.82	-0.09 ± 0.31
03	1.97 ± 1.01	0.52 ± 1.01	0.68 ± 1.52	-0.48 ± 0.80
04	2.38 ± 1.18	0.66 ± 1.18	0.85 ± 1.80	-0.58 ± 0.95
05	2.38 ± 1.34	0.56 ± 1.10	1.21 ± 1.82	-0.92 ± 0.56
06	2.45 ± 1.40	0.71 ± 1.53	1.30 ± 1.75	-0.35 ± 0.52
07	2.66 ± 1.57	0.82 ± 1.55	1.42 ± 2.04	-0.30 ± 0.47
08	2.54 ± 1.73	0.81 ± 1.60	1.35 ± 2.03	0.23 ± 0.55
09	2.66 ± 1.57	0.82 ± 1.55	1.42 ± 2.04	-0.30 ± 0.47
10	2.62 ± 1.51	0.03 ± 1.29	0.65 ± 2.33	1.06 ± 0.73
11	2.93 ± 1.35	-0.28 ± 1.35	0.54 ± 2.45	1.21 ± 0.86
12	2.92 ± 1.29	-0.15 ± 1.38	0.38 ± 2.48	1.06 ± 0.93
13	2.62 ± 0.98	-0.14 ± 1.35	-0.06 ± 2.01	1.08 ± 0.85
14	2.53 ± 1.11	-0.10 ± 1.38	0.03 ± 2.01	0.99 ± 0.82
15	2.62 ± 1.10	-0.27 ± 1.42	-0.12 ± 2.03	1.15 ± 0.75
16	2.09 ± 0.92	-0.12 ± 0.93	-0.14 ± 1.60	1.15 ± 0.63
17	1.49 ± 0.63	0.53 ± 0.57	-0.10 ± 0.82	0.99 ± 0.58
18	1.97 ± 0.91	0.49 ± 1.03	0.03 ± 0.53	1.39 ± 1.10
19	0.99 ± 0.64	0.23 ± 0.74	0.08 ± 0.74	-0.12 ± 0.47

Table 1.20: Patient 4, LPV: Mean and standard deviation of target motion in all phases of the heartbeat, relative to the reference phase.

motion phase	ABS [mm]	SI [mm]	AP [mm]	LR [mm]
01	1.31 ± 0.54	-1.07 ± 0.67	0.23 ± 0.28	-0.36 ± 0.39
02	2.73 ± 0.90	-2.06 ± 1.06	0.46 ± 0.68	-1.04 ± 1.07
03	4.04 ± 1.73	-3.06 ± 1.69	1.09 ± 0.96	-1.07 ± 1.96
04	4.54 ± 2.11	-3.38 ± 1.91	1.13 ± 1.20	-0.93 ± 2.53
05	4.41 ± 2.41	-2.97 ± 2.01	1.08 ± 1.34	-1.37 ± 2.76
06	4.94 ± 2.74	-3.27 ± 2.29	1.29 ± 1.43	-1.97 ± 2.90
07	5.13 ± 3.09	-3.52 ± 2.40	1.27 ± 1.82	-2.00 ± 2.96
08	5.39 ± 3.44	-3.66 ± 2.89	0.68 ± 1.97	-1.63 ± 3.48
09	5.13 ± 3.09	-3.52 ± 2.40	1.27 ± 1.82	-2.00 ± 2.96
10	5.87 ± 3.53	-4.43 ± 3.15	0.27 ± 2.13	-1.49 ± 3.25
11	5.52 ± 3.06	-4.39 ± 2.94	0.18 ± 1.81	-0.27 ± 2.93
12	5.09 ± 2.83	-3.82 ± 3.15	-0.16 ± 1.64	-0.26 ± 2.58
13	4.87 ± 2.87	-3.73 ± 3.16	-0.24 ± 1.37	-0.32 ± 2.45
14	4.84 ± 2.83	-3.64 ± 3.22	-0.43 ± 1.28	-0.21 ± 2.45
15	4.94 ± 2.95	-3.78 ± 3.30	-0.20 ± 1.27	-0.40 ± 2.49
16	5.10 ± 2.90	-3.73 ± 3.35	-0.35 ± 1.42	-0.21 ± 2.68
17	4.32 ± 2.42	-3.06 ± 2.76	-0.36 ± 1.44	0.09 ± 2.32
18	2.57 ± 0.99	-1.23 ± 1.34	-0.63 ± 1.30	0.44 ± 1.43
19	0.47 ± 0.24	-0.01 ± 0.26	-0.07 ± 0.22	0.26 ± 0.30

Table 1.21: Patient 4, RPV: Mean and standard deviation of target motion in all phases of the heartbeat, relative to the reference phase.

motion phase	ABS [mm]	SI [mm]	AP [mm]	LR [mm]
01	1.31 ± 0.92	-0.85 ± 1.17	0.03 ± 0.62	0.21 ± 0.19
02	2.07 ± 1.03	-0.90 ± 1.66	0.65 ± 1.04	0.43 ± 0.34
03	3.56 ± 2.05	-1.50 ± 2.11	1.99 ± 2.11	1.24 ± 0.48
04	4.59 ± 2.44	-1.82 ± 2.81	2.28 ± 2.68	1.71 ± 0.70
05	4.76 ± 2.66	-1.30 ± 2.81	2.62 ± 3.11	1.72 ± 0.84
06	5.30 ± 3.05	-1.59 ± 3.20	2.90 ± 3.48	1.68 ± 1.13
07	5.82 ± 3.35	-1.63 ± 3.51	3.30 ± 3.75	1.70 ± 1.50
08	6.18 ± 3.19	-1.78 ± 3.93	3.02 ± 3.74	2.10 ± 1.51
09	5.82 ± 3.35	-1.63 ± 3.51	3.30 ± 3.75	1.70 ± 1.50
10	6.49 ± 3.00	-1.78 ± 4.11	2.68 ± 3.85	2.70 ± 1.38
11	6.43 ± 2.55	-2.25 ± 3.95	2.20 ± 3.41	3.14 ± 0.98
12	5.94 ± 2.18	-2.32 ± 3.65	1.52 ± 3.11	2.94 ± 0.87
13	5.54 ± 2.05	-2.35 ± 3.58	1.12 ± 2.76	2.67 ± 0.75
14	5.23 ± 2.13	-2.34 ± 3.58	0.73 ± 2.57	2.41 ± 0.81
15	5.25 ± 2.25	-2.42 ± 3.69	0.63 ± 2.73	2.22 ± 0.61
16	5.62 ± 2.23	-2.35 ± 3.81	0.93 ± 2.86	2.61 ± 0.84
17	4.61 ± 1.70	-1.80 ± 3.02	1.03 ± 2.56	1.88 ± 0.82
18	2.66 ± 0.54	-1.03 ± 1.15	0.72 ± 1.19	1.64 ± 0.60
19	0.62 ± 0.33	-0.20 ± 0.47	0.06 ± 0.33	0.17 ± 0.30

Table 1.22: Patient 5, LPV: Mean and standard deviation of target motion in all phases of the heartbeat, relative to the reference phase.

motion phase	ABS [mm]	SI [mm]	AP [mm]	LR [mm]
01	0.38 ± 0.23	0.12 ± 0.29	0.03 ± 0.25	0.09 ± 0.17
02	1.13 ± 0.51	0.32 ± 0.80	0.07 ± 0.68	0.20 ± 0.52
03	1.63 ± 0.64	-0.03 ± 1.23	0.35 ± 0.79	-0.53 ± 0.73
04	1.86 ± 0.72	0.03 ± 1.22	0.49 ± 0.85	-0.59 ± 1.10
05	1.77 ± 0.69	0.04 ± 1.20	0.43 ± 0.87	-0.51 ± 0.98
06	2.12 ± 1.25	0.30 ± 1.18	0.73 ± 1.28	-1.03 ± 1.17
07	2.46 ± 1.33	0.05 ± 1.34	0.85 ± 1.68	-1.27 ± 0.92
08	2.76 ± 1.27	-0.11 ± 1.19	0.98 ± 1.86	-1.63 ± 0.88
09	2.46 ± 1.33	0.05 ± 1.34	0.85 ± 1.68	-1.27 ± 0.92
10	2.58 ± 1.56	-1.13 ± 1.57	1.32 ± 1.60	-0.43 ± 0.94
11	2.56 ± 1.37	-1.31 ± 1.85	0.98 ± 0.99	-0.31 ± 1.12
12	2.68 ± 1.58	-1.58 ± 2.07	0.84 ± 0.91	-0.06 ± 1.17
13	2.73 ± 1.68	-1.62 ± 2.11	0.77 ± 0.92	0.46 ± 1.24
14	2.48 ± 1.46	-1.63 ± 1.78	0.70 ± 0.93	0.36 ± 0.97
15	2.70 ± 1.55	-1.90 ± 1.83	0.90 ± 0.95	0.38 ± 0.91
16	2.92 ± 1.54	-2.16 ± 1.72	0.91 ± 0.94	0.44 ± 1.17
17	2.70 ± 1.63	-2.10 ± 1.61	0.97 ± 0.90	0.56 ± 0.94
18	2.13 ± 0.90	-1.15 ± 1.03	0.52 ± 0.94	1.13 ± 0.72
19	0.84 ± 0.47	-0.38 ± 0.37	0.08 ± 0.32	0.53 ± 0.52

Table 1.23: Patient 5, RPV: Mean and standard deviation of target motion in all phases of the heartbeat, relative to the reference phase.

motion phase	ABS [mm]	SI [mm]	AP [mm]	LR [mm]
01	0.61 ± 0.33	0.22 ± 0.50	0.04 ± 0.22	0.17 ± 0.32
02	1.56 ± 0.82	0.61 ± 1.15	0.10 ± 0.57	0.63 ± 0.82
03	2.21 ± 1.10	0.77 ± 1.61	0.22 ± 0.67	0.95 ± 1.24
04	2.42 ± 1.48	1.12 ± 1.37	0.60 ± 0.89	1.49 ± 1.23
05	2.69 ± 2.22	1.27 ± 1.62	1.23 ± 1.26	1.29 ± 1.78
06	2.89 ± 2.15	1.32 ± 1.23	1.75 ± 1.81	0.85 ± 1.65
07	3.08 ± 2.12	1.29 ± 1.54	1.87 ± 1.69	0.89 ± 1.69
08	3.14 ± 2.11	1.17 ± 1.59	1.96 ± 1.85	0.50 ± 1.69
09	3.08 ± 2.12	1.29 ± 1.54	1.87 ± 1.69	0.89 ± 1.69
10	3.05 ± 1.96	0.79 ± 1.99	1.75 ± 1.60	0.94 ± 1.44
11	2.98 ± 1.74	0.12 ± 1.99	1.24 ± 1.29	1.34 ± 1.73
12	3.24 ± 1.63	-0.15 ± 2.09	1.19 ± 1.36	1.96 ± 1.28
13	3.61 ± 1.58	-0.28 ± 2.26	1.09 ± 1.30	2.48 ± 1.15
14	3.73 ± 1.97	-0.78 ± 2.57	1.01 ± 1.16	2.49 ± 1.41
15	3.95 ± 2.27	-1.16 ± 2.83	0.92 ± 1.15	2.54 ± 1.68
16	3.65 ± 1.84	-1.11 ± 2.18	0.94 ± 1.14	2.46 ± 1.59
17	3.54 ± 1.95	-1.11 ± 2.06	1.02 ± 1.18	2.39 ± 1.65
18	2.53 ± 0.93	-0.77 ± 1.02	0.53 ± 0.85	2.00 ± 0.81
19	0.74 ± 0.45	-0.35 ± 0.32	0.17 ± 0.33	0.31 ± 0.54

Values of dose analysis parameters for all patients

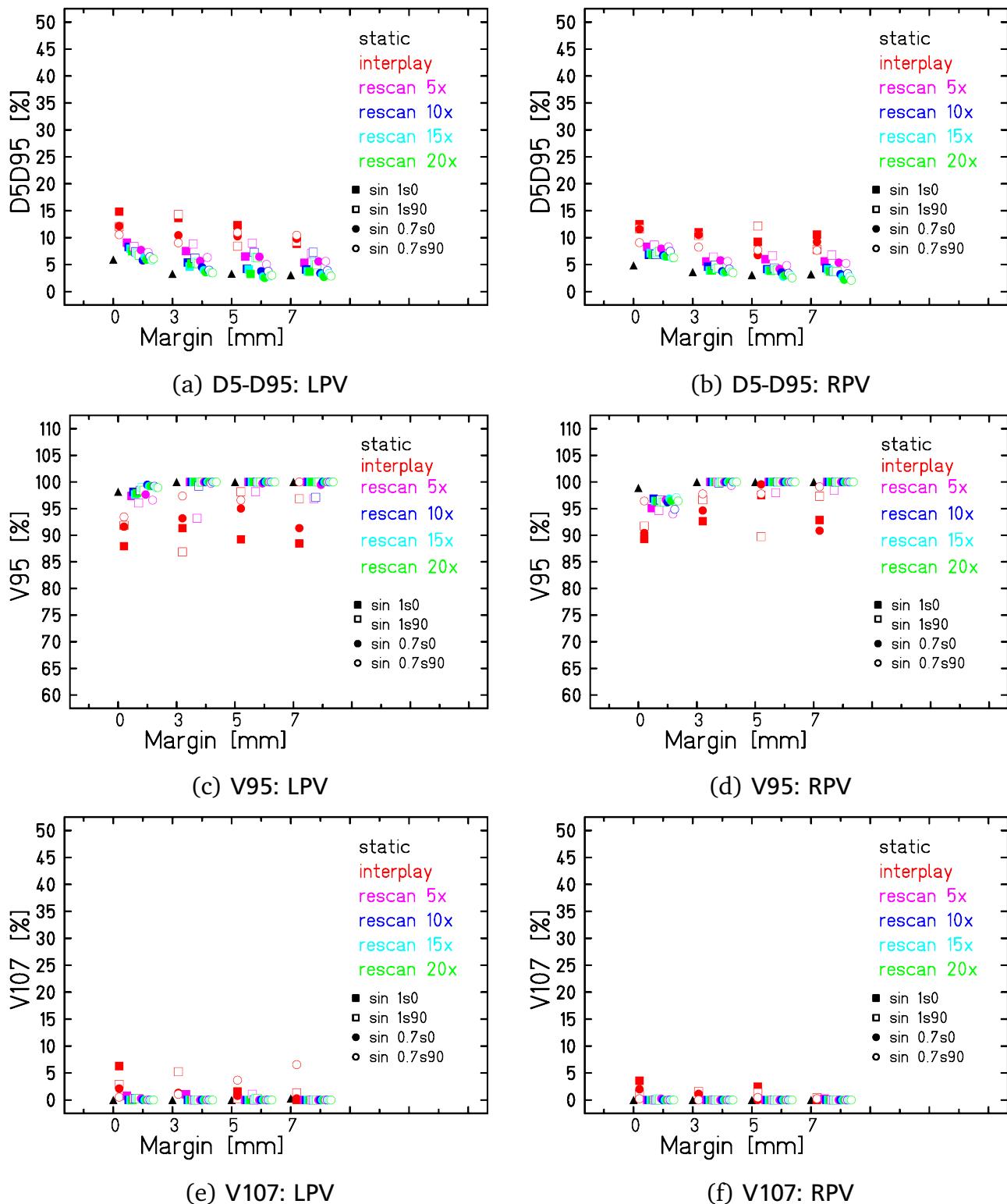


Figure 1.20: Patient 1: Dose analysis parameters D5-D95 (first row), V95 (middle row) and V107 (last row). The LPV (left column) and RPV (right column) were studied separately. Static (black) as well as interplay (red) and rescanning (5,10,15,20 rescans) are compared for four different motions and different safety margins. For better visualization, the data for interplay and rescanning was shifted.

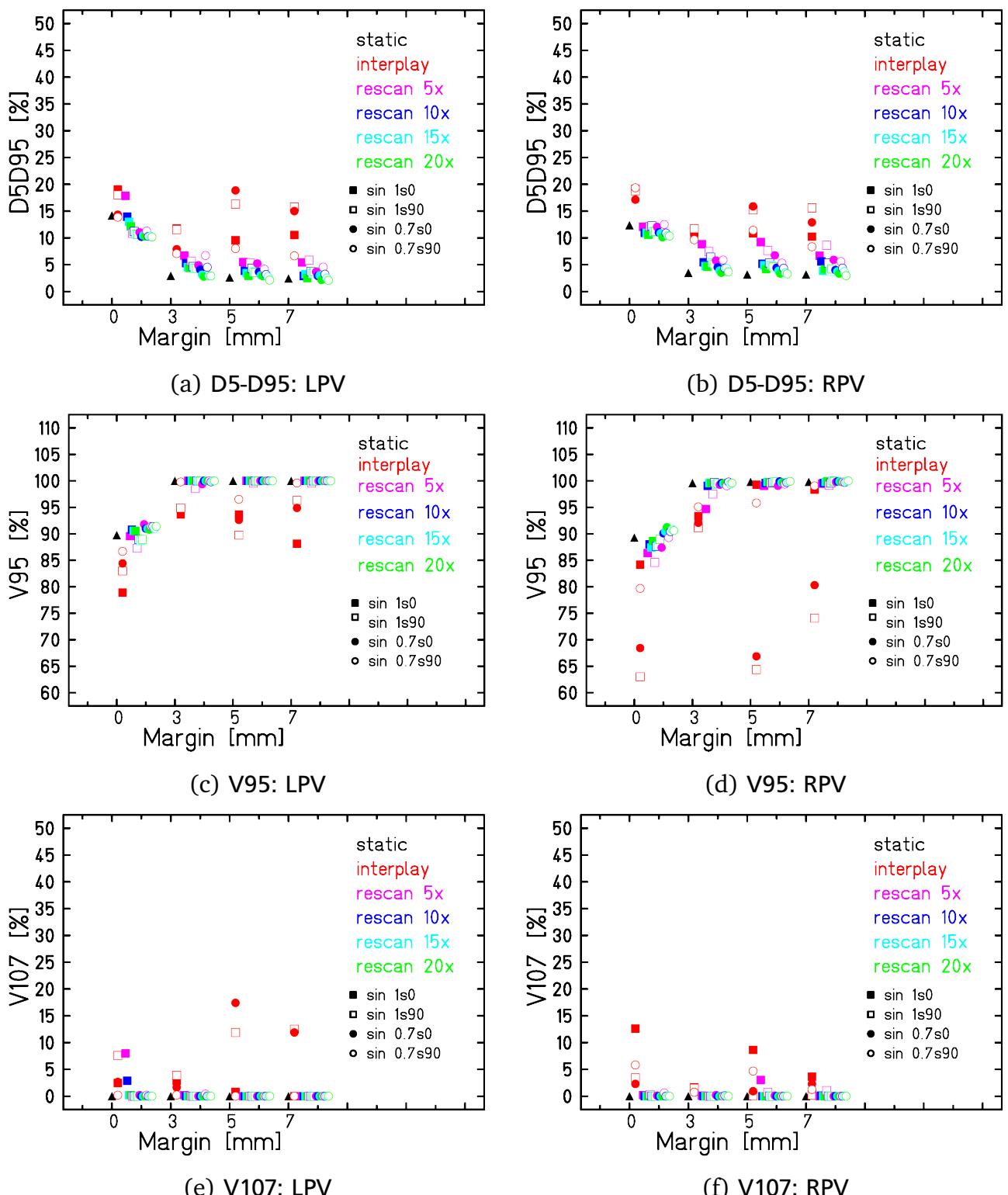


Figure 1.21: Patient 2: Dose analysis parameters D₅-D₉₅ (first row), V₉₅ (middle row) and V₁₀₇ (last row). The LPV (left column) and RPV (right column) were studied separately. Static (black) as well as interplay (red) and rescanning (5,10,15,20 rescans) are compared for four different motions and different safety margins. For better visualization, the data for interplay and rescanning was shifted.

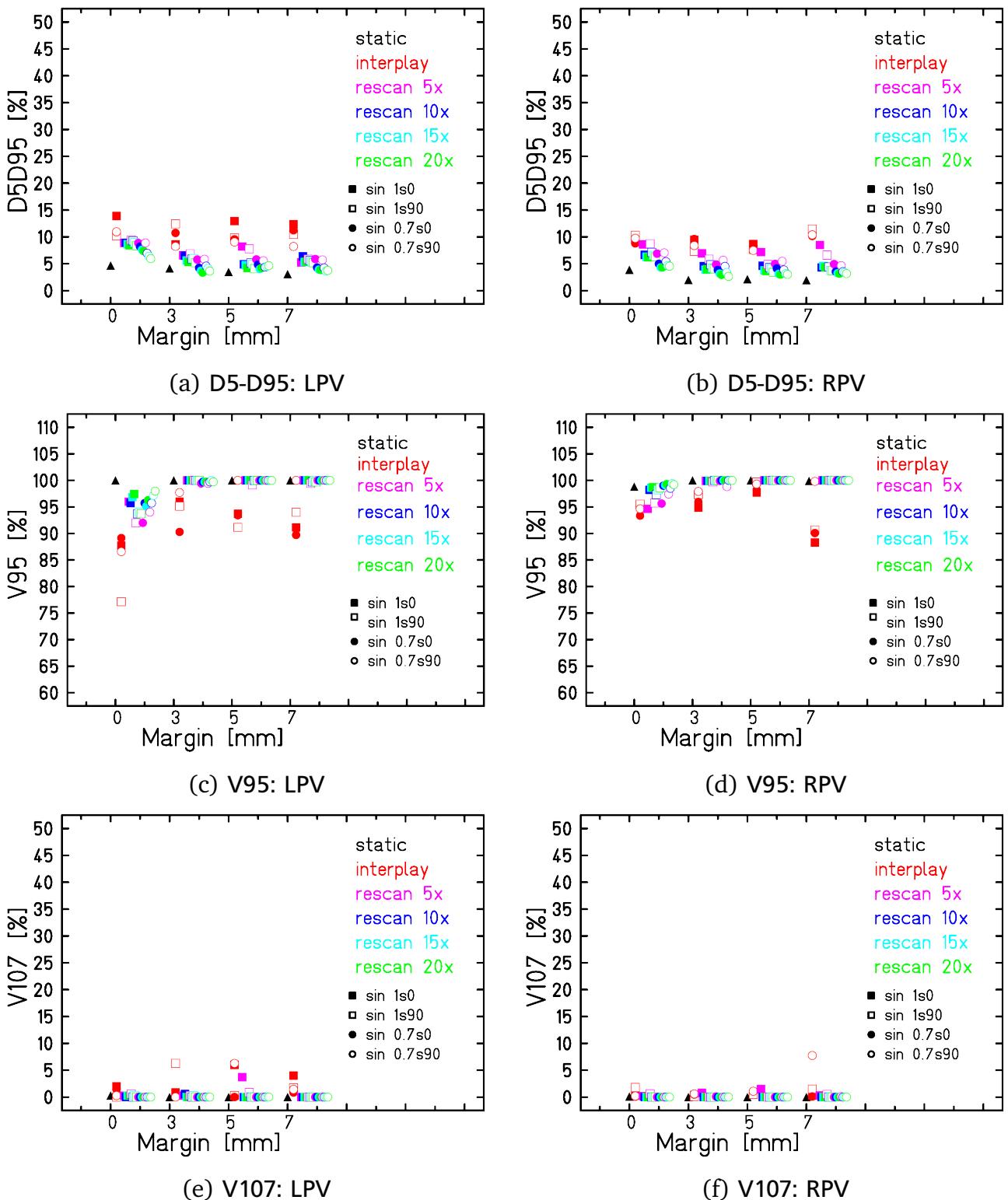


Figure 1.22: Patient 3:Dose analysis parameters D5-D95 (first row), V95 (middle row) and V107 (last row). The LPV (left column) and RPV (right column) were studied separately. Static (black) as well as interplay (red) and rescanning (5,10,15,20 rescans) are compared for four different motions and different safety margins. For better visualization, the data for interplay and rescanning was shifted.

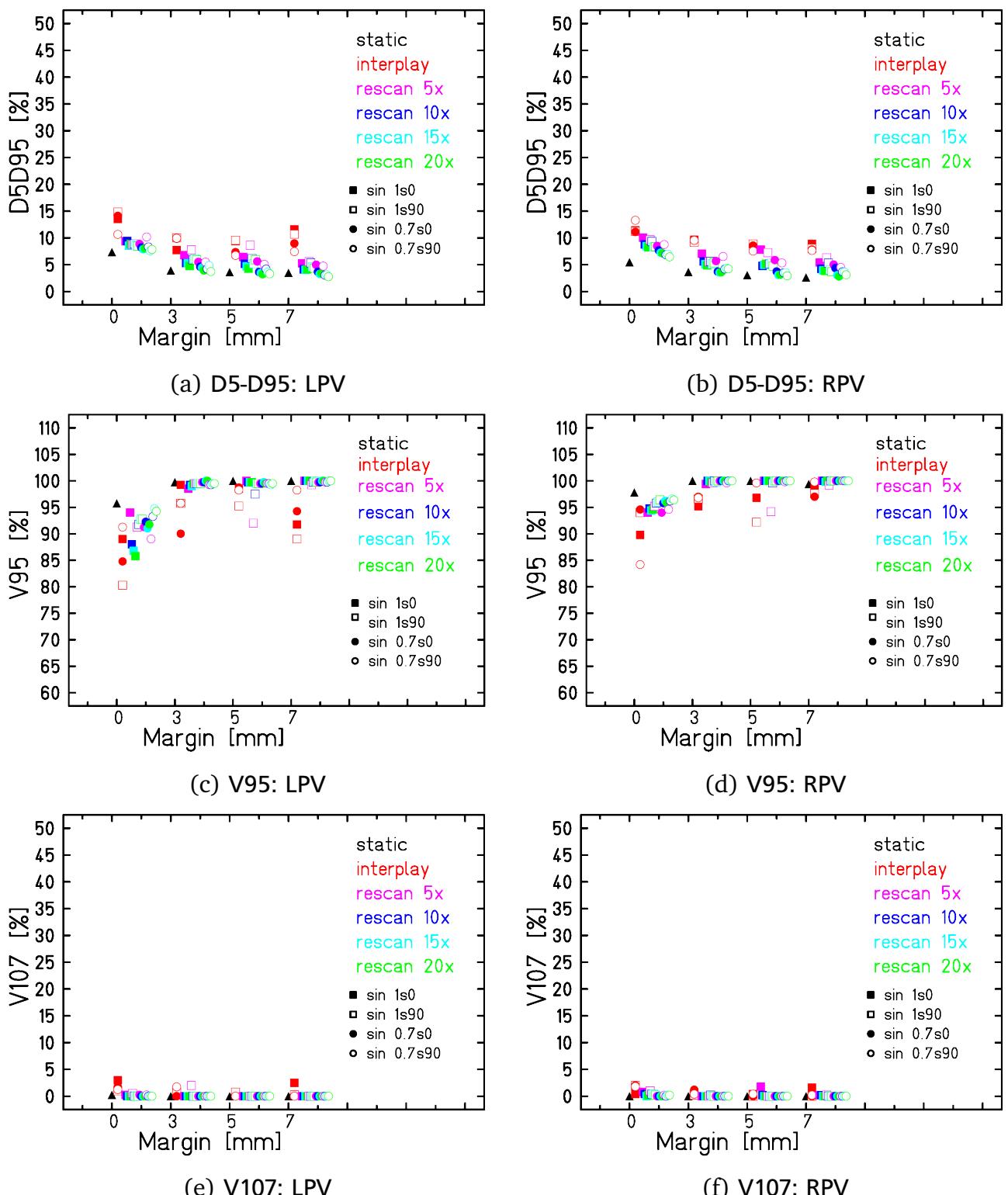


Figure 1.23: Patient 4: Dose analysis parameters D5-D95 (first row), V95 (middle row) and V107 (last row). The LPV (left column) and RPV (right column) were studied separately. Static (black) as well as interplay (red) and rescanning (5,10,15,20 rescans) are compared for four different motions and different safety margins. For better visualization, the data for interplay and rescanning was shifted.

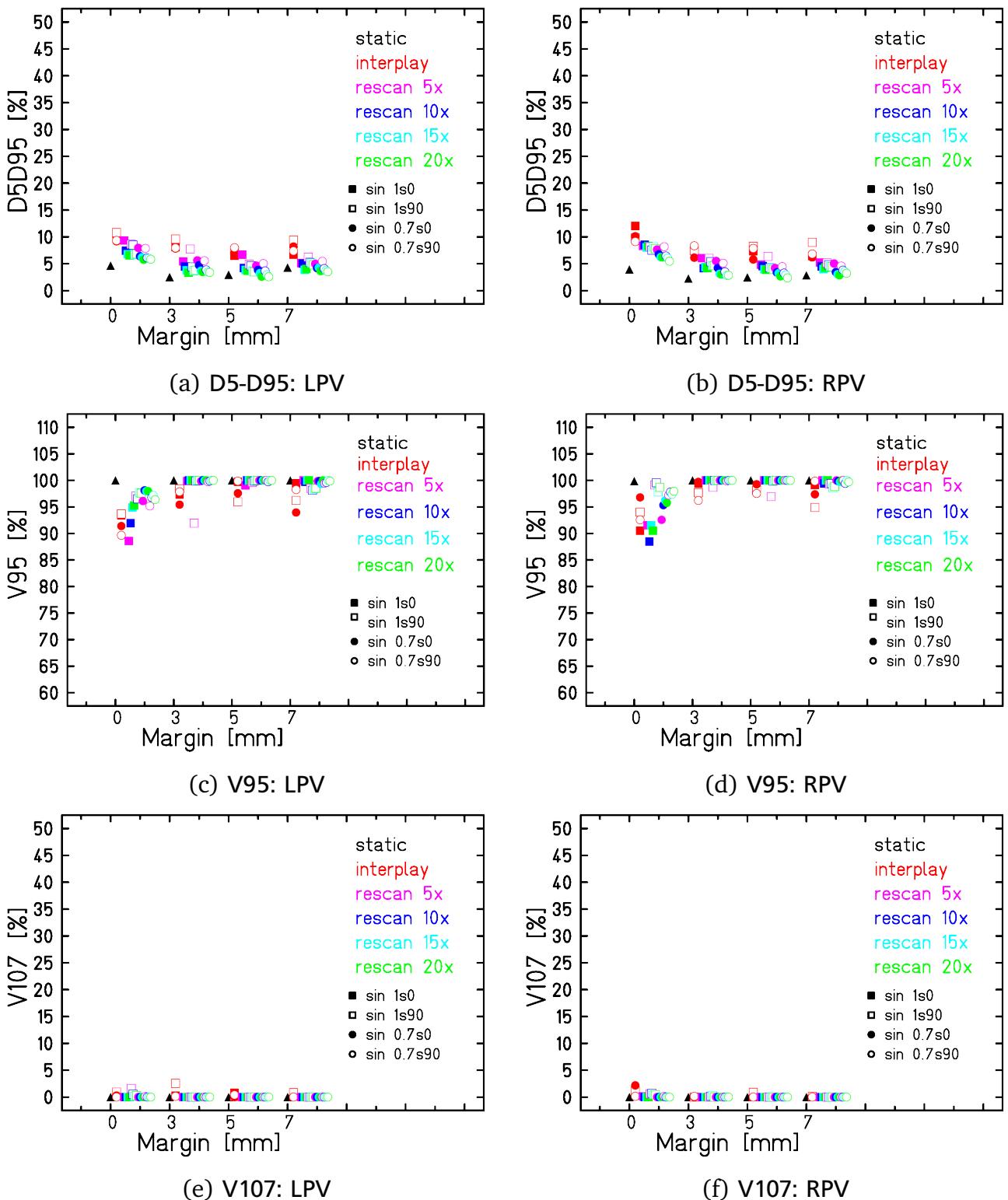


Figure 1.24: Patient 5: Dose analysis parameters D5-D95 (first row), V95 (middle row) and V107 (last row). The LPV (left column) and RPV (right column) were studied separately. Static (black) as well as interplay (red) and rescanning (5,10,15,20 rescans) are compared for four different motions and different safety margins. For better visualization, the data for interplay and rescanning was shifted.

Table 1.24: Patient 1, LPV

Case	motion period	motion starting phase	Margin	rescan no.	D5-D95 [%]	V95 [%]	V107 [%]	
STATIC	-	-	0mm	-	5.94	98.16	0.00	
STATIC	-	-	3mm	-	3.31	100.00	0.00	
STATIC	-	-	5mm	-	3.32	100.00	0.00	
STATIC	-	-	7mm	-	3.06	100.00	0.26	
INTERPLAY	1s	0	0mm	-	14.84	87.93	6.30	
INTERPLAY	1s	90	0mm	-	12.05	91.86	2.89	
INTERPLAY	0.7s	0	0mm	-	12.16	91.60	2.10	
INTERPLAY	0.7s	90	0mm	-	10.54	93.44	0.52	
INTERPLAY	1s	0	3mm	-	13.68	91.34	5.25	
INTERPLAY	1s	90	3mm	-	14.30	86.88	5.25	
INTERPLAY	0.7s	0	3mm	-	10.45	93.18	1.31	
INTERPLAY	0.7s	90	3mm	-	9.04	97.38	1.05	
INTERPLAY	1s	0	5mm	-	7.59	98.43	0.00	
INTERPLAY	1s	90	5mm	-	7.45	99.48	0.79	
INTERPLAY	0.7s	0	5mm	-	10.24	95.01	1.31	
INTERPLAY	0.7s	90	5mm	-	9.22	96.85	0.52	
INTERPLAY	1s	0	7mm	-	7.46	98.16	0.00	
INTERPLAY	1s	90	7mm	-	7.48	98.95	0.79	
INTERPLAY	0.7s	0	7mm	-	9.67	95.54	1.05	
INTERPLAY	0.7s	90	7mm	-	9.29	97.38	0.79	
RESCANNING	1s	0	0mm	5	9.07	97.38	0.79	
RESCANNING	1s	0	0mm	10	8.28	98.16	0.00	
RESCANNING	1s	0	0mm	15	7.95	97.64	0.00	
RESCANNING	1s	0	0mm	20	7.49	97.90	0.00	
RESCANNING	1s	90	0mm	5	8.34	96.06	0.26	
RESCANNING	1s	90	0mm	10	7.37	98.43	0.26	
RESCANNING	1s	90	0mm	15	7.12	98.95	0.26	
RESCANNING	1s	90	0mm	20	6.75	98.43	0.26	
RESCANNING	0.7s	0	0mm	5	7.71	97.64	0.26	
RESCANNING	0.7s	0	0mm	10	5.79	99.48	0.00	
RESCANNING	0.7s	0	0mm	15	6.43	99.21	0.00	
RESCANNING	0.7s	0	0mm	20	5.90	99.21	0.00	
RESCANNING	0.7s	90	0mm	5	7.29	96.59	0.00	
RESCANNING	0.7s	90	0mm	10	6.46	99.21	0.00	
RESCANNING	0.7s	90	0mm	15	5.82	98.95	0.00	
RESCANNING	0.7s	90	0mm	20	6.08	98.95	0.00	
RESCANNING	1s	0	3mm	5	7.52	100.00	1.05	
RESCANNING	1s	0	3mm	10	5.41	100.00	0.00	
RESCANNING	1s	0	3mm	15	4.63	100.00	0.00	
RESCANNING	1s	0	3mm	20	5.22	100.00	0.00	
RESCANNING	1s	90	3mm	5	8.83	93.18	0.00	
RESCANNING	1s	90	3mm	10	6.19	99.21	0.00	
RESCANNING	1s	90	3mm	15	5.40	100.00	0.00	
RESCANNING	1s	90	3mm	20	5.17	100.00	0.00	
RESCANNING	0.7s	0	3mm	5	5.68	100.00	0.00	
RESCANNING	0.7s	0	3mm	10	4.49	100.00	0.00	
RESCANNING	0.7s	0	3mm	15	3.95	100.00	0.00	
RESCANNING	0.7s	0	3mm	20	3.59	100.00	0.00	
RESCANNING	0.7s	90	3mm	5	6.34	99.74	0.00	
RESCANNING	0.7s	90	3mm	10	3.98	100.00	0.00	
RESCANNING	0.7s	90	3mm	15	3.53	100.00	0.00	
RESCANNING	0.7s	90	3mm	20	3.47	100.00	0.00	
RESCANNING	1s	0	5mm	5	6.49	100.00	0.00	
RESCANNING	1s	0	5mm	10	4.21	100.00	0.00	
RESCANNING	1s	0	5mm	15	4.11	100.00	0.00	
RESCANNING	1s	0	5mm	20	3.26	100.00	0.00	
RESCANNING	1s	90	5mm	5	9.00	98.16	1.05	
RESCANNING	1s	90	5mm	10	7.27	100.00	0.00	
RESCANNING	1s	90	5mm	15	6.34	100.00	0.26	
RESCANNING	1s	90	5mm	20	6.26	100.00	0.26	
RESCANNING	0.7s	0	5mm	5	6.45	99.74	0.00	
RESCANNING	0.7s	0	5mm	10	3.77	100.00	0.00	
RESCANNING	0.7s	0	5mm	15	2.77	100.00	0.00	
RESCANNING	0.7s	0	5mm	20	2.54	100.00	0.00	
RESCANNING	0.7s	90	5mm	5	5.04	100.00	0.00	
RESCANNING	0.7s	90	5mm	10	3.75	100.00	0.00	
RESCANNING	0.7s	90	5mm	15	2.88	100.00	0.00	
RESCANNING	0.7s	90	5mm	20	3.00	100.00	0.00	
RESCANNING	1s	0	7mm	5	5.35	100.00	0.00	
RESCANNING	1s	0	7mm	10	4.10	100.00	0.00	
RESCANNING	1s	0	7mm	15	3.74	100.00	0.00	
RESCANNING	1s	0	7mm	20	3.69	100.00	0.00	
RESCANNING	1s	90	7mm	5	7.05	96.85	0.00	
RESCANNING	1s	90	7mm	10	7.30	97.11	0.00	
RESCANNING	1s	90	7mm	15	5.47	100.00	0.00	
RESCANNING	1s	90	7mm	20	4.97	100.00	0.00	
RESCANNING	0.7s	0	7mm	5	5.60	99.48	0.00	
RESCANNING	0.7s	0	7mm	10	3.41	100.00	0.00	
RESCANNING	0.7s	0	7mm	15	3.18	100.00	0.00	
RESCANNING	0.7s	0	7mm	20	2.72	100.00	0.00	
50	RESCANNING	0.7s	90	7mm	5	5.61	100.00	0.00
	RESCANNING	0.7s	90	7mm	10	3.90	100.00	0.00
	RESCANNING	0.7s	90	7mm	15	3.35	100.00	0.00
	RESCANNING	0.7s	90	7mm	20	2.87	100.00	0.00

Table 1.25: Patient 1, RPV

Case	motion period	motion starting phase	Margin	rescan no.	D5-D95 [%]	V95 [%]	V107 [%]
STATIC	-	-	0mm	-	4.86	98.88	0.00
STATIC	-	-	3mm	-	3.63	100.00	0.00
STATIC	-	-	5mm	-	3.08	100.00	0.00
STATIC	-	-	7mm	-	3.23	100.00	0.00
INTERPLAY	1s	0	0mm	-	12.50	89.29	3.57
INTERPLAY	1s	90	0mm	-	11.64	91.74	1.12
INTERPLAY	0.7s	0	0mm	-	11.57	90.40	2.01
INTERPLAY	0.7s	90	0mm	-	9.08	96.43	0.22
INTERPLAY	1s	0	3mm	-	11.01	92.63	1.56
INTERPLAY	1s	90	3mm	-	10.40	96.65	1.56
INTERPLAY	0.7s	0	3mm	-	10.55	94.64	1.12
INTERPLAY	0.7s	90	3mm	-	8.24	97.77	0.00
INTERPLAY	1s	0	5mm	-	9.34	95.98	0.00
INTERPLAY	1s	90	5mm	-	7.92	98.66	0.22
INTERPLAY	0.7s	0	5mm	-	6.41	98.88	0.00
INTERPLAY	0.7s	90	5mm	-	6.07	100.00	0.00
INTERPLAY	1s	0	7mm	-	9.21	95.76	0.00
INTERPLAY	1s	90	7mm	-	7.78	98.21	0.00
INTERPLAY	0.7s	0	7mm	-	6.20	98.44	0.00
INTERPLAY	0.7s	90	7mm	-	6.10	99.78	0.00
RESCANNING	1s	0	0mm	5	8.32	95.09	0.00
RESCANNING	1s	0	0mm	10	6.81	96.88	0.00
RESCANNING	1s	0	0mm	15	7.15	96.43	0.00
RESCANNING	1s	0	0mm	20	6.85	96.43	0.00
RESCANNING	1s	90	0mm	5	8.61	94.64	0.00
RESCANNING	1s	90	0mm	10	6.91	96.65	0.00
RESCANNING	1s	90	0mm	15	7.26	96.21	0.22
RESCANNING	1s	90	0mm	20	7.45	96.21	0.00
RESCANNING	0.7s	0	0mm	5	7.96	96.65	0.22
RESCANNING	0.7s	0	0mm	10	6.70	96.21	0.00
RESCANNING	0.7s	0	0mm	15	6.52	96.88	0.00
RESCANNING	0.7s	0	0mm	20	6.52	96.43	0.00
RESCANNING	0.7s	90	0mm	5	8.30	93.97	0.00
RESCANNING	0.7s	90	0mm	10	7.46	94.87	0.00
RESCANNING	0.7s	90	0mm	15	6.28	97.10	0.00
RESCANNING	0.7s	90	0mm	20	6.28	96.43	0.00
RESCANNING	1s	0	3mm	5	5.59	100.00	0.00
RESCANNING	1s	0	3mm	10	4.61	100.00	0.00
RESCANNING	1s	0	3mm	15	3.90	100.00	0.00
RESCANNING	1s	0	3mm	20	3.94	100.00	0.00
RESCANNING	1s	90	3mm	5	6.41	100.00	0.00
RESCANNING	1s	90	3mm	10	4.90	99.78	0.00
RESCANNING	1s	90	3mm	15	4.24	100.00	0.00
RESCANNING	1s	90	3mm	20	4.36	100.00	0.00
RESCANNING	0.7s	0	3mm	5	5.79	100.00	0.00
RESCANNING	0.7s	0	3mm	10	3.75	100.00	0.00
RESCANNING	0.7s	0	3mm	15	3.54	100.00	0.00
RESCANNING	0.7s	0	3mm	20	3.67	100.00	0.00
RESCANNING	0.7s	90	3mm	5	5.59	99.33	0.00
RESCANNING	0.7s	90	3mm	10	4.18	100.00	0.00
RESCANNING	0.7s	90	3mm	15	3.67	100.00	0.00
RESCANNING	0.7s	90	3mm	20	3.48	100.00	0.00
RESCANNING	1s	0	5mm	5	6.01	100.00	0.00
RESCANNING	1s	0	5mm	10	4.16	100.00	0.00
RESCANNING	1s	0	5mm	15	3.96	100.00	0.00
RESCANNING	1s	0	5mm	20	3.86	100.00	0.00
RESCANNING	1s	90	5mm	5	6.67	97.99	0.00
RESCANNING	1s	90	5mm	10	4.37	100.00	0.00
RESCANNING	1s	90	5mm	15	4.00	100.00	0.00
RESCANNING	1s	90	5mm	20	4.01	100.00	0.00
RESCANNING	0.7s	0	5mm	5	4.21	100.00	0.00
RESCANNING	0.7s	0	5mm	10	3.52	100.00	0.00
RESCANNING	0.7s	0	5mm	15	2.79	100.00	0.00
RESCANNING	0.7s	0	5mm	20	3.02	100.00	0.00
RESCANNING	0.7s	90	5mm	5	4.83	100.00	0.00
RESCANNING	0.7s	90	5mm	10	3.38	100.00	0.00
RESCANNING	0.7s	90	5mm	15	3.00	100.00	0.00
RESCANNING	0.7s	90	5mm	20	2.54	100.00	0.00
RESCANNING	1s	0	7mm	5	5.61	100.00	0.22
RESCANNING	1s	0	7mm	10	4.34	100.00	0.00
RESCANNING	1s	0	7mm	15	4.10	100.00	0.00
RESCANNING	1s	0	7mm	20	3.71	100.00	0.00
RESCANNING	1s	90	7mm	5	6.77	98.44	0.00
RESCANNING	1s	90	7mm	10	3.75	100.00	0.00
RESCANNING	1s	90	7mm	15	3.80	100.00	0.00
RESCANNING	1s	90	7mm	20	3.74	100.00	0.00
RESCANNING	0.7s	0	7mm	5	5.37	100.00	0.00
RESCANNING	0.7s	0	7mm	10	3.22	100.00	0.00
RESCANNING	0.7s	0	7mm	15	2.75	100.00	0.00
RESCANNING	0.7s	0	7mm	20	2.20	100.00	0.00
RESCANNING	0.7s	90	7mm	5	5.23	100.00	0.00
RESCANNING	0.7s	90	7mm	10	3.33	100.00	0.00
RESCANNING	0.7s	90	7mm	15	2.74	100.00	0.00
RESCANNING	0.7s	90	7mm	20	2.09	100.00	0.00

Table 1.26: Patient 2, LPV

Case	motion period	motion starting phase	Margin	rescan no.	D5-D95 [%]	V95 [%]	V107 [%]	
STATIC	-	-	0mm	-	14.19	89.75	0.00	
STATIC	-	-	3mm	-	2.93	100.00	0.00	
STATIC	-	-	5mm	-	2.64	100.00	0.00	
STATIC	-	-	7mm	-	2.42	100.00	0.00	
INTERPLAY	1s	0	0mm	-	8.27	96.93	0.41	
INTERPLAY	1s	90	0mm	-	9.61	95.29	2.66	
INTERPLAY	0.7s	0	0mm	-	9.22	94.88	0.82	
INTERPLAY	0.7s	90	0mm	-	6.65	99.39	0.20	
INTERPLAY	1s	0	3mm	-	11.75	93.65	2.87	
INTERPLAY	1s	90	3mm	-	11.56	94.88	3.89	
INTERPLAY	0.7s	0	3mm	-	7.90	99.80	1.64	
INTERPLAY	0.7s	90	3mm	-	7.07	99.80	0.20	
INTERPLAY	1s	0	5mm	-	8.06	97.75	0.20	
INTERPLAY	1s	90	5mm	-	9.78	95.49	2.66	
INTERPLAY	0.7s	0	5mm	-	8.89	95.29	0.82	
INTERPLAY	0.7s	90	5mm	-	6.54	98.98	0.00	
INTERPLAY	1s	0	7mm	-	6.78	98.16	0.00	
INTERPLAY	1s	90	7mm	-	7.06	99.59	0.20	
INTERPLAY	0.7s	0	7mm	-	8.90	95.08	1.02	
INTERPLAY	0.7s	90	7mm	-	6.41	99.18	0.20	
RESCANNING	1s	0	0mm	5	17.86	89.55	7.99	
RESCANNING	1s	0	0mm	10	13.98	90.78	2.87	
RESCANNING	1s	0	0mm	15	13.00	90.57	0.20	
RESCANNING	1s	0	0mm	20	12.15	90.57	0.20	
RESCANNING	1s	90	0mm	5	10.86	87.30	0.00	
RESCANNING	1s	90	0mm	10	11.21	88.93	0.00	
RESCANNING	1s	90	0mm	15	10.70	88.73	0.00	
RESCANNING	1s	90	0mm	20	10.65	88.93	0.00	
RESCANNING	0.7s	0	0mm	5	11.05	91.80	0.20	
RESCANNING	0.7s	0	0mm	10	10.21	90.98	0.00	
RESCANNING	0.7s	0	0mm	15	10.46	90.98	0.00	
RESCANNING	0.7s	0	0mm	20	10.29	90.78	0.00	
RESCANNING	0.7s	90	0mm	5	11.30	91.39	0.20	
RESCANNING	0.7s	90	0mm	10	10.28	91.39	0.00	
RESCANNING	0.7s	90	0mm	15	10.33	90.98	0.00	
RESCANNING	0.7s	90	0mm	20	10.18	91.39	0.00	
RESCANNING	1s	0	3mm	5	6.72	100.00	0.20	
RESCANNING	1s	0	3mm	10	5.28	100.00	0.00	
RESCANNING	1s	0	3mm	15	4.54	100.00	0.00	
RESCANNING	1s	0	3mm	20	4.41	100.00	0.00	
RESCANNING	1s	90	3mm	5	5.67	98.57	0.00	
RESCANNING	1s	90	3mm	10	4.67	100.00	0.00	
RESCANNING	1s	90	3mm	15	4.33	100.00	0.00	
RESCANNING	1s	90	3mm	20	4.34	100.00	0.00	
RESCANNING	0.7s	0	3mm	5	4.89	99.39	0.00	
RESCANNING	0.7s	0	3mm	10	4.09	100.00	0.00	
RESCANNING	0.7s	0	3mm	15	3.13	100.00	0.00	
RESCANNING	0.7s	0	3mm	20	2.79	100.00	0.00	
RESCANNING	0.7s	90	3mm	5	6.72	100.00	0.41	
RESCANNING	0.7s	90	3mm	10	4.54	99.80	0.00	
RESCANNING	0.7s	90	3mm	15	2.94	100.00	0.00	
RESCANNING	0.7s	90	3mm	20	2.91	100.00	0.00	
RESCANNING	1s	0	5mm	5	5.50	100.00	0.00	
RESCANNING	1s	0	5mm	10	3.87	100.00	0.00	
RESCANNING	1s	0	5mm	15	3.43	100.00	0.00	
RESCANNING	1s	0	5mm	20	2.92	100.00	0.00	
RESCANNING	1s	90	5mm	5	5.31	99.59	0.00	
RESCANNING	1s	90	5mm	10	4.35	100.00	0.00	
RESCANNING	1s	90	5mm	15	3.63	100.00	0.00	
RESCANNING	1s	90	5mm	20	3.53	100.00	0.00	
RESCANNING	0.7s	0	5mm	5	5.23	100.00	0.00	
RESCANNING	0.7s	0	5mm	10	3.65	100.00	0.00	
RESCANNING	0.7s	0	5mm	15	3.03	100.00	0.00	
RESCANNING	0.7s	0	5mm	20	2.88	100.00	0.00	
RESCANNING	0.7s	90	5mm	5	4.18	100.00	0.00	
RESCANNING	0.7s	90	5mm	10	3.17	100.00	0.00	
RESCANNING	0.7s	90	5mm	15	2.73	100.00	0.00	
RESCANNING	0.7s	90	5mm	20	2.12	100.00	0.00	
RESCANNING	1s	0	7mm	5	5.42	100.00	0.00	
RESCANNING	1s	0	7mm	10	2.90	100.00	0.00	
RESCANNING	1s	0	7mm	15	3.26	100.00	0.00	
RESCANNING	1s	0	7mm	20	2.51	100.00	0.00	
RESCANNING	1s	90	7mm	5	5.85	99.59	0.00	
RESCANNING	1s	90	7mm	10	3.76	100.00	0.00	
RESCANNING	1s	90	7mm	15	3.32	100.00	0.00	
RESCANNING	1s	90	7mm	20	3.73	100.00	0.00	
RESCANNING	0.7s	0	7mm	5	3.68	100.00	0.00	
RESCANNING	0.7s	0	7mm	10	2.89	100.00	0.00	
RESCANNING	0.7s	0	7mm	15	3.01	100.00	0.00	
RESCANNING	0.7s	0	7mm	20	2.16	100.00	0.00	
52	RESCANNING	0.7s	90	7mm	5	4.56	100.00	0.00
	RESCANNING	0.7s	90	7mm	10	3.22	100.00	0.00
	RESCANNING	0.7s	90	7mm	15	2.51	100.00	0.00
	RESCANNING	0.7s	90	7mm	20	2.07	100.00	0.00

Table 1.27: Patient 2, RPV

Case	motion period	motion starting phase	Margin	rescan no.	D5-D95 [%]	V95 [%]	V107 [%]
STATIC	-	-	0mm	-	12.37	89.27	0.00
STATIC	-	-	3mm	-	3.47	99.58	0.00
STATIC	-	-	5mm	-	3.17	99.79	0.00
STATIC	-	-	7mm	-	3.18	99.79	0.00
INTERPLAY	1s	0	0mm	-	9.41	94.38	1.15
INTERPLAY	1s	90	0mm	-	10.47	92.19	1.15
INTERPLAY	0.7s	0	0mm	-	8.64	97.71	0.31
INTERPLAY	0.7s	90	0mm	-	7.85	98.54	0.10
INTERPLAY	1s	0	3mm	-	11.05	93.33	1.67
INTERPLAY	1s	90	3mm	-	11.73	91.15	1.46
INTERPLAY	0.7s	0	3mm	-	9.84	92.08	0.73
INTERPLAY	0.7s	90	3mm	-	9.66	95.10	0.73
INTERPLAY	1s	0	5mm	-	9.29	94.38	1.15
INTERPLAY	1s	90	5mm	-	10.39	91.98	1.25
INTERPLAY	0.7s	0	5mm	-	8.71	98.23	0.52
INTERPLAY	0.7s	90	5mm	-	7.74	99.06	0.10
INTERPLAY	1s	0	7mm	-	8.48	97.40	0.42
INTERPLAY	1s	90	7mm	-	9.19	95.94	0.10
INTERPLAY	0.7s	0	7mm	-	8.91	97.60	0.73
INTERPLAY	0.7s	90	7mm	-	7.87	98.54	0.31
RESCANNING	1s	0	0mm	5	12.09	86.35	0.21
RESCANNING	1s	0	0mm	10	10.92	88.02	0.00
RESCANNING	1s	0	0mm	15	10.94	87.40	0.00
RESCANNING	1s	0	0mm	20	10.60	88.65	0.00
RESCANNING	1s	90	0mm	5	12.14	84.58	0.31
RESCANNING	1s	90	0mm	10	12.24	87.60	0.00
RESCANNING	1s	90	0mm	15	11.13	87.71	0.00
RESCANNING	1s	90	0mm	20	11.21	88.96	0.00
RESCANNING	0.7s	0	0mm	5	12.06	87.40	0.10
RESCANNING	0.7s	0	0mm	10	11.01	90.10	0.00
RESCANNING	0.7s	0	0mm	15	10.87	90.42	0.00
RESCANNING	0.7s	0	0mm	20	10.12	91.25	0.00
RESCANNING	0.7s	90	0mm	5	12.50	89.27	0.62
RESCANNING	0.7s	90	0mm	10	10.91	90.42	0.00
RESCANNING	0.7s	90	0mm	15	10.45	90.83	0.00
RESCANNING	0.7s	90	0mm	20	10.35	90.62	0.00
RESCANNING	1s	0	3mm	5	8.82	94.69	0.10
RESCANNING	1s	0	3mm	10	5.45	99.06	0.00
RESCANNING	1s	0	3mm	15	4.74	99.58	0.00
RESCANNING	1s	0	3mm	20	4.63	99.58	0.00
RESCANNING	1s	90	3mm	5	7.45	97.50	0.00
RESCANNING	1s	90	3mm	10	6.43	99.69	0.00
RESCANNING	1s	90	3mm	15	5.33	99.38	0.00
RESCANNING	1s	90	3mm	20	5.09	99.48	0.00
RESCANNING	0.7s	0	3mm	5	5.78	99.27	0.21
RESCANNING	0.7s	0	3mm	10	4.53	99.58	0.00
RESCANNING	0.7s	0	3mm	15	3.91	99.48	0.00
RESCANNING	0.7s	0	3mm	20	3.50	99.58	0.00
RESCANNING	0.7s	90	3mm	5	5.88	99.06	0.00
RESCANNING	0.7s	90	3mm	10	4.34	99.79	0.10
RESCANNING	0.7s	90	3mm	15	4.35	99.38	0.00
RESCANNING	0.7s	90	3mm	20	3.66	99.58	0.00
RESCANNING	1s	0	5mm	5	9.22	99.06	3.02
RESCANNING	1s	0	5mm	10	5.18	99.58	0.00
RESCANNING	1s	0	5mm	15	4.89	99.79	0.00
RESCANNING	1s	0	5mm	20	4.16	99.79	0.00
RESCANNING	1s	90	5mm	5	7.67	99.58	0.73
RESCANNING	1s	90	5mm	10	5.36	99.69	0.00
RESCANNING	1s	90	5mm	15	4.88	99.79	0.00
RESCANNING	1s	90	5mm	20	4.62	99.79	0.00
RESCANNING	0.7s	0	5mm	5	6.76	99.06	0.10
RESCANNING	0.7s	0	5mm	10	4.43	99.90	0.00
RESCANNING	0.7s	0	5mm	15	3.87	99.69	0.00
RESCANNING	0.7s	0	5mm	20	3.35	99.69	0.00
RESCANNING	0.7s	90	5mm	5	5.31	99.38	0.00
RESCANNING	0.7s	90	5mm	10	4.33	99.69	0.00
RESCANNING	0.7s	90	5mm	15	3.49	99.79	0.00
RESCANNING	0.7s	90	5mm	20	3.28	99.90	0.00
RESCANNING	1s	0	7mm	5	6.68	99.48	0.00
RESCANNING	1s	0	7mm	10	5.61	99.58	0.10
RESCANNING	1s	0	7mm	15	3.83	99.79	0.00
RESCANNING	1s	0	7mm	20	4.13	99.90	0.00
RESCANNING	1s	90	7mm	5	8.62	99.17	1.04
RESCANNING	1s	90	7mm	10	5.34	99.58	0.00
RESCANNING	1s	90	7mm	15	3.79	100.00	0.00
RESCANNING	1s	90	7mm	20	4.22	99.90	0.00
RESCANNING	0.7s	0	7mm	5	5.92	99.79	0.00
RESCANNING	0.7s	0	7mm	10	4.01	99.90	0.00
RESCANNING	0.7s	0	7mm	15	3.75	99.90	0.00
RESCANNING	0.7s	0	7mm	20	3.35	99.79	0.00
RESCANNING	0.7s	90	7mm	5	5.60	99.79	0.00
RESCANNING	0.7s	90	7mm	10	4.37	99.69	0.00
RESCANNING	0.7s	90	7mm	15	3.70	99.90	0.00
RESCANNING	0.7s	90	7mm	20	2.96	100.00	0.00

Table 1.28: Patient 3, LPV

Case	motion period	motion starting phase	Margin	rescan no.	D5-D95 [%]	V95 [%]	V107 [%]	
STATIC	-	-	0mm	-	4.67	100.00	0.29	
STATIC	-	-	3mm	-	4.14	100.00	0.00	
STATIC	-	-	5mm	-	3.47	100.00	0.00	
STATIC	-	-	7mm	-	3.08	100.00	0.00	
INTERPLAY	1s	0	0mm	-	13.88	87.71	2.00	
INTERPLAY	1s	90	0mm	-	10.18	77.14	0.00	
INTERPLAY	0.7s	0	0mm	-	10.92	89.14	1.43	
INTERPLAY	0.7s	90	0mm	-	10.96	86.57	0.29	
INTERPLAY	1s	0	3mm	-	7.79	100.00	0.86	
INTERPLAY	1s	90	3mm	-	8.30	97.14	0.00	
INTERPLAY	0.7s	0	3mm	-	9.59	95.71	0.29	
INTERPLAY	0.7s	90	3mm	-	7.41	99.43	2.00	
INTERPLAY	1s	0	5mm	-	7.79	100.00	1.14	
INTERPLAY	1s	90	5mm	-	8.40	96.86	0.00	
INTERPLAY	0.7s	0	5mm	-	9.47	95.71	0.00	
INTERPLAY	0.7s	90	5mm	-	7.55	99.43	1.14	
INTERPLAY	1s	0	7mm	-	7.82	100.00	1.43	
INTERPLAY	1s	90	7mm	-	8.33	96.57	0.00	
INTERPLAY	0.7s	0	7mm	-	9.42	96.00	0.29	
INTERPLAY	0.7s	90	7mm	-	7.81	98.86	1.14	
RESCANNING	1s	0	0mm	5	8.88	96.00	0.29	
RESCANNING	1s	0	0mm	10	8.90	95.71	0.00	
RESCANNING	1s	0	0mm	15	8.63	96.86	0.29	
RESCANNING	1s	0	0mm	20	8.46	97.43	0.29	
RESCANNING	1s	90	0mm	5	9.42	92.00	0.57	
RESCANNING	1s	90	0mm	10	9.27	93.71	0.00	
RESCANNING	1s	90	0mm	15	8.93	94.00	0.29	
RESCANNING	1s	90	0mm	20	8.35	93.71	0.00	
RESCANNING	0.7s	0	0mm	5	8.86	92.00	0.00	
RESCANNING	0.7s	0	0mm	10	8.19	95.71	0.00	
RESCANNING	0.7s	0	0mm	15	7.61	95.14	0.00	
RESCANNING	0.7s	0	0mm	20	7.36	96.29	0.00	
RESCANNING	0.7s	90	0mm	5	8.88	94.00	0.00	
RESCANNING	0.7s	90	0mm	10	6.94	95.71	0.00	
RESCANNING	0.7s	90	0mm	15	6.40	97.14	0.00	
RESCANNING	0.7s	90	0mm	20	5.96	98.00	0.00	
RESCANNING	1s	0	3mm	5	6.57	100.00	0.29	
RESCANNING	1s	0	3mm	10	6.50	100.00	0.57	
RESCANNING	1s	0	3mm	15	5.61	100.00	0.00	
RESCANNING	1s	0	3mm	20	5.32	100.00	0.00	
RESCANNING	1s	90	3mm	5	6.86	100.00	0.29	
RESCANNING	1s	90	3mm	10	5.89	100.00	0.00	
RESCANNING	1s	90	3mm	15	5.94	100.00	0.29	
RESCANNING	1s	90	3mm	20	5.17	100.00	0.00	
RESCANNING	0.7s	0	3mm	5	5.78	99.43	0.00	
RESCANNING	0.7s	0	3mm	10	4.23	99.71	0.00	
RESCANNING	0.7s	0	3mm	15	3.69	99.71	0.00	
RESCANNING	0.7s	0	3mm	20	3.34	99.71	0.00	
RESCANNING	0.7s	90	3mm	5	5.85	99.43	0.00	
RESCANNING	0.7s	90	3mm	10	4.57	99.71	0.00	
RESCANNING	0.7s	90	3mm	15	4.14	100.00	0.00	
RESCANNING	0.7s	90	3mm	20	3.62	99.71	0.00	
RESCANNING	1s	0	5mm	5	8.21	100.00	3.71	
RESCANNING	1s	0	5mm	10	4.89	100.00	0.00	
RESCANNING	1s	0	5mm	15	4.73	100.00	0.00	
RESCANNING	1s	0	5mm	20	4.20	100.00	0.00	
RESCANNING	1s	90	5mm	5	7.77	99.14	0.86	
RESCANNING	1s	90	5mm	10	5.17	100.00	0.00	
RESCANNING	1s	90	5mm	15	4.91	100.00	0.00	
RESCANNING	1s	90	5mm	20	4.08	100.00	0.00	
RESCANNING	0.7s	0	5mm	5	5.81	100.00	0.00	
RESCANNING	0.7s	0	5mm	10	4.83	100.00	0.00	
RESCANNING	0.7s	0	5mm	15	4.02	100.00	0.00	
RESCANNING	0.7s	0	5mm	20	4.23	100.00	0.00	
RESCANNING	0.7s	90	5mm	5	5.57	100.00	0.00	
RESCANNING	0.7s	90	5mm	10	4.37	100.00	0.00	
RESCANNING	0.7s	90	5mm	15	4.52	100.00	0.00	
RESCANNING	0.7s	90	5mm	20	4.65	100.00	0.00	
RESCANNING	1s	0	7mm	5	5.24	100.00	0.00	
RESCANNING	1s	0	7mm	10	6.37	100.00	0.00	
RESCANNING	1s	0	7mm	15	5.31	100.00	0.00	
RESCANNING	1s	0	7mm	20	5.39	100.00	0.00	
RESCANNING	1s	90	7mm	5	5.87	99.43	0.00	
RESCANNING	1s	90	7mm	10	5.61	99.71	0.00	
RESCANNING	1s	90	7mm	15	5.35	100.00	0.00	
RESCANNING	1s	90	7mm	20	5.19	99.71	0.00	
RESCANNING	0.7s	0	7mm	5	5.89	100.00	0.00	
RESCANNING	0.7s	0	7mm	10	4.29	100.00	0.00	
RESCANNING	0.7s	0	7mm	15	3.90	100.00	0.00	
RESCANNING	0.7s	0	7mm	20	3.84	100.00	0.00	
54	RESCANNING	0.7s	90	7mm	5	5.72	100.00	0.00
	RESCANNING	0.7s	90	7mm	10	4.22	100.00	0.00
	RESCANNING	0.7s	90	7mm	15	3.62	100.00	0.00
	RESCANNING	0.7s	90	7mm	20	3.75	100.00	0.00

Table 1.29: Patient 3, RPV

Case	motion period	motion starting phase	Margin	rescan no.	D5-D95 [%]	V95 [%]	V107 [%]
STATIC	-	-	0mm	-	3.87	98.81	0.10
STATIC	-	-	3mm	-	1.99	100.00	0.00
STATIC	-	-	5mm	-	2.14	100.00	0.00
STATIC	-	-	7mm	-	1.94	99.90	0.00
INTERPLAY	1s	0	0mm	-	9.50	95.03	0.50
INTERPLAY	1s	90	0mm	-	10.30	95.53	1.79
INTERPLAY	0.7s	0	0mm	-	8.79	93.35	0.10
INTERPLAY	0.7s	90	0mm	-	9.74	94.64	0.20
INTERPLAY	1s	0	3mm	-	6.12	99.90	0.10
INTERPLAY	1s	90	3mm	-	7.18	99.60	0.79
INTERPLAY	0.7s	0	3mm	-	6.07	100.00	0.10
INTERPLAY	0.7s	90	3mm	-	6.56	100.00	0.79
INTERPLAY	1s	0	5mm	-	6.09	99.60	0.00
INTERPLAY	1s	90	5mm	-	7.27	99.60	0.70
INTERPLAY	0.7s	0	5mm	-	6.09	100.00	0.10
INTERPLAY	0.7s	90	5mm	-	6.46	100.00	0.60
INTERPLAY	1s	0	7mm	-	6.15	99.70	0.00
INTERPLAY	1s	90	7mm	-	7.26	99.50	0.30
INTERPLAY	0.7s	0	7mm	-	6.20	99.90	0.40
INTERPLAY	0.7s	90	7mm	-	6.47	100.00	0.50
RESCANNING	1s	0	0mm	5	8.60	94.64	0.20
RESCANNING	1s	0	0mm	10	6.64	98.21	0.00
RESCANNING	1s	0	0mm	15	6.30	98.61	0.00
RESCANNING	1s	0	0mm	20	6.18	98.71	0.00
RESCANNING	1s	90	0mm	5	8.73	95.73	0.60
RESCANNING	1s	90	0mm	10	7.11	97.32	0.00
RESCANNING	1s	90	0mm	15	6.55	98.21	0.00
RESCANNING	1s	90	0mm	20	6.29	98.61	0.00
RESCANNING	0.7s	0	0mm	5	6.89	95.63	0.00
RESCANNING	0.7s	0	0mm	10	4.98	99.01	0.00
RESCANNING	0.7s	0	0mm	15	4.31	99.11	0.00
RESCANNING	0.7s	0	0mm	20	4.33	99.30	0.00
RESCANNING	0.7s	90	0mm	5	7.03	97.42	0.00
RESCANNING	0.7s	90	0mm	10	5.39	98.51	0.00
RESCANNING	0.7s	90	0mm	15	4.66	99.40	0.00
RESCANNING	0.7s	90	0mm	20	4.55	99.21	0.00
RESCANNING	1s	0	3mm	5	6.94	99.90	0.79
RESCANNING	1s	0	3mm	10	4.55	99.90	0.00
RESCANNING	1s	0	3mm	15	3.88	99.90	0.00
RESCANNING	1s	0	3mm	20	4.00	99.90	0.00
RESCANNING	1s	90	3mm	5	5.86	99.70	0.00
RESCANNING	1s	90	3mm	10	4.82	100.00	0.00
RESCANNING	1s	90	3mm	15	4.19	100.00	0.00
RESCANNING	1s	90	3mm	20	4.05	100.00	0.00
RESCANNING	0.7s	0	3mm	5	4.87	99.90	0.10
RESCANNING	0.7s	0	3mm	10	3.82	100.00	0.00
RESCANNING	0.7s	0	3mm	15	3.17	100.00	0.00
RESCANNING	0.7s	0	3mm	20	2.93	100.00	0.00
RESCANNING	0.7s	90	3mm	5	5.65	98.81	0.00
RESCANNING	0.7s	90	3mm	10	4.50	100.00	0.00
RESCANNING	0.7s	90	3mm	15	3.36	100.00	0.00
RESCANNING	0.7s	90	3mm	20	2.65	100.00	0.00
RESCANNING	1s	0	5mm	5	7.18	100.00	1.49
RESCANNING	1s	0	5mm	10	4.62	100.00	0.00
RESCANNING	1s	0	5mm	15	3.76	100.00	0.00
RESCANNING	1s	0	5mm	20	3.66	100.00	0.00
RESCANNING	1s	90	5mm	5	4.85	100.00	0.00
RESCANNING	1s	90	5mm	10	4.30	100.00	0.00
RESCANNING	1s	90	5mm	15	4.07	100.00	0.00
RESCANNING	1s	90	5mm	20	3.39	100.00	0.00
RESCANNING	0.7s	0	5mm	5	4.97	100.00	0.00
RESCANNING	0.7s	0	5mm	10	4.12	100.00	0.00
RESCANNING	0.7s	0	5mm	15	3.10	100.00	0.00
RESCANNING	0.7s	0	5mm	20	2.98	100.00	0.00
RESCANNING	0.7s	90	5mm	5	5.46	100.00	0.00
RESCANNING	0.7s	90	5mm	10	3.85	100.00	0.00
RESCANNING	0.7s	90	5mm	15	3.19	100.00	0.00
RESCANNING	0.7s	90	5mm	20	3.02	100.00	0.00
RESCANNING	1s	0	7mm	5	8.50	100.00	0.30
RESCANNING	1s	0	7mm	10	4.30	100.00	0.00
RESCANNING	1s	0	7mm	15	4.59	100.00	0.00
RESCANNING	1s	0	7mm	20	4.32	100.00	0.00
RESCANNING	1s	90	7mm	5	6.61	100.00	0.50
RESCANNING	1s	90	7mm	10	4.42	100.00	0.00
RESCANNING	1s	90	7mm	15	3.73	100.00	0.00
RESCANNING	1s	90	7mm	20	3.71	100.00	0.00
RESCANNING	0.7s	0	7mm	5	4.93	100.00	0.00
RESCANNING	0.7s	0	7mm	10	3.53	100.00	0.00
RESCANNING	0.7s	0	7mm	15	3.24	100.00	0.00
RESCANNING	0.7s	0	7mm	20	3.16	100.00	0.00
RESCANNING	0.7s	90	7mm	5	4.64	100.00	0.10
RESCANNING	0.7s	90	7mm	10	3.53	100.00	0.00
RESCANNING	0.7s	90	7mm	15	3.36	100.00	0.00
RESCANNING	0.7s	90	7mm	20	3.16	100.00	0.00

Table 1.30: Patient 4, LPV

Case	motion period	motion starting phase	Margin	rescan no.	D5-D95 [%]	V95 [%]	V107 [%]	
STATIC	-	-	0mm	-	7.36	95.76	0.25	
STATIC	-	-	3mm	-	3.92	99.75	0.00	
STATIC	-	-	5mm	-	3.63	100.00	0.00	
STATIC	-	-	7mm	-	3.49	100.00	0.00	
INTERPLAY	1s	0	0mm	-	13.55	89.03	2.99	
INTERPLAY	1s	90	0mm	-	14.82	80.30	1.00	
INTERPLAY	0.7s	0	0mm	-	14.10	84.79	1.75	
INTERPLAY	0.7s	90	0mm	-	10.66	91.27	1.25	
INTERPLAY	1s	0	3mm	-	7.73	99.25	0.25	
INTERPLAY	1s	90	3mm	-	10.01	95.76	0.75	
INTERPLAY	0.7s	0	3mm	-	9.86	90.02	0.00	
INTERPLAY	0.7s	90	3mm	-	9.94	95.76	1.75	
INTERPLAY	1s	0	5mm	-	9.38	98.50	0.25	
INTERPLAY	1s	90	5mm	-	9.57	95.26	0.75	
INTERPLAY	0.7s	0	5mm	-	7.35	98.75	0.00	
INTERPLAY	0.7s	90	5mm	-	6.73	98.25	0.00	
INTERPLAY	1s	0	7mm	-	11.59	91.77	2.49	
INTERPLAY	1s	90	7mm	-	10.69	89.03	0.25	
INTERPLAY	0.7s	0	7mm	-	8.97	94.26	0.00	
INTERPLAY	0.7s	90	7mm	-	7.44	98.25	0.00	
RESCANNING	1s	0	0mm	5	9.37	94.01	0.25	
RESCANNING	1s	0	0mm	10	9.43	88.03	0.00	
RESCANNING	1s	0	0mm	15	8.56	86.78	0.00	
RESCANNING	1s	0	0mm	20	8.89	85.79	0.00	
RESCANNING	1s	90	0mm	5	8.74	91.27	0.50	
RESCANNING	1s	90	0mm	10	8.88	91.77	0.00	
RESCANNING	1s	90	0mm	15	8.54	92.77	0.00	
RESCANNING	1s	90	0mm	20	8.46	92.77	0.00	
RESCANNING	0.7s	0	0mm	5	8.87	91.27	0.25	
RESCANNING	0.7s	0	0mm	10	8.20	92.27	0.00	
RESCANNING	0.7s	0	0mm	15	7.89	91.02	0.00	
RESCANNING	0.7s	0	0mm	20	8.08	91.77	0.00	
RESCANNING	0.7s	90	0mm	5	10.18	89.03	0.25	
RESCANNING	0.7s	90	0mm	10	8.33	93.27	0.00	
RESCANNING	0.7s	90	0mm	15	7.59	94.76	0.00	
RESCANNING	0.7s	90	0mm	20	7.85	94.26	0.00	
RESCANNING	1s	0	3mm	5	6.77	98.50	0.00	
RESCANNING	1s	0	3mm	10	5.30	99.25	0.00	
RESCANNING	1s	0	3mm	15	5.27	99.00	0.00	
RESCANNING	1s	0	3mm	20	4.75	99.50	0.00	
RESCANNING	1s	90	3mm	5	7.77	99.50	2.00	
RESCANNING	1s	90	3mm	10	5.94	99.50	0.00	
RESCANNING	1s	90	3mm	15	6.11	99.50	0.00	
RESCANNING	1s	90	3mm	20	5.90	99.50	0.00	
RESCANNING	0.7s	0	3mm	5	5.52	99.75	0.00	
RESCANNING	0.7s	0	3mm	10	4.62	99.75	0.00	
RESCANNING	0.7s	0	3mm	15	4.44	100.00	0.00	
RESCANNING	0.7s	0	3mm	20	3.93	100.00	0.00	
RESCANNING	0.7s	90	3mm	5	5.50	99.25	0.00	
RESCANNING	0.7s	90	3mm	10	4.21	99.25	0.00	
RESCANNING	0.7s	90	3mm	15	4.85	99.50	0.00	
RESCANNING	0.7s	90	3mm	20	3.72	99.50	0.00	
RESCANNING	1s	0	5mm	5	6.45	100.00	0.00	
RESCANNING	1s	0	5mm	10	5.15	99.75	0.00	
RESCANNING	1s	0	5mm	15	4.70	99.75	0.00	
RESCANNING	1s	0	5mm	20	4.27	99.75	0.00	
RESCANNING	1s	90	5mm	5	8.63	92.02	0.00	
RESCANNING	1s	90	5mm	10	6.15	97.51	0.00	
RESCANNING	1s	90	5mm	15	5.18	99.50	0.00	
RESCANNING	1s	90	5mm	20	5.93	99.50	0.00	
RESCANNING	0.7s	0	5mm	5	5.61	99.50	0.00	
RESCANNING	0.7s	0	5mm	10	3.64	99.50	0.00	
RESCANNING	0.7s	0	5mm	15	3.47	99.75	0.00	
RESCANNING	0.7s	0	5mm	20	3.23	99.50	0.00	
RESCANNING	0.7s	90	5mm	5	5.07	99.50	0.00	
RESCANNING	0.7s	90	5mm	10	4.18	99.50	0.00	
RESCANNING	0.7s	90	5mm	15	3.63	99.25	0.00	
RESCANNING	0.7s	90	5mm	20	3.30	99.50	0.00	
RESCANNING	1s	0	7mm	5	5.26	100.00	0.00	
RESCANNING	1s	0	7mm	10	4.14	100.00	0.00	
RESCANNING	1s	0	7mm	15	4.03	100.00	0.00	
RESCANNING	1s	0	7mm	20	4.15	100.00	0.00	
RESCANNING	1s	90	7mm	5	5.59	99.25	0.00	
RESCANNING	1s	90	7mm	10	5.34	99.75	0.00	
RESCANNING	1s	90	7mm	15	4.57	100.00	0.00	
RESCANNING	1s	90	7mm	20	4.35	99.75	0.00	
RESCANNING	0.7s	0	7mm	5	5.00	99.75	0.00	
RESCANNING	0.7s	0	7mm	10	3.66	99.75	0.00	
RESCANNING	0.7s	0	7mm	15	3.28	100.00	0.00	
RESCANNING	0.7s	0	7mm	20	3.41	100.00	0.00	
56	RESCANNING	0.7s	90	7mm	5	4.74	99.75	0.00
	RESCANNING	0.7s	90	7mm	10	3.04	99.75	0.00
	RESCANNING	0.7s	90	7mm	15	3.12	100.00	0.00
	RESCANNING	0.7s	90	7mm	20	2.76	100.00	0.00

Table 1.31: Patient 4, RPV

Case	motion period	motion starting phase	Margin	rescan no.	D5-D95 [%]	V95 [%]	V107 [%]
STATIC	-	-	0mm	-	5.46	97.80	0.00
STATIC	-	-	3mm	-	3.65	100.00	0.00
STATIC	-	-	5mm	-	3.07	100.00	0.00
STATIC	-	-	7mm	-	2.63	99.40	0.00
INTERPLAY	1s	0	0mm	-	11.43	89.80	0.40
INTERPLAY	1s	90	0mm	-	11.22	94.00	2.00
INTERPLAY	0.7s	0	0mm	-	11.12	94.60	2.00
INTERPLAY	0.7s	90	0mm	-	13.29	84.20	1.80
INTERPLAY	1s	0	3mm	-	9.67	95.20	0.60
INTERPLAY	1s	90	3mm	-	9.16	96.60	0.20
INTERPLAY	0.7s	0	3mm	-	9.68	97.00	1.20
INTERPLAY	0.7s	90	3mm	-	9.55	96.80	0.40
INTERPLAY	1s	0	5mm	-	8.83	96.80	0.40
INTERPLAY	1s	90	5mm	-	8.88	92.20	0.00
INTERPLAY	0.7s	0	5mm	-	8.56	96.80	0.00
INTERPLAY	0.7s	90	5mm	-	7.55	99.60	0.40
INTERPLAY	1s	0	7mm	-	8.88	98.80	1.60
INTERPLAY	1s	90	7mm	-	8.05	97.60	0.00
INTERPLAY	0.7s	0	7mm	-	7.81	97.00	0.00
INTERPLAY	0.7s	90	7mm	-	7.66	99.80	0.20
RESCANNING	1s	0	0mm	5	10.05	94.00	0.80
RESCANNING	1s	0	0mm	10	8.77	94.80	0.40
RESCANNING	1s	0	0mm	15	8.47	94.40	0.00
RESCANNING	1s	0	0mm	20	8.27	94.60	0.20
RESCANNING	1s	90	0mm	5	9.65	95.20	1.00
RESCANNING	1s	90	0mm	10	9.35	95.80	0.40
RESCANNING	1s	90	0mm	15	8.28	96.00	0.40
RESCANNING	1s	90	0mm	20	8.35	96.40	0.20
RESCANNING	0.7s	0	0mm	5	8.51	94.00	0.00
RESCANNING	0.7s	0	0mm	10	7.67	95.80	0.00
RESCANNING	0.7s	0	0mm	15	7.24	96.20	0.00
RESCANNING	0.7s	0	0mm	20	7.13	95.80	0.00
RESCANNING	0.7s	90	0mm	5	8.77	94.60	0.20
RESCANNING	0.7s	90	0mm	10	6.86	96.20	0.00
RESCANNING	0.7s	90	0mm	15	6.98	96.60	0.20
RESCANNING	0.7s	90	0mm	20	6.46	96.40	0.20
RESCANNING	1s	0	3mm	5	7.05	99.40	0.00
RESCANNING	1s	0	3mm	10	5.62	100.00	0.00
RESCANNING	1s	0	3mm	15	5.10	100.00	0.00
RESCANNING	1s	0	3mm	20	4.86	99.80	0.00
RESCANNING	1s	90	3mm	5	5.56	99.60	0.00
RESCANNING	1s	90	3mm	10	5.62	100.00	0.20
RESCANNING	1s	90	3mm	15	5.14	99.80	0.00
RESCANNING	1s	90	3mm	20	5.36	100.00	0.00
RESCANNING	0.7s	0	3mm	5	5.69	100.00	0.00
RESCANNING	0.7s	0	3mm	10	3.71	100.00	0.00
RESCANNING	0.7s	0	3mm	15	3.54	100.00	0.00
RESCANNING	0.7s	0	3mm	20	3.59	100.00	0.00
RESCANNING	0.7s	90	3mm	5	6.53	99.60	0.00
RESCANNING	0.7s	90	3mm	10	4.21	100.00	0.00
RESCANNING	0.7s	90	3mm	15	4.37	100.00	0.00
RESCANNING	0.7s	90	3mm	20	4.23	100.00	0.00
RESCANNING	1s	0	5mm	5	7.82	100.00	1.80
RESCANNING	1s	0	5mm	10	4.77	100.00	0.20
RESCANNING	1s	0	5mm	15	4.98	100.00	0.00
RESCANNING	1s	0	5mm	20	5.16	100.00	0.00
RESCANNING	1s	90	5mm	5	7.26	94.20	0.00
RESCANNING	1s	90	5mm	10	5.12	99.60	0.00
RESCANNING	1s	90	5mm	15	5.27	100.00	0.00
RESCANNING	1s	90	5mm	20	4.74	100.00	0.00
RESCANNING	0.7s	0	5mm	5	5.87	100.00	0.00
RESCANNING	0.7s	0	5mm	10	3.72	100.00	0.00
RESCANNING	0.7s	0	5mm	15	3.09	100.00	0.00
RESCANNING	0.7s	0	5mm	20	3.14	100.00	0.00
RESCANNING	0.7s	90	5mm	5	5.34	99.80	0.00
RESCANNING	0.7s	90	5mm	10	3.52	100.00	0.00
RESCANNING	0.7s	90	5mm	15	3.53	100.00	0.00
RESCANNING	0.7s	90	5mm	20	2.93	100.00	0.00
RESCANNING	1s	0	7mm	5	5.44	100.00	0.20
RESCANNING	1s	0	7mm	10	4.23	100.00	0.20
RESCANNING	1s	0	7mm	15	3.95	99.80	0.00
RESCANNING	1s	0	7mm	20	3.84	100.00	0.00
RESCANNING	1s	90	7mm	5	6.29	99.20	0.20
RESCANNING	1s	90	7mm	10	5.31	100.00	0.00
RESCANNING	1s	90	7mm	15	4.04	100.00	0.00
RESCANNING	1s	90	7mm	20	3.69	100.00	0.00
RESCANNING	0.7s	0	7mm	5	5.03	100.00	0.00
RESCANNING	0.7s	0	7mm	10	4.37	100.00	0.00
RESCANNING	0.7s	0	7mm	15	3.03	100.00	0.00
RESCANNING	0.7s	0	7mm	20	2.81	100.00	0.00
RESCANNING	0.7s	90	7mm	5	4.49	100.00	0.00
RESCANNING	0.7s	90	7mm	10	3.68	100.00	0.00
RESCANNING	0.7s	90	7mm	15	3.62	100.00	0.00
RESCANNING	0.7s	90	7mm	20	3.12	100.00	0.00

Table 1.32: Patient 5, LPV

Case	motion period	motion starting phase	Margin	rescan no.	D5-D95 [%]	V95 [%]	V107 [%]
STATIC	-	-	0mm	-	4.65	100.00	0.00
STATIC	-	-	3mm	-	2.52	100.00	0.00
STATIC	-	-	5mm	-	2.95	100.00	0.00
STATIC	-	-	7mm	-	4.29	100.00	0.00
INTERPLAY	1s	0	0mm	-	10.55	93.41	0.94
INTERPLAY	1s	90	0mm	-	10.79	93.68	0.94
INTERPLAY	0.7s	0	0mm	-	9.18	91.40	0.27
INTERPLAY	0.7s	90	0mm	-	9.34	89.65	0.00
INTERPLAY	1s	0	3mm	-	8.09	97.31	0.27
INTERPLAY	1s	90	3mm	-	9.60	98.39	2.55
INTERPLAY	0.7s	0	3mm	-	7.84	95.43	0.13
INTERPLAY	0.7s	90	3mm	-	7.95	97.85	0.13
INTERPLAY	1s	0	5mm	-	6.48	99.73	0.81
INTERPLAY	1s	90	5mm	-	7.43	95.97	0.13
INTERPLAY	0.7s	0	5mm	-	6.99	97.58	0.00
INTERPLAY	0.7s	90	5mm	-	8.00	99.87	0.40
INTERPLAY	1s	0	7mm	-	6.71	99.46	0.13
INTERPLAY	1s	90	7mm	-	9.40	96.24	0.81
INTERPLAY	0.7s	0	7mm	-	8.18	93.95	0.00
INTERPLAY	0.7s	90	7mm	-	7.38	98.25	0.00
RESCANNING	1s	0	0mm	5	9.34	88.58	0.00
RESCANNING	1s	0	0mm	10	7.44	91.94	0.00
RESCANNING	1s	0	0mm	15	6.78	94.89	0.00
RESCANNING	1s	0	0mm	20	6.57	95.30	0.00
RESCANNING	1s	90	0mm	5	8.62	97.04	1.61
RESCANNING	1s	90	0mm	10	8.47	96.51	0.54
RESCANNING	1s	90	0mm	15	6.67	97.72	0.13
RESCANNING	1s	90	0mm	20	6.82	97.58	0.27
RESCANNING	0.7s	0	0mm	5	7.95	96.10	0.00
RESCANNING	0.7s	0	0mm	10	6.38	98.12	0.00
RESCANNING	0.7s	0	0mm	15	6.20	97.98	0.00
RESCANNING	0.7s	0	0mm	20	5.74	97.98	0.00
RESCANNING	0.7s	90	0mm	5	7.87	95.16	0.13
RESCANNING	0.7s	90	0mm	10	6.10	96.77	0.00
RESCANNING	0.7s	90	0mm	15	6.01	97.18	0.00
RESCANNING	0.7s	90	0mm	20	5.84	96.37	0.00
RESCANNING	1s	0	3mm	5	5.44	99.87	0.00
RESCANNING	1s	0	3mm	10	4.47	100.00	0.00
RESCANNING	1s	0	3mm	15	3.79	100.00	0.00
RESCANNING	1s	0	3mm	20	3.33	100.00	0.00
RESCANNING	1s	90	3mm	5	7.74	91.94	0.00
RESCANNING	1s	90	3mm	10	4.42	99.87	0.00
RESCANNING	1s	90	3mm	15	3.67	100.00	0.00
RESCANNING	1s	90	3mm	20	3.78	100.00	0.00
RESCANNING	0.7s	0	3mm	5	5.64	99.87	0.00
RESCANNING	0.7s	0	3mm	10	4.74	100.00	0.00
RESCANNING	0.7s	0	3mm	15	3.68	100.00	0.00
RESCANNING	0.7s	0	3mm	20	3.45	100.00	0.00
RESCANNING	0.7s	90	3mm	5	5.58	99.73	0.00
RESCANNING	0.7s	90	3mm	10	3.86	99.87	0.00
RESCANNING	0.7s	90	3mm	15	3.46	100.00	0.00
RESCANNING	0.7s	90	3mm	20	3.38	100.00	0.00
RESCANNING	1s	0	5mm	5	6.69	99.06	0.00
RESCANNING	1s	0	5mm	10	4.19	100.00	0.00
RESCANNING	1s	0	5mm	15	3.85	100.00	0.00
RESCANNING	1s	0	5mm	20	3.67	100.00	0.00
RESCANNING	1s	90	5mm	5	4.90	99.60	0.00
RESCANNING	1s	90	5mm	10	4.63	99.87	0.00
RESCANNING	1s	90	5mm	15	3.60	100.00	0.00
RESCANNING	1s	90	5mm	20	3.49	100.00	0.00
RESCANNING	0.7s	0	5mm	5	4.64	100.00	0.00
RESCANNING	0.7s	0	5mm	10	3.83	100.00	0.00
RESCANNING	0.7s	0	5mm	15	3.25	100.00	0.00
RESCANNING	0.7s	0	5mm	20	2.60	100.00	0.00
RESCANNING	0.7s	90	5mm	5	5.04	100.00	0.00
RESCANNING	0.7s	90	5mm	10	3.66	99.73	0.00
RESCANNING	0.7s	90	5mm	15	2.97	100.00	0.00
RESCANNING	0.7s	90	5mm	20	2.58	100.00	0.00
RESCANNING	1s	0	7mm	5	5.11	100.00	0.00
RESCANNING	1s	0	7mm	10	5.04	99.73	0.00
RESCANNING	1s	0	7mm	15	3.86	100.00	0.00
RESCANNING	1s	0	7mm	20	4.02	100.00	0.00
RESCANNING	1s	90	7mm	5	6.23	98.52	0.00
RESCANNING	1s	90	7mm	10	5.25	98.12	0.00
RESCANNING	1s	90	7mm	15	5.12	98.39	0.00
RESCANNING	1s	90	7mm	20	4.80	98.52	0.00
RESCANNING	0.7s	0	7mm	5	4.98	99.87	0.00
RESCANNING	0.7s	0	7mm	10	4.18	99.87	0.00
RESCANNING	0.7s	0	7mm	15	4.29	99.33	0.00
RESCANNING	0.7s	0	7mm	20	3.64	100.00	0.00

Table 1.33: Patient 5, RPV

Case	motion period	motion starting phase	Margin	rescan no.	D5-D95 [%]	V95 [%]	V107 [%]
STATIC	-	-	0mm	-	3.94	99.85	0.00
STATIC	-	-	3mm	-	2.26	100.00	0.00
STATIC	-	-	5mm	-	2.46	100.00	0.00
STATIC	-	-	7mm	-	2.83	100.00	0.00
INTERPLAY	1s	0	0mm	-	12.04	90.52	0.87
INTERPLAY	1s	90	0mm	-	9.83	94.02	1.17
INTERPLAY	0.7s	0	0mm	-	10.12	96.79	2.19
INTERPLAY	0.7s	90	0mm	-	9.12	92.57	0.15
INTERPLAY	1s	0	3mm	-	7.44	99.42	0.00
INTERPLAY	1s	90	3mm	-	7.43	97.67	0.00
INTERPLAY	0.7s	0	3mm	-	6.13	99.71	0.00
INTERPLAY	0.7s	90	3mm	-	8.35	96.21	0.15
INTERPLAY	1s	0	5mm	-	7.34	98.83	0.00
INTERPLAY	1s	90	5mm	-	8.23	98.11	0.87
INTERPLAY	0.7s	0	5mm	-	5.79	99.27	0.00
INTERPLAY	0.7s	90	5mm	-	7.86	97.52	0.00
INTERPLAY	1s	0	7mm	-	6.45	99.13	0.15
INTERPLAY	1s	90	7mm	-	8.99	94.90	0.15
INTERPLAY	0.7s	0	7mm	-	6.18	97.38	0.00
INTERPLAY	0.7s	90	7mm	-	6.82	99.85	0.00
RESCANNING	1s	0	0mm	5	8.32	91.55	0.15
RESCANNING	1s	0	0mm	10	8.53	88.48	0.00
RESCANNING	1s	0	0mm	15	8.04	91.55	0.00
RESCANNING	1s	0	0mm	20	8.30	90.52	0.00
RESCANNING	1s	90	0mm	5	8.14	99.13	0.58
RESCANNING	1s	90	0mm	10	7.53	99.56	0.73
RESCANNING	1s	90	0mm	15	8.16	97.81	0.44
RESCANNING	1s	90	0mm	20	7.82	98.69	0.44
RESCANNING	0.7s	0	0mm	5	7.65	92.57	0.00
RESCANNING	0.7s	0	0mm	10	6.75	95.34	0.00
RESCANNING	0.7s	0	0mm	15	6.24	96.21	0.00
RESCANNING	0.7s	0	0mm	20	6.19	95.77	0.00
RESCANNING	0.7s	90	0mm	5	8.18	97.23	0.15
RESCANNING	0.7s	90	0mm	10	6.45	97.81	0.00
RESCANNING	0.7s	90	0mm	15	6.04	97.38	0.00
RESCANNING	0.7s	90	0mm	20	5.46	97.96	0.00
RESCANNING	1s	0	3mm	5	6.04	100.00	0.00
RESCANNING	1s	0	3mm	10	4.16	100.00	0.00
RESCANNING	1s	0	3mm	15	4.39	100.00	0.00
RESCANNING	1s	0	3mm	20	4.21	100.00	0.00
RESCANNING	1s	90	3mm	5	6.01	98.69	0.00
RESCANNING	1s	90	3mm	10	5.38	100.00	0.15
RESCANNING	1s	90	3mm	15	4.65	100.00	0.29
RESCANNING	1s	90	3mm	20	4.65	100.00	0.00
RESCANNING	0.7s	0	3mm	5	5.52	100.00	0.00
RESCANNING	0.7s	0	3mm	10	4.20	100.00	0.00
RESCANNING	0.7s	0	3mm	15	3.12	100.00	0.00
RESCANNING	0.7s	0	3mm	20	2.99	100.00	0.00
RESCANNING	0.7s	90	3mm	5	5.10	99.85	0.00
RESCANNING	0.7s	90	3mm	10	3.49	100.00	0.00
RESCANNING	0.7s	90	3mm	15	2.83	100.00	0.00
RESCANNING	0.7s	90	3mm	20	2.85	100.00	0.00
RESCANNING	1s	0	5mm	5	4.83	100.00	0.00
RESCANNING	1s	0	5mm	10	4.56	100.00	0.00
RESCANNING	1s	0	5mm	15	3.96	100.00	0.00
RESCANNING	1s	0	5mm	20	3.87	100.00	0.00
RESCANNING	1s	90	5mm	5	6.37	96.94	0.00
RESCANNING	1s	90	5mm	10	4.26	99.85	0.00
RESCANNING	1s	90	5mm	15	4.18	100.00	0.00
RESCANNING	1s	90	5mm	20	3.94	100.00	0.00
RESCANNING	0.7s	0	5mm	5	4.21	100.00	0.00
RESCANNING	0.7s	0	5mm	10	3.38	100.00	0.00
RESCANNING	0.7s	0	5mm	15	3.24	100.00	0.00
RESCANNING	0.7s	0	5mm	20	2.66	100.00	0.00
RESCANNING	0.7s	90	5mm	5	4.47	100.00	0.00
RESCANNING	0.7s	90	5mm	10	3.26	100.00	0.00
RESCANNING	0.7s	90	5mm	15	2.93	100.00	0.00
RESCANNING	0.7s	90	5mm	20	2.37	100.00	0.00
RESCANNING	1s	0	7mm	5	5.23	100.00	0.00
RESCANNING	1s	0	7mm	10	4.50	99.42	0.00
RESCANNING	1s	0	7mm	15	4.01	100.00	0.00
RESCANNING	1s	0	7mm	20	4.29	100.00	0.00
RESCANNING	1s	90	7mm	5	5.15	99.27	0.00
RESCANNING	1s	90	7mm	10	4.81	99.42	0.00
RESCANNING	1s	90	7mm	15	4.47	98.54	0.00
RESCANNING	1s	90	7mm	20	4.44	98.83	0.00
RESCANNING	0.7s	0	7mm	5	5.04	100.00	0.00
RESCANNING	0.7s	0	7mm	10	3.43	99.85	0.00
RESCANNING	0.7s	0	7mm	15	3.04	99.71	0.00
RESCANNING	0.7s	0	7mm	20	2.84	100.00	0.00
RESCANNING	0.7s	90	7mm	5	4.58	100.00	0.00
RESCANNING	0.7s	90	7mm	10	3.81	99.42	0.00
RESCANNING	0.7s	90	7mm	15	3.53	100.00	0.00
RESCANNING	0.7s	90	7mm	20	3.23	99.71	0.00



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