strategy combining these systems may increase set up control and motion monitoring robustness.

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Impact of physiological breathing motion for breast cancer radiotherapy proton beam scanning

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Purpose or Objective: To study the impact of breathing motion on proton breast treatment plans using scanned proton beams.

Material and Methods: The study cohort was composed of twelve thoracic patients who had CT-datasets acquired during breath-hold at inhalation phase, breath-hold at exhalation phase and in free breathing mode. Proton treatment plans were designed for the left breast for the breath-hold at inhalation phase and were subsequently recalculated for the breath-hold at exhalation phase. Similarly, plans devised for the CT acquired in free breathing mode were recalculated for the extreme breath-hold phases. Four different field arrangements were used for each patient: two plans with three fields and two with one field. The dosimetric features of the plans were compared from the point of view of their coverage of the target and the doses to the organs at risk.

Results: Breathing motion led to a degradation of the dose coverage of the target (heterogeneity index increased from about 6% to 8-11%). Exhalation tended to decrease the lung burden (average dose 3.1-4.2 GyRBE), while inhalation increased it (average dose 4.7-5.8 GyRBE). The absolute values depended on the field arrangement, but the trend was similar across the plans considered. Smaller differences in dosimetric parameters were seen for the heart (average dose 0.1-0.2 GyRBE) and the left anterior descending artery (2.0-4.0 GyRBE). The absolute values of the dosimetric parameters corresponding to various breathing phases were rather small and their expected clinical impact is therefore quite small. Furthermore, the plans parameters in either breathing phase were generally superior to the corresponding ones that could be achieved with photon plans.

Conclusion: The results of this study indicated that the differences between the mean dosimetric parameters of the plans corresponding to the two extreme breathing phases are not significantly different, thus suggesting that breathing might have little impact for the chosen beam arrangements in proton scanned beam planning for breast cancer. Further investigations are needed to investigate the impact of interplay effects and whether the conclusions might be extended beyond the population considered in this study.

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Experimental analysis of interplay effects in flattening filter free VMAT treatment techniques

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Purpose or Objective: In SBRT of lung lesions, respiratory motion is commonly considered by 4DCT imaging to define the internal target volume (ITV). Dose optimization is often performed on average CT using VMAT-based treatment techniques. However, average CT data ignores individual respiratory motion patterns during dose delivery and thus fluctuations in density distribution in the ITV. Additionally, interaction of MLC dose modulation and variable target motion might result in under-dosage of the target volume (interplay effect). This study analyses the efficiency of flattening filter free dose delivery and its impact on interplay effects in lung SBRT.

Material and Methods: SBRT treatment plans were created for a lung tumor phantom using VMAT techniques employing the flattening filter (FF) and flattening filter free (FFF) mode (600MU and 1400MU per min). The phantom consists of a high resolution 2D detector array plus solid-water, bone, lung and tumor inserts. It is mounted on a 4D motion platform to simulate regular and irregular tumor motion trajectories extracted from clinical 4DCT data with max peak-to-peak amplitudes of 1.6/2.3cm in SI and 1.2/2.4cm in AP. The ITV includes a 2cm x 2cm lung tumor (CTV) plus 1.8cm safety margin in SI. Changes in dose distributions through interplay effects were investigated by analyzing static reference and dynamic dose measurements in FF and FFF mode at regular and irregular tumor motion using a planning structure-based evaluation method.

Results: VMAT techniques in FF and FFF mode achieved almost identical dose distributions at static measurements (plan comparison). FFF allowed for approximately 40% shorter treatment time. For regular tumor motion (TM), FFF resulted in greater under- and over dosages of approximately 5-10% compared to FF in the CTV (cf. figure 1 for dose differences of dynamic and static measurements). However, corresponding γ-passing maps illustrate the increased interplay effect. Furthermore, FFF generated considerable under-dosages in the CTV in case of irregular TM. γ-passing rates (local γ of 3% / 1mm) decreased from 68% to 62% for regular TM and 41% to 34% for irregular TM within the ITV (cf. figure 1). Dose area histograms for CTV and ITV complementarily confirm above changes in dose differences and γ-maps.

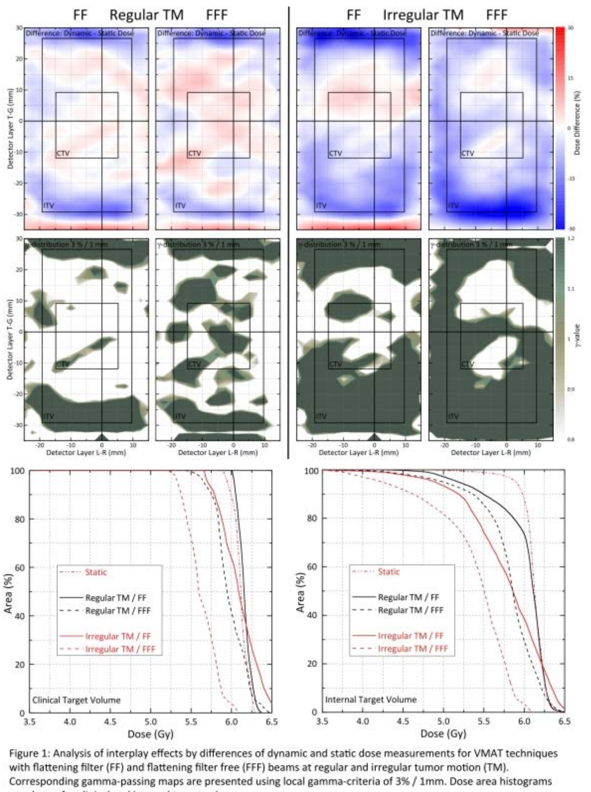

Figure 1: Analysis of interplay effects by differences of dynamic and static dose measurements for VMAT techniques with flattening filter (FF) and flattening filter free (FFF) beams at regular and irregular tumor motion (TM). Corresponding gamma-passing maps are presented using local gamma-criteria of 3% / 1mm. Dose area histograms are shown for clinical and internal target volume.

Conclusion: FFF dose delivery in lung SBRT provides shorter treatment times. However, the risk of interplay effects is increased, in particular for irregular tumor motion. Further analysis is required to evaluate the appropriateness of FFF in lung SBRT.

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development and validation of a tool to evaluate prostate motion due to patient's breathing

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Purpose or Objective: An electromagnetic (ELM) system (Calypso, Varian Medical System, Palo Alto, CA, USA) based on sub-millimeter high frequency localization of three transponders permanently implanted in the prostate, was recently introduced for continuous real-time tracking of the tumor. Several studies of the tracks acquired over thousands of patients were reported in literature and allowed to give a detailed insight of intra-fraction prostate motion. Aim of this work was to develop and validate a tool to selectively filter the signal produced by the ELM transponders and to apply it for the evaluation of the amplitude of prostate motion only due to patient's breathing.

Material and Methods: To selectively filter the signal produced by ELM transponders a software was developed in the Matlab environment (version R2014b). Briefly, the developed software computes the power density spectrum (PDS) of the recorded tracks and isolates the 'breathing peak', i.e. the peak which is centered at the frequency corresponding to the breathing average frequency of each single analyzed session. A bandpass filter on the breathing peak is then applied to the original tracking data, in order to isolate the motion of the prostate due to the breathing of the patient. The software was validated with data recorded with QUASAR moving phantom, provided with an home-made insert of three transponders. Simulated breathing frequencies of 10, 12, 14, 16, 18, 20, 22 and 24 cycles per minute were recorded for at least one minute with the ELM system. After validation, tracks of 6 prostate patients who underwent EBRT were analyzed for a total of 180 treatments sessions. For each session, the corresponding maximum amplitude of prostate motion along the three main directions was obtained. Intra patients average data and standard deviations were reported along with the overall maximum amplitude.

Results: For the in-phantom validation, the developed software automatically computed the correct cycles per minute within a 0.52% uncertainty. The average amplitudes of prostate motion due to patient's breathing are listed in Table 1. As expected, the smallest motion resulted in left-right direction. The limited standard deviations indicate a low intra-patient motion variability. For each patient, the overall maximum amplitude turned out to be not negligible, but at the same time less than 0.5 mm.

TABLE 1 - Amplitudes of prostate motion due to patient's breathing

		Left-Right (mm)		Cranio-Caudal (mm)		Antero-Posterior (mm)		overall
	# sessions	average	std. dev.	average	std. dev.	average	std. dev.	maximum (mm)
Pt #1	33	0.10	0.05	0.22	0.04	0.15	0.06	0.29
Pt #2	37	0.14	0.04	0.16	0.04	0.26	0.06	0.38
Pt #3	24	0.18	0.03	0.27	0.04	0.24	0.06	0.41
Pt #4	29	0.12	0.02	0.31	0.06	0.22	0.06	0.48
Pt #5	26	0.11	0.04	0.16	0.04	0.19	0.05	0.29
Pt #6	31	0.09	0.02	0.15	0.03	0.13	0.07	0.26

Conclusion: A tool to quantify prostate motion due to patient's breathing was successfully developed, validated and applied to a consistent number of treatments sessions. Although small compared to the motion caused by the modifications of near organs (i.e. bladder and rectum), the achieved results show that the motion associated to patient's breathing should be carefully considered in the definition of an adequate Internal Target Volume.
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Monitoring of intra-fraction eye motion during proton radiotherapy of intraocular tumors

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Purpose or Objective: In proton therapy treatments of intraocular tumors, patients actively participate by fixating a red diode, prepositioned according to planning prescriptions, to stabilize gaze direction. This work aims to evaluate safety margins effectiveness against involuntary eye movement that may occur in the course of the treatment.

Material and Methods: A custom eye tracking system (ETS), able to monitor eye position and orientation through 3D video-oculography techniques, was installed in a proton therapy (PT) treatment room (fig.1). All ocular PT centers are equipped with an in-room orthogonal X-ray imaging system used to verify treatment geometry. Tantalum radio-opaque markers, sutured to the sclera of the diseased eye, aid to determine the gaze angle of the eye during simulation, and the correct eye position at treatment. During simulation, the ETS monitored the eye simultaneously with X-ray acquisition to assess the tantalum markers pose relative to eye position and orientation. As a result, the ETS was able to assess eye motion and markers position in physical coordinates during dose delivery.
A first analysis was performed on two patients with three and two monitored treatment fraction respectively. Both patients had four implanted markers. To enable 3D localization of markers identified in X-ray images, the geometry of the imaging system was calibrated by means of the Direct Linear Transform (DLT) algorithm. We measured the distance between markers 3D position seen by the ETS during irradiation and identified on setup verification X-ray images acquired prior dose delivery to quantify intra-fraction eye motion. Margins expansions of 2.5 mm were applied laterally and distally. Median, interquartile range (IQR) and maximum values for the clip-to-clip distance are reported in table 1.