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Multi-dimensional dosimetric tools for verification of high precision radiotherapy techniques

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A major concern in the field of radiotherapy is that the pace of innovation in radiation delivery has not been complemented by corresponding technological advances capable of verifying the delivered dose distributions. In the framework of this thesis, novel quality assurance (QA) solutions for sophisticated treatment techniques like VMAT/IMRT were developed, evaluated and clinically established in order to safely and accurately deliver the planned treatment to the patients.

The newly developed VMAT solutions apply additional constraints on the linear accelerator to actuate in 'real time' to optimize the efficiency of delivery. The challenge with VMAT delivery is the synchronization of leaf speed, dose rate and gantry rotation to deliver accurate dose. The high degree of freedom of VMAT delivery and the complexity of the systems involved necessitate new procedures and potentially new tools for QA of these treatments. In order to verify the VMAT treatment plans, different setups of a 2D array in combination with phantom/holder are explored. In general, when a 2D detector array is used in a stationary phantom, the measured dose was shown to be dependent on the angle of beam incidence. Therefore, in-house software was developed which could generate correction factors (CFs) for each detector element and calibrates the measured dose. Thus, the calibrated dose was independent of the angle of beam incidence. The agreement was ~100% (3%/3mm) after applying the CFs. The other setup was with 2D array in a holder. This setup also showed passing rates of ~100% for 3%/3mm criteria. With the developed QA solutions, a single setup either in a stationary phantom or in a holder would speed up the whole QA procedure for an increasing number of patient verification plans in busy radiotherapy departments.

The quality of dose delivery of treatment techniques like VMAT/IMRT is strongly dependent on the accurate position of the leaves. The impact of multi leaf collimator (MLC) positional errors is well understood for IMRT. However, the influence of these errors on patients' dose during VMAT delivery was under-investigation. To understand the nature of these errors, software was developed to simulate MLC positional errors as well as gantry errors. The consequences of MLC (±1mm) and gantry (±1°) errors on the studied brain tumor cases showed minimal absolute dose difference. However, when errors are in the order of 2mm, significant dose deviations were observed. Extending the above studies, the sensitivity of routine QA to MLC positional uncertainties was investigated. A 2D detector array was used for acquisition of the delivered dose. This work not only revealed the limitations of the present 2D detector arrays but also the evaluation procedures for a routine VMAT verification. Our results showed that errors in the order of ±2mm were clearly identifiable as the passing rate was very low. Errors with ±1mm were overlapping with error-free measurements in certain cases and therefore were difficult to detect. Therefore, to enhance the overall radiation therapy treatment quality, it is important to perform MLC QA regularly while consistently maintaining its accuracy (position and speed) within the tolerances.

Dose deviations found in the 2D array for example due to MLC/gantry positional errors (within/outside acceptable tolerances) are impossible to translate those discrepancies directly to the dose deviations of the tumour or critical structures. No comprehensive 3D QA solution was available to meet the complexities associated with the advance treatment techniques such as IMRT/VMAT. The steep dose gradients created in these techniques make single point-dose measurements inadequate for verifying the significantly non-uniform dose distributions. The limitation of film dosimetry or 2D detector arrays is that they show dose only in one plane. A novel 3D dosimetric QA system was proposed for verification of complex treatment plans. The system has three components: (i) dedicated beam model, a virtual accelerator that was created with the photon beam data of the linac. A beam model describes the characteristics of an accelerator (e.g., energy spectrum, lateral beam quality

variations). (ii) A dose engine based on collapsed cone convolution/superposition algorithm for calculating 3D dose distribution. (iii) A reconstruction algorithm, which takes the measured fluences of a regular 2D array as an input and reconstructs 3D dose distribution on the patient anatomy. This system could measure the delivered dose with sufficient accuracy and could project 3D dose distribution directly on the patient's anatomy. Therefore, it offers the possibility to compare not only the 2D dose distributions on the structures but also the dose volume histograms with those of the planning system.

In general, pre-treatment QA is performed for verification of IMRT/VMAT plans. However, errors could potentially occur for subsequent fractions. Online treatment monitoring systems may become an important QA tool to safely and accurately deliver complex treatment plans for an error-free treatment delivery. A novel 2D radiation transparent detector located between the patient and the head of the accelerator is presented. It provides a 2D map of measurements on a plane orthogonal to the beam direction. Using the measured 2D fluences, 3D dose distribution on the patient anatomy can be reconstructed. Thus, it can potentially be used for continuous online treatment verification, ensuring the highest level of treatment delivery control.

The dosimetric consequences of intra-fractional motion during IMRT treatments have shown large discrepancies. However, not much is known about the effects of intra-fractional motion during a rotational therapy. A special phantom which simulates a typical breathing motion was implemented for the 4D treatment plan verification. A 2D detector array was placed on it and generated various breathing patterns by the moving phantom. The motion patterns described an exhale-pronounced cosine-to-the-fourth trajectory in cranio-caudal direction with different motion amplitudes (2.5mm, 5mm, 10mm) and different breathing cycle times (3.6s, 6.6s). Cumulative doses with static and motion measurements were recorded. Our results show excellent agreement with a passing rate of ~100% (3%/3mm) for up to 5mm amplitudes. Therefore, with the proposed setup, it is possible to verify 4D treatment plans.

The traditional practice of using the same treatment plan for the entire radiotherapy course can lead to clinically relevant deficiencies. The tumour geometry and location acquired at a single time point may not represent the actual situation during the whole treatment. This is due to inter and intra-fractional organ movements or positioning errors occurring at different fractions. To reduce such deviations, margins are always added around the tumor. However, increased treatment margins result in increased high-dose to the adjacent normal tissues. A novel online adaptive replanning approach based on Cone Beam CT (CBCT) was proposed. An algorithm was developed which can modify the CBCTs by replacing the uncalibrated housfield units (HU) with correct HU obtained from the planning CT. The proposed strategy is intended as an advantage over the practice of mere couch-movement. It introduces a procedure for correction of interfractional target dislocation and deformation for a particular treatment fraction.

In summary, novel comprehensive QA solutions for verification of advanced treatment techniques have been developed and implemented for routine clinical usage. Furthermore, an adaptive radiotherapy strategy was proposed that can pave the way for possible integration into clinical practice, ensuring the safe and precise delivery of complex treatments. The work presented in this thesis could potentially be utilized for exploiting advances in dose verification procedures in order to increase the confidence in delivering complex conformal treatments with highest level of accuracy resulting in substantially reduced toxicity or NTCP (normal tissue complication probability).