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Clinical examples of 3D dose distribution reconstruction, based on the actual MLC leaves movement, for dynamic treatment techniques

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ABSTRACT

Aim: To present practical examples of our new algorithm for reconstruction of 3D dose distribution, based on the actual MLC leaf movement.

Background: DynaLog and RTplan files were used by DDcon software to prepare a new RTplan file for dose distribution reconstruction.

Materials and methods: Four different clinically relevant scenarios were used to assess the feasibility of the proposed new approach: (1) Reconstruction of whole treatment sessions for prostate cancer; (2) Reconstruction of IMRT verification treatment plan; (3) Dose reconstruction in breast cancer; (4) Reconstruction of interrupted arc and complementary plan for an interrupted VMAT treatment session of prostate cancer. The applied reconstruction method was validated by comparing reconstructed and measured fluence maps. For all statistical analysis, the *U* Mann–Whitney test was used.

Results: In the first two and the fourth cases, there were no statistically significant differences between the planned and reconstructed dose distribution ($p = 0.910$, $p = 0.975$, $p = 0.893$, respectively). In the third case the differences were statistically significant ($p = 0.015$). Treatment plan had to be reconstructed.

Conclusion: Developed dose distribution reconstruction algorithm presents a very useful QA tool. It provides means for 3D dose distribution verification in patient volume and allows to evaluate the influence of actual MLC leaf motion on the dose distribution.

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1. Background

Modern radiotherapy takes advantage of the latest developments in technology and informatics to calculate and execute radiation dose distributions according to the highest therapeutic requirements. The radiation dose delivered to the tumor volume should be big enough to destroy cancer cells, while not causing permanent damage to normal tissues. Combination of: (i) multileaf collimators, (ii) accelerator gantry rotation, (iii) dose rate modulation while the beam is on, (iv) precise dose calculation algorithms, and (v) faster computers allows to maximize the therapeutic ratio. One of the tasks of the medical physicist is to verify whether the planned radiation dose is delivered in agreement with previously made calculations. Verification of the radiation dose and its distribution for dynamic treatment techniques presents a rather difficult problem. Although these techniques have been applied for several years, an optimal process of quality assurance (QA) needs to be established.[1,2] In clinical practice, QA methods for in vivo dosimetry for static, CRT (e.g. CRT – Conformal Radio Therapy) techniques, where the shape of the beam does not change continuously during the irradiation, are not suitable for dynamic treatment techniques.[3] Currently, the most common verification method of the calculated dose distribution for dynamic treatment techniques are fluence maps and in-phantom dose distribution measurements before treatment.[4] These measurements utilize: (i) water-equivalent phantom with ionization chamber, (ii) matrix of ionization chambers, or (iii) matrix of semiconductor dosimeters. For example, the latter can be part of an accelerator (e.g. EPID – Electronic Portal Imaging Device, VMS – Varian Medical Systems). Of course, the measurements are made in phantom and do not involve patient. Using an EPID device and Varian Treatment Planning System (TPS) there is possibility to measure fluence maps and compare them with those previously calculated by TPS. For evaluation of the difference between calculated and measured values, gamma index is commonly used. As it is rather difficult to define globally acceptable discrepancies between planned and measured fluence maps, each center must develop its individual standards. Then, one has to identify the proper solution and find out where the difference between the planned and measured fluence maps exceeds the acceptable level. It is known that the accuracy of a fluence map might be affected by many parameters, including dose rate[5] and the optimizing indices value. If the discrepancy between planned and measured fluence maps is unacceptable, a new treatment plan must be prepared.[6,7] At the Maria Skłodowska-Curie Memorial Cancer Center and Institute of Oncology in Gliwice, IMRT (Intensity Modulated Radiation Therapy) and VMAT (Volumetric Modulated Arc Therapy) techniques have been used in clinical practice since 2000 and 2009, respectively. Our experience shows that re-planning is a very time-consuming procedure, which often does not produce the desired results. Therefore, there is a pressing need for other methods to verify compliance of the planned and realized dose distributions. We postulate that data stored in DynaLog files could be used to reconstruct dose distribution not only in the phantom,[8] but also in patient's body after every treatment fraction. Varian log files are generated by Multileaf Collimator (MLC) controller during the performance of dynamic treatment technique.

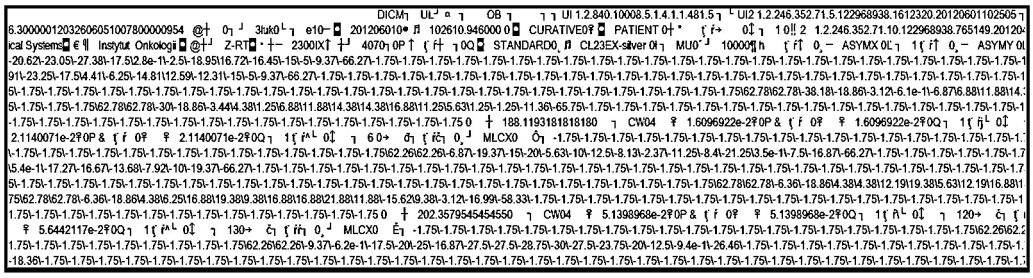
2. Aim

The aim of the work was to present practical examples of our new algorithm for 3D dose distribution reconstruction based on the actual MLC leaf movement.

3. Materials and methods

TPS Eclipse 10 VMS was used for all dose distribution calculations. All measurements were carried out using Varian Clinac 23 EX with Millenium 120 collimator and OBI (e.g. OBI – On-Board Imager) system.

Following is the description of the applied procedures. During the treatment session, for every single field (IMRT) or arc (VMAT) MLC controller generates two DynaLog files in ASCI format for each MLC bank separately. The DynaLog data are taken every 50 ms. The stored information includes: fraction dose, tolerance, beam on state, beam hold-off state, gantry and collimator rotation, jaws positions, and the position of each leaf.[9] During the optimization of dynamic treatment plan, optimal fluence maps are calculated to simulate different beamlet intensity of the field. After completing the optimization process, the system generates DVHs (Dose Volume Histograms – dependence graphs of dose and structure volume) that describe optimal dose distribution. However, oftentimes it is impossible to generate optimal fluence maps on an accelerator and it is necessary to recalculate the leaf movement and convert them to actual fluence maps, which are the basis for 3D dose calculations. Therefore, DVHs generated after calculation of 3D dose distribution differ from the previously accepted ones during the optimization process. Actual fluence maps are different from optimal ones because they consider mechanical limitations of MLC. The differences may increase if the differences between values of the optimization indices are grater or the discrepancies between point doses placed close from each other differ significantly.[10,11] The final treatment plan is stored in the database as RTplan DICOM file to allow its execution on the accelerator. The stored RTplan file contains patient personal data, treatment plan data, information about every field or arc, including leaf position, gantry angle, dose rate, dose, etc. The leaf movement during the treatment is continuous but since the system cannot store all leaf positions in RTplan file, all leaf positions are stored in a discrete manner as control points. During the treatment realization, MLC controller linearly interpolates positions between those control points. The new idea of dose reconstruction is very simple. If the DynaLog files collected during therapy are available and RTplan file can be exported from the treatment planning system, it is possible to create a new RTplan file by changing the planned leaf positions and the gantry position (only for VMAT) in the RTplan file using the data collected in DynaLog files. New RTplan DICOM file can be then imported back to TPS. After obtaining (recalculating) a new (reconstructed) plan, the system will generate a corresponding 3D dose distribution but, this time, it will be the real dose distribution delivered for patient during treatment session.



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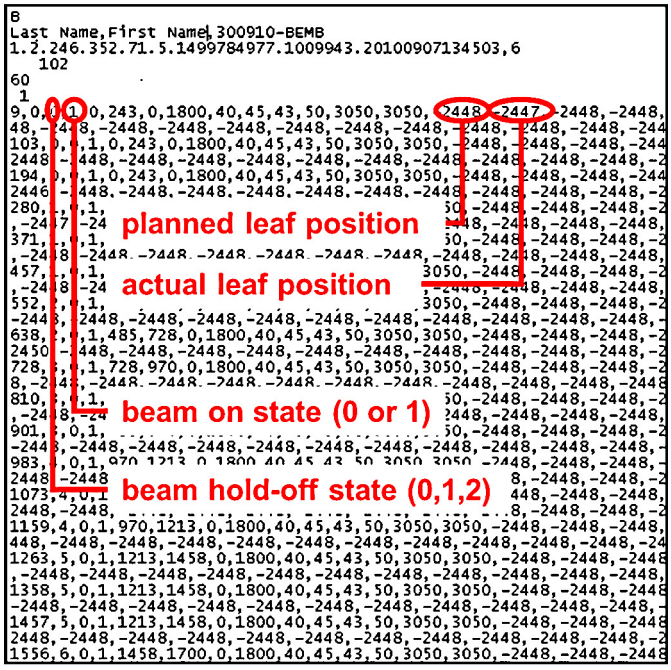

B

Fig. 1 – (A) A part of RTplan DICOM file, (B) a part of DynaLog file.

Thereby, we can assess the real reconstruction of delivered dose distribution, which can be compared with theoretical one in TPS.

The first step in the reconstruction algorithm was to deal with DynaLog files. According to Varian documentation,[9] the MLC controller stores DynaLog data in a temporary buffer. Each loading a new dynamic treatment, the MLC controller overwrites the DynaLog data from the previous treatment. So, for a finished treatment, the DynaLog data are no longer available. To prevent these data from being lost, the auto-save option must be turned on to save all DynaLog files. Because of the limited disk space on the local station, all files have to

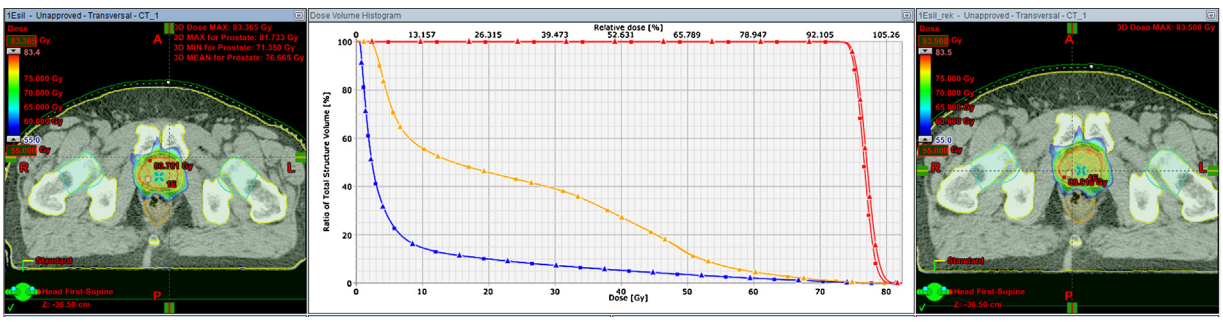

Fig. 2 – The theoretical (left side) and reconstructed (right side) dose distribution for treatment plan prepared for the VMAT technique. Dose reconstruction was made for 38 treatment fractions. The DVH graphs show dose distributions for PTV (red), rectum (orange) and bladder (blue). The differences between the theoretical and reconstructed dose distributions are in the margin of calculation error.

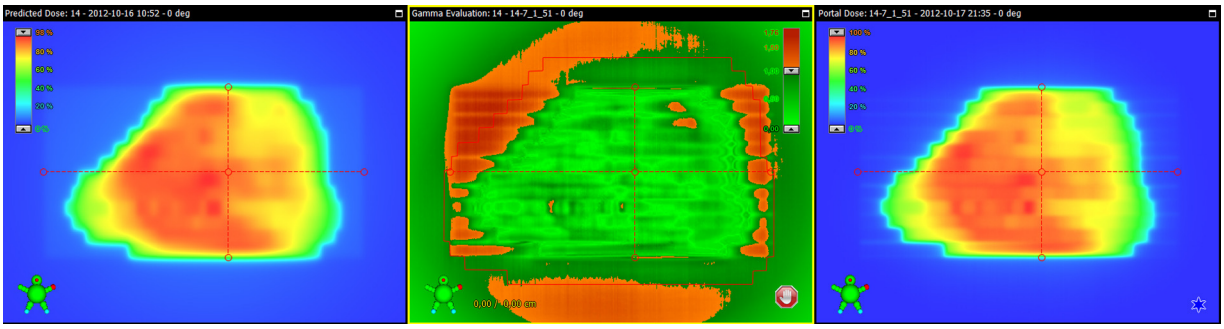

Fig. 3 – An example of the evaluation of the measured (right side) and planned (left side) fluence maps comparison. Gamma index is less than one in 84.8% of the analyzed points of the treatment field. It means that the evaluation is negative and measurement should be repeated. If re-measurement is not satisfactory, then the plan will have to be re-optimized and the verification procedure repeated.

be transferred from the local station to another one having a greater disk capacity. To perform this operation, synchronized software was used.

In the second step, we used Delphi v 5.0 programming language to develop special software, called DDcon, to convert DynaLog files to RTplan DICOM file accepted by TPS Eclipse v 10. Fig. 1 shows examples of RTplan DICOM file and DynaLog file.

DDcon software generates a new RTplan file by changing the planned leaf positions and the gantry position (only for VMAT) in a RTplan file by the data collected in DynaLog files. Then, a new RTplan DICOM file can be imported back to TPS. After recalculating a new (reconstructed) plan, the system will generate 3D dose distributions delivered to the patient during the treatment session.

To compare the reconstructed plan with the calculated dose distribution, DVHs and RPI factor (Radiation Planning Index)[12] were used. RPI is a formula used to compare different treatment plans for one patient. It takes in to account the relation between dose distribution calculated for planning treatment volumes and organs at risk. The comparison of theoretical fluence maps to those generated during reconstruction was performed to assess the level of treatment precision. To evaluate the compared fluence maps, gamma index was used (3% and 2 mm). To verify correct operation of the reconstruction algorithm, fluence maps from the reconstructed plan were compared with the measured ones. For this purpose, we developed a verification algorithm involving the following steps: (1) creating a treatment plan (dose distribution) for a patient, (2) creating a verification plan (VerPlan) of the previously created treatment plan, (3) performing measurements of VerPlan using EPID matrix (collecting fluence maps and DynaLog files for every treatment field or arc), (4) dose distribution reconstruction (DDcon software), based on actual leaf movements (previously collected DynaLog files), (5) crating a verification plan from the reconstructed one (VerRec) to gain access to the reconstructed fluence maps, (6) exporting the measured fluence maps from VerPlan verification plan and importing them to VerRec verification plan, (7) comparison of the reconstructed and measured fluence maps.

Measuring fluence maps using EPID matirx is one of the standard QA methods in radiotherapy.[13] In-phantom measurements are obtained before the first treatment session. The aim of this method is to compare the calculated (theoretical) fluence maps with the measured (actual) ones. To prepare a special QA plan for verifications, the "Create Verification Plan" option in TPS-Eclipse must be used. Evaluation of the theoretical and measured fluence maps comparison is positive when the gamma index is less than one in 95% of the analyzed points of the treatment field. All analyses are made using the 'Portal Dosimetry' application. If the evaluation result is negative, the measurement has to be repeated. If re-measurement is not satisfactory, the plan has to be re-optimized and the verification procedure repeated. This procedure is time

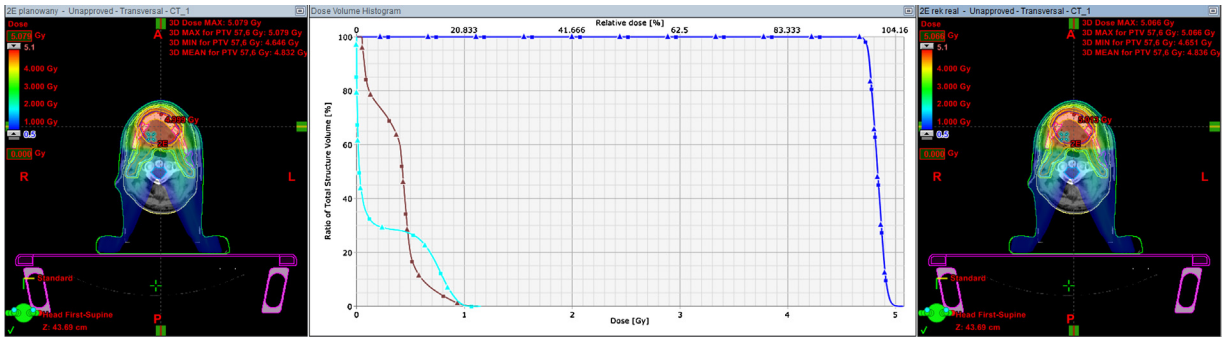

Fig. 4 – Planned (left side) and reconstructed (right side) dose distributions. DVHs show that the dose distributions for PTV (dark blue), spinal canal (cyan), and brainstem (brown) are within the margin of calculation error.

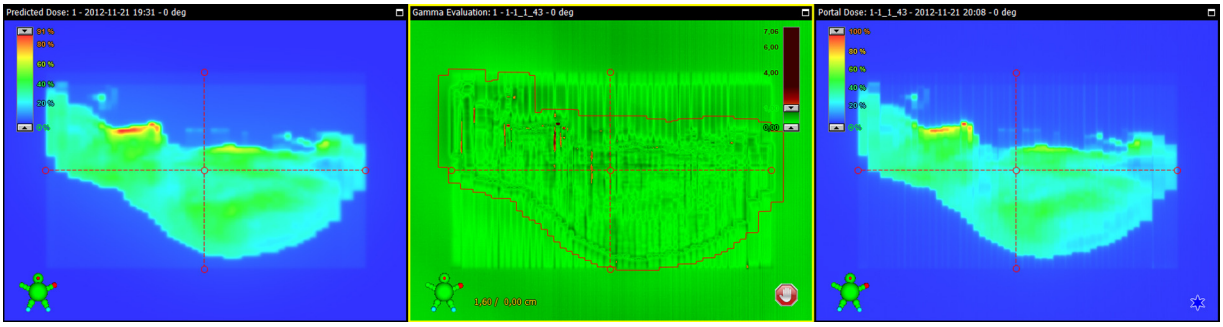

Fig. 5 – Evaluation of the measured (right side) and planned (left side) fluence maps comparison for one treatment field. Maximum gamma index for that field was 6.74. The evaluation was negative.

consuming and sometimes leads to a delay or interruption of the treatment. Therefore, the reconstruction procedure, based on actual leaf positions, might present an attractive, less time-consuming solution. After the calculations are completed, the real 3D dose distribution is compared with the theoretical one using DVH's or RPI index. If the evaluation meets our expectations, then treatment can be started.

To assess the feasibility of the proposed method, dose reconstructions were performed for the following four cases.

The first case involved the reconstruction of VMAT treatment plan for all treatment fractions. The treatment plan was prepared for a prostate cancer patient and it consisted of one 360-degree arc. The total dose was 76 Gy, delivered in 38 2-Gy fractions.

The second case involved the reconstruction of head&neck IMRT verification treatment plan. The measurements were performed before the treatment using EPID matrix.

The third case involved dose reconstruction in breast cancer. It was planned to deliver 50 Gy in 2-Gy fractions for PTV (Planning Treatment Volume), 60 Gy (+10 Gy) for PTV-boost and 60 Gy in axillary and supraclavicular lymph nodes. The treatment was planned for the IMRT technique. To verify the quality of the treatment plan, EPID matrix was used. The measurements were performed before treatment.

The fourth case involved an interrupted VMAT treatment plan consisting of one 340-degree arc. The treatment volume was the prostate and the fraction dose was 2 Gy (441 MU). A complementary treatment plan for a missing arc was prepared using: DynaLog files for the incomplete arc, theoretical RTplan from TPS and DDcon software.

The statistical analyses were based on reconstructed and theoretical treatment plans DVHs exported from the TPS. All analyses were made using STATISTICA v.10 software. For all analyses, non-parametric U Mann–Whitney test for two independent samples with $p = 0.05$ was used.

4. Results and discussion

The first case: dose reconstruction for all executed treatment fractions of VMAT treatment plan. Fig. 2 shows the theoretical and reconstructed (executed) dose distributions and DVH graphs for PTV, the rectum, and bladder structures. Calculated RPI index values for the theoretical and reconstructed dose distributions were 0.13415 and 0.13275, respectively. It means that the difference between the two plans was not significant. The theoretical and reconstructed differential DVHs were compared. Statistical analysis showed that there were no statistically significant differences ($p = 0.910$) between the theoretical and reconstructed dose distributions.

The second case: reconstruction based on actual leave motion of head&neck IMRT verification treatment plan.

Measured and calculated fluence maps were compared using "Portal dosimetry" application (Fig. 3). Treatment can be started only when the evaluation of fluence maps comparison is positive. In the analyzed example, the evaluation of the measured and calculated fluence maps comparison was negative for 2 of 7 treatment fields. In this case, dose reconstruction based on actual leaf positions was made. Fig. 4 shows that the planned and reconstructed dose distributions were

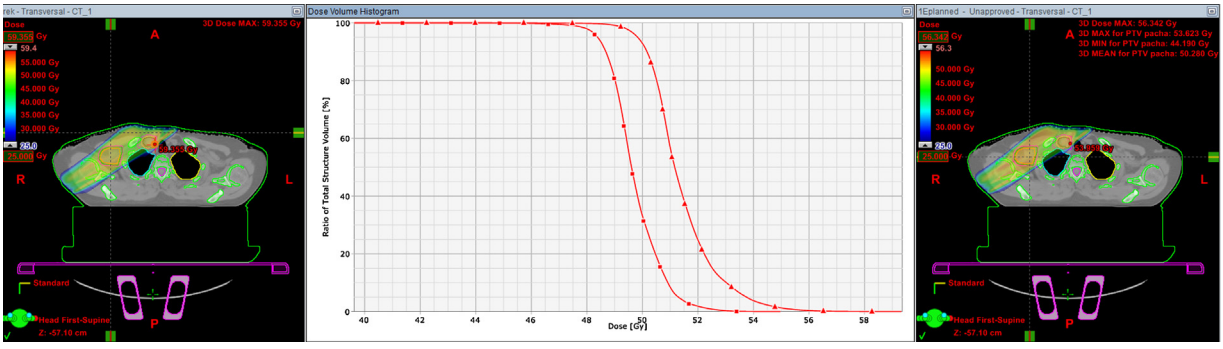

Fig. 6 – Maximum dose in the reconstructed dose distribution (left side) is 4.37 Gy greater than that in the planned one (right side). DVH shows the differences between the planned and reconstructed dose distributions for PTV (upper clavicle region).

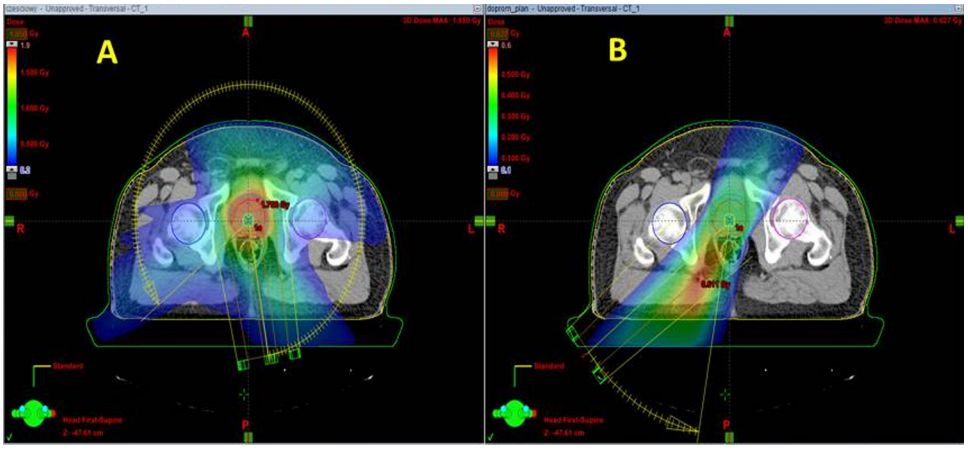

Fig. 7 – The reconstructed dose distribution for the interrupted arc of 297.8° (A) and the complementary arc of 42.2° (B). For both cases, the dose distributions are shown in lateral, frontal and sagittal slices.

consistent within the calculation error of 1.5%. The maximal planned and reconstructed doses for PTV were 5.079 Gy and 5.066 Gy, respectively. The planned total dose in the isocenter was 4.8 Gy, delivered in three 1.6-Gy fractions. Considering the dose distributions for PTV, the spinal canal and brainstem RPI index for the planned and reconstructed dose distribution was 0.77153 and 0.77149, respectively, indicating no significant differences between both treatment plans. The theoretical and reconstructed differential DVHs were also compared. Statistical analysis showed no statistically significant differences ($p = 0.975$) between the theoretical and reconstructed dose distributions.

The third case: dose reconstruction in breast cancer. The treatment was planned for the IMRT technique. To verify the quality of the treatment plan, EPID matrix was used. The measurements were performed before treatment. The evaluation of the measured and calculated fluence maps comparison was negative for 3 of 7 treatment fields. Fig. 5 shows the measured and planned fluence maps for one of the treatment fields. As one can see, there are a few large point differences between the planned and measured fluence maps. The maximum gamma index for that field was 6.74. According to the routine approach, this treatment plan should be measured once again. The proposed dose distribution reconstruction method, based on actual leaf movement, allows checking whether the differences visible on the fluence maps comparison have an influence on the dose distribution.

Fig. 6 shows the planned and reconstructed dose distributions. As one can see, the maximum dose for PTV (upper clavicle region) in the reconstructed dose distribution is 4.37 Gy greater than that in the planned one.

This result indicated that, because of big differences between the planned and reconstructed dose distributions for PTV volume, another verification measurement was unnecessary. Statistical analysis showed that there was a statistically significant ($p = 0.015$) difference between the planned and reconstructed dose distributions for PTV (upper clavicle region) volume. Therefore, the treatment plan had to be reconstructed.

Fourth case: dose reconstruction of interrupted fraction in the VMAT treatment technique. The treatment plan consisted of one 340-degree arc. During one of the treatment sessions, after 297.8° (381 from 441 MUs), an error occurred and the beam was off. There were some problems with MLC equipment and treatment could not be continued. Fig. 7 shows the reconstructed dose distribution for the interrupted arc

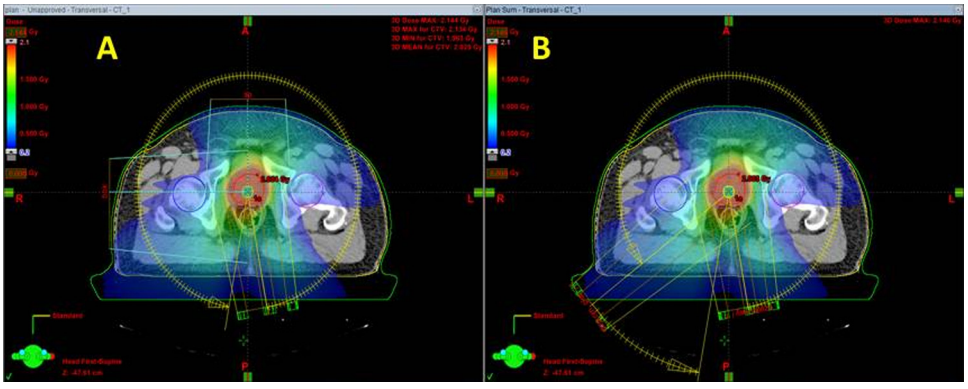

Fig. 8 – Comparison of the planned dose distribution (A) with the planned sum of reconstructed combination of interrupted and missing arc (B).

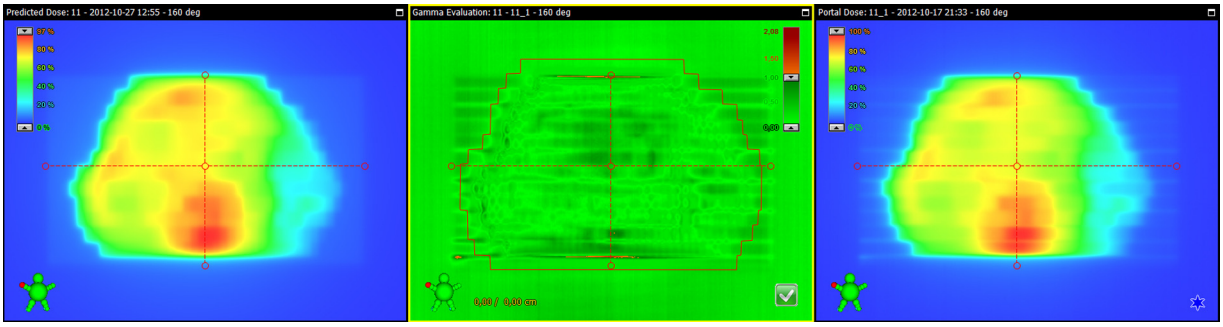

Fig. 9 – Comparison of the measured (right side) and reconstructed (left side) fluence maps. Gamma index (3%, 2 mm) was less than one in 99.6% of the analyzed points of the treatment field.

(reconstruction based on actual leaf motion) and the dose distribution for the complementary arc (42.2 degrees arc, 60 MU).

Sum of the interrupted (delivered) and missing arc was compared with the original (theoretical) full arc. Comparison of both dose distributions is shown in Fig. 8. Reconstruction of the dose distribution for the interrupted arc allowed to calculate the delivered dose of 1.628 Gy. To receive the total fraction dose of 2 Gy, 0.372 Gy was missing. This information was crucial for the treatment planning and treatment delivery. The maximum planned and reconstructed dose for CTV was 2.134 Gy and 2.136 Gy, respectively. The difference was acceptably small.

Statistical analysis showed no statistically significant difference ($p = 0.893$) between the planned and reconstructed dose distributions.

According to the presented verification method (see Section 3), the reconstructed and measured fluence maps were compared for all fields and arcs in the first three cases. For the fourth one, there was no measured fluence map during the interrupted session, so analyses were not possible. Fig. 9 shows an example of the fluence map comparison for one of the analyzed fields. As one can see, there is very good agreement between the reconstructed and measured fluence maps.

M. Dinesh Kumar[8] presented a similar reconstruction method, but with the use of a phantom and for the IMRT technique only. New algorithm, developed in our center, allows to reconstruct not only IMRT but also the VMAT technique, including interrupted arcs. All analyses and calculations showed that the presented reconstruction method might be very useful for evaluation of the treatment plan delivery (IMRT and VMAT). It can also be applied to evaluate the influence of discrepancies between the planned and actual MLC leaf motion on the dose distribution. This very comfortable verification method can be used before, during or after treatment to evaluate the whole treatment process by reconstructing any treatment fraction. In addition, it is extremely useful in situations when delivery of the dose was interrupted. This software provides means not only to reconstruct an interrupted VMAT treatment, but also to generate a complementary treatment plan.

A separate issue in dose distribution reconstruction is the CT (Computed Tomography) scans used for the reconstruction.[14,15] In the presented method, the reconstruction is performed using CT scans made before treatment, so no anatomical changes are considered. The next step to improve this reconstruction method will require inclusion of those changes into the calculation process, using CBCT (Cone Beam Computed Tomography) scans that are obtained during the treatment session. However, the quality of CBCT images is still insufficient, which affects the calculated dose distributions and leads to significant inaccuracy. Our experience is consistent with J. Qian findings.[16] As the quality of CBCT scans continuously improves, it might be possible to use them for this purpose in the foreseeable future.

5. Conclusions

Using four different scenarios, we showed that our dose distribution reconstruction algorithm, based on actual MLC leaf motion, presents a very useful tool for radiotherapy QA procedures. It provides means to verify 3D dose distribution in the patient and allows to evaluate the influence of actual MLC leaf motion on the dose distribution. It should be emphasized that one have to remember about the dose and MLC calibrations to prepare linac for IMRT and VMAT deliveries.

Conflict of interest

None declared.

Financial disclosure

None declared.

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