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Beam rate influence on dose distribution and fluence map in IMRT dynamic technique

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ABSTRACT

Aim: To examine the impact of beam rate on dose distribution in IMRT plans and then to evaluate agreement of calculated and measured dose distributions for various beam rate values.

Background: Accelerators used in radiotherapy utilize some beam rate modes which can shorten irradiation time and thus reduce ability of patient movement during a treatment session. This aspect should be considered in high conformal dynamic techniques.

Materials and methods: Dose calculation was done for two different beam rates (100 MU/min and 600 MU/min) in an IMRT plan. For both, a comparison of Radiation Planning Index (RPI) and MU was conducted. Secondly, the comparison of optimal fluence maps and corresponding actual fluence maps was done. Next, actual fluence maps were measured and compared with the calculated ones. Gamma index was used for that assessment. Additionally, positions of each leaf of the MLC were controlled by home made software.

Results: Dose distribution obtained for lower beam rates was slightly better than for higher beam rates in terms of target coverage and risk structure protection. Lower numbers of MUs were achieved in 100 MU/min plans than in 600 MU/min plans. Actual fluence maps converted from optimal ones demonstrated more similarity in 100 MU/min plans. Better conformity of the measured maps to the calculated ones was obtained when a lower beam rate was applied. However, these differences were small. No correlation was found between quality of fluence map conversion and leaf motion accuracy.

Conclusion: Execution of dynamic techniques is dependent on beam rate. However, these differences are minor. Analysis shows a slight superiority of a lower beam rate. It does not significantly affect treatment accuracy.

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1. Background

Medical accelerators (Clinacs – Varian Medical Systems, Palo Alto, CA, USA) used at Radiotherapy Department, Center of Oncology – Institute in Gliwice enable the use of a sliding window IMRT delivery method.[1,2] These accelerators utilize several beam rates, which correlate with dose rates. In this investigation we distinguish two terms: dose rate and beam rate. Dose rate measurements are carried out in precisely defined conditions (depth in water, source-phantom surface distance, field size), according to international recommendations and reports. If dose rate measured in standard conditions equals 1 Gy/min and measurement is made for 100 MU/min beam rate (MUs, monitor units), then during 1 min the dose of 1 Gy is delivered. There are following beam rates available for Varian accelerators: 100, 200, 300, 400, 500, 600 MU/min, ranging from 1 up to 6 Gy/min. Nowadays, the beam rate of 300 MU/min is routinely applied.[2]

Selection of different beam rates does not affect dose distribution in non-dynamic techniques. Field sizes in static techniques are constant and beam rate changes do not cause meaningful changes in dose distribution calculated in computer treatment planning systems. The situation is disparate in dynamic techniques where field sizes are changed during a treatment session. Dose distribution calculated in a treatment planning system (TPS) and presented on CT scans are not visibly different when using various beam rates. However, some fine differences can be found on dose–volume histograms (DVHs).[1,3] In IMRT technique field size is a function of time, therefore, beam rate and dose distribution dependence becomes more complicated. In everyday radiotherapy, dynamic techniques are more and more often used.[4,5] Dynamic techniques are applied either as a self-contained or supplement therapy.[1] In dynamic techniques such as IMRT, the number of MUs is higher than in other conformal but static techniques because treatment field is the sum of smaller component segments. Consequently, in dynamic techniques treatment session time is longer.[3] It is known that a longer treatment time can cause patient repositioning or movement during a therapeutic session.[3] Therefore, treatment time shortening seems to be a good approach to avoid undesired patient movements. It can be achieved by beam rate increase. However, there is not enough data in the literature concerning the influence of beam rate on dose distribution and radiotherapy accuracy.

2. Aim

The aim of the study was to evaluate beam rate influence on dose distribution, calculated in treatment planning system and its execution during treatment session for two beam rates: 100 MU/min and 600 MU/min.

3. Materials and methods

In order to calculate IMRT dose distribution, Eclipse-Helios v. 8.6 (Varian Medical Systems, Palo Alto, CA, USA) TPS was utilized. Dose calculations were made for 11 patients with prostate cancer. All plans were calculated for two beam rates: 100 MU/min and 600 MU/min. Dose distributions were calculated with AAA v.8.6.14 algorithm,[6] for the same X-20MV beam arrangement and optimization parameters, closing optimization and reaching a plateau after the same time. The only difference between both plans was in beam rate.

It may be debatable whether to perform two optimization processes – the one for 100 MU/min and the other one for 600 MU/min. The authors applied separate calculations for different beam rates from the beginning of the planning process, while preserving the number and arrangement of the beams, dose–volume constraints and number of iterations. This methodological approach differs from the other one that uses one optimization with one set of fluence maps and two dose distribution calculations for different beam rates. Obtaining the same results for all cases examined and described later in this work, allows us to argue that the differences arise only from the use of two different beam rates thus confirming the correctness of the methodology adopted.

For both beam rates the following properties were compared:

- dose distribution with the help of Radiation Planning Index (RPI) computed with a self-made software,[7]
- number of MUs per treatment plan,
- optimal and actual fluence maps calculated in TPS, on the base of gamma index calculated in OmniPro-I'm*RT* software (IBA, Uppsala, Sweden),
- actual fluence maps calculated in TPS and measured with the electronic portal imaging device (EPID) by the mean of gamma indices calculated with the Eclipse Portal Dosimetry application,
- precision of dose delivery by leaves position monitoring done with a self-made software MLCtracker.

3.1. *Comparison of dose distributions*

Dose distribution differences presented in the form of isodoses are often unclear particularly when differences between two plans are small. It is difficult to indicate the best plan, considering both dose to target and organs at risk. Very helpful in such cases are all sorts of evaluation factors and dose–volume histograms (DVHs) allowing to compare dose distribution in selected volumes in a more exact way.[1,3]

RPI is a plan evaluation coefficient, which takes into account a dose–volume graph calculated for selected structures. On this basis, integral doses of organs at risk and tumor volumes are analyzed. It also enables to assign specific weights to structures and to diversify their importance. DVHs calculated in TPS for selected structures are exported and used for RPI calculation. The value of RPI is within the 0–1 range. The value of 1 is reported by the software for the ideal plan.[7] In computation, the following structures were taken into account as organs at risk: bladder, rectum, and femoral heads. Tumor volumes and possibly seminal vesicles with appropriate margins (GTV, CTV, PTV) were considered as target volumes. This analysis evaluates which of the plans, 100 MU/min or 600 MU/min, is better as regards target

coverage and organs at risk protection at the same time. For both types of plans, the average RPI was calculated.

3.2. Comparison of MUs

For both beam rates the number of beams and their arrangement were kept. Calculations of dose distributions and MUs were done with the same optimization criteria, i.e. dose–volume objectives, priorities defined for the structures and equal time of optimization represented by number of iterations.[1–3]

It is expected that in the course of optimization different total numbers of MUs per plan can be obtained for different beam rates.

3.3. Comparison between optimal and actual fluence maps

The congruity between the optimal and the actual fluence was assessed with gamma index using the OmniPro-I'mRT software. Pairs of fluence maps were exported from TPS. The criteria of 3% of the maximum dose difference and 2 mm dose-to-agreement (DTA) were used. Optimal fluence map was the reference one. When the criteria were fulfilled the gamma index was smaller than 1 and doses in the analyzed points agreed.[8,9] This statement is true in the case of one selected point. However, in practice, dose assessment at multiple points of a fluence map is necessary. Such evaluation is usually done in several ways. Let us consider the two quantities: the average gamma index and the percentage or number of points for which the criteria are met. The second quantity describes well the compatibility of maps but does not provide information on the location of non-compliance. The first tool is not a perfect one, either. If the average gamma is less than one, full compatibility of the maps is actually excluded. There are certainly points of dose non-compliance. It should be noted that the average gamma value lower than one is possible even with some points not meeting the criteria. Although, it can be concluded that a lower average gamma value indicates a better match of maps than the higher value. In this paper, an average gamma value was chosen to analyze the fluence maps and further on the term gamma index will be used to mean the average gamma index.

Optimal fluence maps are ideal fluence maps estimated initially by the iteration process in TPS. They meet the optimal dose–volume objectives contained in the inverse planning algorithm. Optimal fluence map is then converted into an actual fluence map by a Leaf Motion Calculator (LMC). Actual fluence maps take into account leaf motion speed limits and treatment delivery method. These maps are realized finally on accelerators.[1,2]

This part of the study attempts at establishing whether beam rate in the treatment plan has an effect on the fluence map conversion. In theory, a lower gamma index value indicates an exact fluence map conversion and, accordingly, a higher gamma index value demonstrates bigger differences between optimal and actual fluence maps.

3.4. Comparison between calculated actual fluence maps and measured actual fluence maps

Additionally, for every treatment plan calculated for both beam rates, the verification plan was prepared, using the Portal Dosimetry option of Eclipse TPS. Verification plans contain predicted actual fluence maps, which are dose matrix, calculated in a given Source-Detector Distance. Fluence maps were measured by aS1000 EPID for both beam rates and registered.[8–13] All measurements were performed on one accelerator with one MLC. For gamma index calculation, 3% dose difference and 2 mm DTA were used. The calculated fluence map was used as reference. It is believed that gamma evaluation method is able to provide information about the quality of irradiation. Its value corresponds to the quality of treatment delivery.

Gamma index was calculated in the surface area equal to the rectangular treatment field extended by 1 cm around treatment field sizes. This area covers part of portal detectors covering the treatment field, so it shows how the dose is deposited within the treatment field. In the study, the gamma index calculated in a limited area is denoted by GI_{+1}. In this part of the study, different nomenclature for gamma index was used to make a clear distinction between this calculation and the one in Section 3.3.

3.5. Comparison of leaf motion

MLCtracker is a self-made software, deriving leaf motion details from DynaLog files containing, among other data, MLC details.[14–16] It allows to read out leaf position every 50 ms and to analyze inaccuracy in MLC motion for bank A and B, separately. Predictable pattern of leaf position, changeable over time, is compared with the actual one. For calculation of total leaf movement deviation, the root mean square is used. The error values of leaf positions are a function of the number of leaves. Then, MLCtracker calculates relative surface under the curved line. Ultimately, an aggregate value is calculated for both banks and marked as a relative integral. The value of the relative integral represents inaccuracy in every motion of a pair of leaves. The work of all pairs of leaves is analyzed, even leaves outside treatment field are considered. In this study, the software serves for analysis of leaves' precision for both beam rates. Utilization of different beam rates in treatment fields can be an important factor in discussion of accuracy in treatment delivery.

4. Results

4.1. Comparison of dose distribution

Analysis of RPI indicates that there is no significant difference between its values calculated for 100 MU/min and 600 MU/min, separately. Although 100 MU/min plans are characterized by higher RPI values for every patient. The average value for 100 MU/min is 0.525 while for 600 MU/min it is 0.522. Average RPI values calculated for every patient separately are shown in Fig. 1.

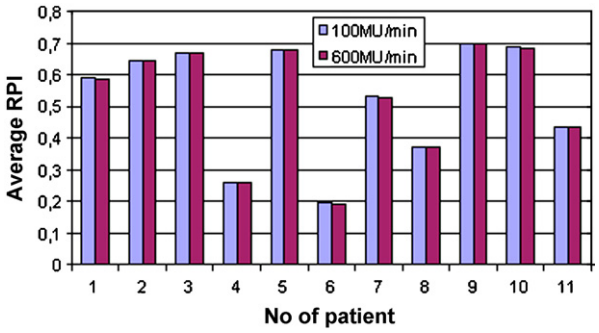

Fig. 1 – Comparison of average RPI value calculated for plans with 100 MU/min and 600 MU/min beam rate. For most cases average RPI value is higher in 100 MU/min than in 600 MU/min plans, what means better dose distribution in plans with lower beam rate.

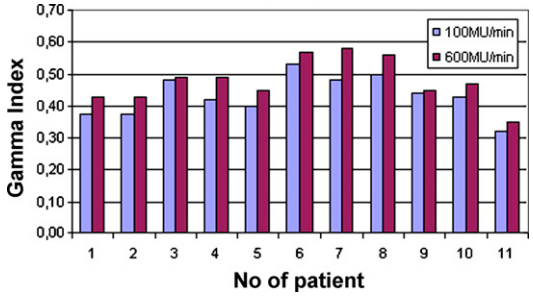

Fig. 3 – Optimal fluence maps vs. actual fluence maps. Comparison of gamma index calculated for plans with 100 MU/min and 600 MU/min beam rate. Lower gamma index value indicates better congruity of optimal and actual fluence maps. For all cases lower gamma index for 100 MU/min was achieved.

4.2. *Comparison of MUs*

In both types of plans total number of MUs differed clearly. For 100 MU/min plans, the average total MU number is 594 while for 600 MU/min the average total number of MU is higher and equals 740. Numbers of MUs calculated for both beam rates and for all patients are presented in Fig. 2.

4.3. *Comparison between optimal and actual fluence maps*

The comparison between optimal and actual fluence maps shows that the gamma index values are lower for 100 MU/min than for 600 MU/min. The minimum gamma value is lower for 100 MU/min (0.28 vs. 0.31) and the same trend is visible for the maximum value (0.59 vs. 0.67), the average value (0.43 vs. 0.48) and the median value (0.42 vs. 0.47). Standard deviations are respectively: 0.08 and 0.09. Thus, average gamma calculated to assess accuracy of fluence map conversion indicates better results for lower beam rate. Gamma indices calculated for every patient are shown in Fig. 3.

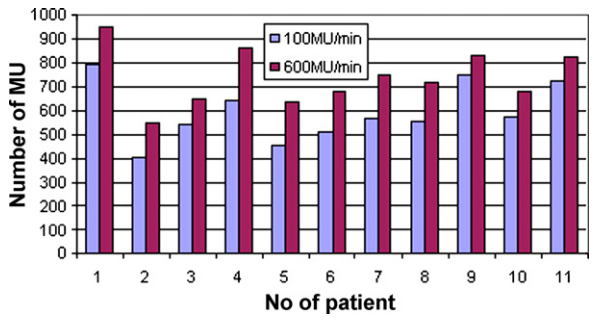

Fig. 2 – Comparison of number of monitor units (MUs) calculated in 100 MU/min and 600 MU/min plans. For all cases lower MU number is achieved in 100 MU/min plans than in 600 MU/min plans.

4.4. *Comparison between calculated actual fluence maps and measured actual fluence maps*

Differences between the predicted actual maps and the measured actual maps were evaluated with the gamma index. The GI_{+1} parameter calculated for two beam rates shows better results for 100 MU/min than for 600 MU/min. The gamma index values calculated from all treatment fields in the described area are as follows: minimum – 0.42 vs. 0.45, maximum – 0.57 vs. 0.65, median – 0.42 vs. 0.46, average – 0.42 vs. 0.45 and standard deviation – 0.06 vs. 0.07. Fig. 4 represents comparison of GI_{+1} calculated for both beam rates.

4.5. *Comparison of leaf motion*

Accuracy of leaf motion was evaluated by comparing calculated and actually reached leaf positions. It was found that there is a correlation between beam rate and leaf motion accuracy. Better compatibility of calculated and actual leaf positions was represented in all plans with 100 MU/min beam rate. Results achieved for both beam rates are presented in Fig. 5.

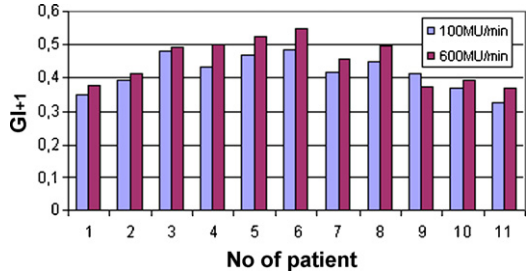

Fig. 4 – Calculated vs. measured actual fluence maps. Comparison of gamma index (GI_{+1}) calculated for 100 MU/min and 600 MU/min in area limited to treatment field plus 1 cm. Lower gamma index value indicates better congruity of calculated and measured actual fluence maps. For all cases lower value of GI_{+1} for 100 MU/min was obtained.

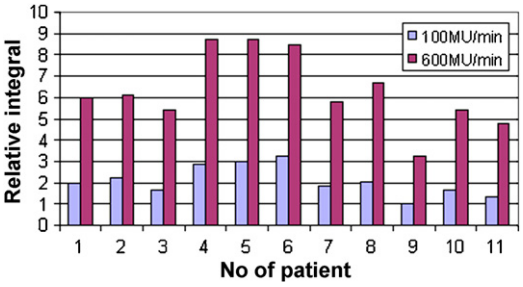

Fig. 5 – Comparison of summary leaves position inaccuracy detected for 100 MU/min and 600 MU/min beam rates. Leaves position error is expressed by sum of integrals calculated for root mean square curve and named relative integral. For all cases bigger error occurs in 600 MU/min plans.

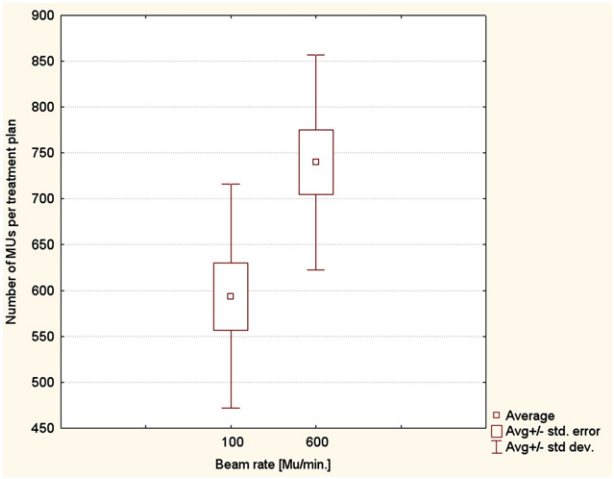

Fig. 7 – Changes of total number of monitor units (MUs) per treatment plan with the beam rate.

5. Discussion

Similar dynamic IMRT plans can be obtained with different beam rates, correlating with given dose rates. Different accelerator modes thus help deliver dose with different beam rates in a shorter or longer time. However, analysis of several values let us observe some differences in treatment plans. Generally, favorable dose distribution, assessed with RPI, was found in plans with a lower beam rate (0.525 vs. 0.522 in Fig. 6). But it cannot be claimed that the usage of a higher beam rate leads to unacceptable dose distribution. Differences between dose distributions are subtle, but are in favor of lower beam rates for all analyzed cases ($p = 0.0033$, Wilcoxon Test).

When analyzing the total treatment time expressed by the number of MUs, it was shown that average number of MUs per fraction is lower for 100 MU/min beam rate (594 MU) than for 600 MU/min (740 MU) ($p = 0.0022$, Wilcoxon Test). The comparison is shown in Fig. 7. The minimum and maximum numbers of MUs for the 100 MU/min plans were respectively 26% and 16%, and were lower than for the 600 MU/min plans. Similarly, the average and median numbers of MUs were respectively 20% and 21% and were lower for 100 MU/min plans. Another study has also examined the effect of altering dose rates from 100 MU/min to 600 MU/min on the number of monitor units.[17] The results demonstrated the same tendency, i.e. the higher the dose rate the higher the number of MUs.

However, treatment time expressed in minutes equaled about 1.2 min for 600 MU/min and was shorter than treatment time for 100 MU/min, which equaled almost 6 min per fraction. Our conclusions coincide with those of the above mentioned study.[17] This aspect should be considered for the sake of treatment accuracy. Longer treatment time can cause significant patient mobility and thus worsen irradiation precision.[17] Possible patient motions implicate dose delivery problems. This may result in unintended tumor underdosage or overdosage in organ at risk volumes. Frequent patient imaging during treatment would reduce such problems.[18–21] But common imaging procedures for patient setup are carried out before beam on. In practice, intrafraction patient repositioning is very rarely performed. This may not be sufficient to ensure an accurate treatment. Therefore, it should also be discussed if favorable dose distribution in the treatment plan (obtained with longer treatment time calculated in TPS) outweighs the gains of a shorter overall treatment session. On the other hand, extensive and long-term procedures would also result in longer total treatment time. On line correction prolongs the irradiation procedure.[18,19] As well known, longer treatment delivery can cause more frequent patient motions and higher probability of complications.

With regard to gamma indices calculated in the OmniPro-I'mRT software for comparison of optimal and actual fluence maps, it was shown that beam rate influences conversion accuracy. The converted fluence maps were in a better agreement with calculated ones for 100 MU/min (mean gamma index value equals 0.43) than for 600 MU/min beam rate (mean gamma index value equals 0.48). The results were statistically significant ($p < 0.05$, Wilcoxon Test).

Therefore, another question arises of whether conversion accuracy is correlated with treatment accuracy. In this study, treatment accuracy was analyzed in two ways: firstly, leaf motion precision was evaluated in fluence maps

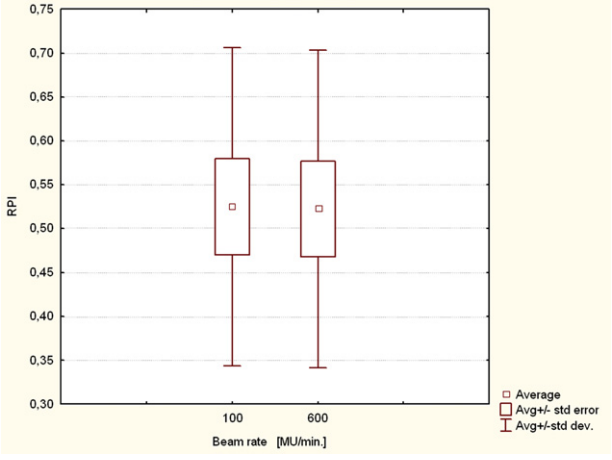

Fig. 6 – Changes of average Radiation Planning Index (RPI) with the beam rate.

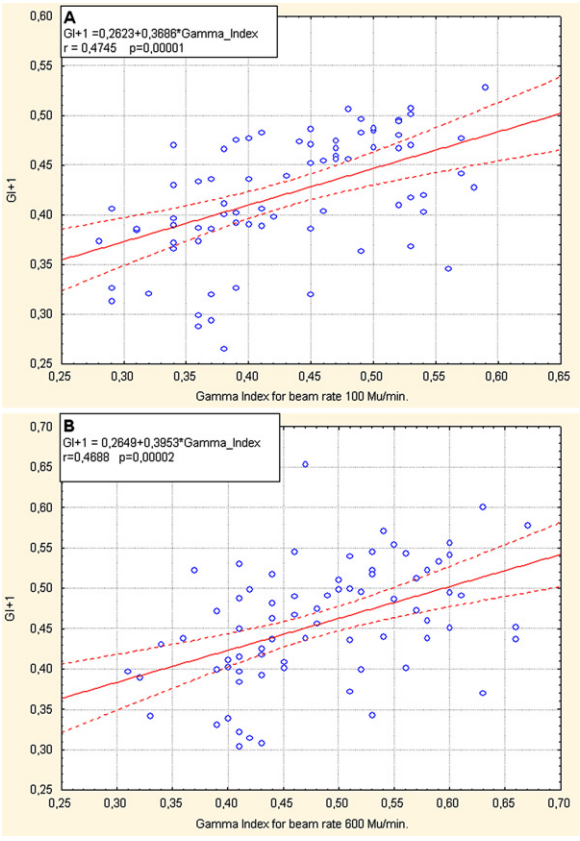

Fig. 8 – Dependence between inaccuracy of map conversion represented by gamma index calculated in OmniPro-I'mRT software and treatment execution represented by GI_{+1} calculated in Portal Dosimetry option for (A) 100 MU/min and (B) 600 MU/min beam rates. The dashed line indicates 95% confidence range (Statistica v.8).

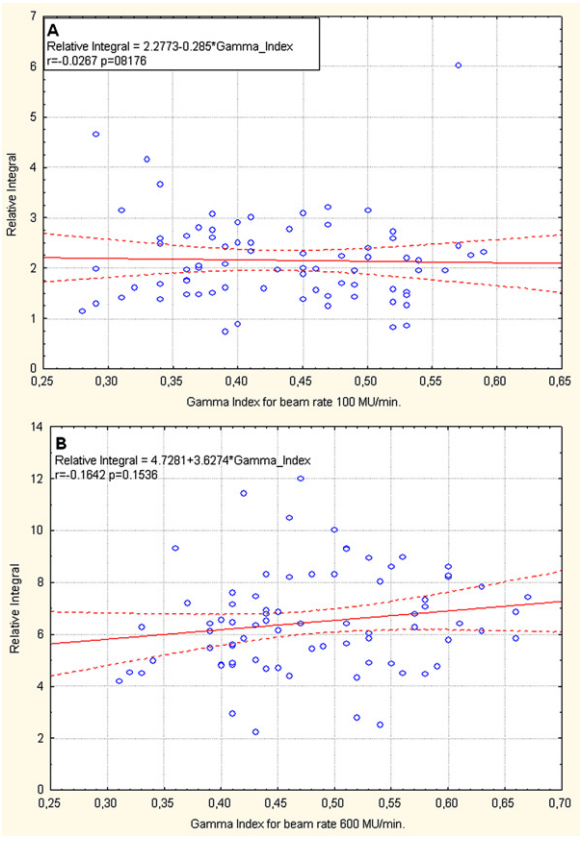

Fig. 9 – Dependence between inaccuracy of map conversion represented by gamma index calculated in OmniPro-I'mRT software and treatment execution represented by leaves motion precision, calculated in MLCtracker software for (A) 100 MU/min and (B) 600 MU/min beam rates. The dashed line indicates 95% confidence range (Statistica v.8).

measurement assessing gamma index GI_{+1} and secondly, with MLCtracker software. Then, the correlation of conversion accuracy with GI_{+1} and, additionally, with leaves' motion precision was examined.

There was a small correlation between the conversion quality and treatment delivery made on the basis of GI_{+1} for both beam rates. GI_{+1} represented agreement between calculated and measured maps, that is fluence map execution. An increase in inaccuracy of map conversion caused the increase in inaccuracy of fluence map execution, i.e. gamma index values calculated for both comparisons varied in direct proportion. The relationship is presented in Fig. 8. Single points on the graph show values calculated for every treatment field, separately. This dependence is slightly bigger for 600 MU/min than for 100 MU/min. Consequently, lower treatment precision for higher beam rate can be expected. The correlation factor is low but the result is statistically significant ($p < 0.005$).

The impact of different dose rates on actual fluence maps was tested by Vorwerk et al. as well.[17] The results indicated that gamma index was correlated with the dose rate. The mean gamma index was lower using a dose rate of 100 MU/min than 600 MU/min.

Another test could also demonstrate how the differences in optimal and actual maps corresponded to the leaf positioning precision. The conclusion can be drawn that there is no correlation between the deviation of optimal and actual fluence maps found in the planning phase and the inaccuracy during a treatment session. Again the result is statistically significant. The relationship between leaf motion precision and fluence map conversion accuracy is presented in Fig. 9.

It is notable that changes in fluence map delivery can be caused not only by improper leaf motion but also by beam rate changes. These changes are unintentional, but do occur in the IMRT modality. Obviously, such discrepancy can make a considerable contribution to fluence map variances. If so, we have to make sure what exactly we are testing. The MLCtracker controls MLC files only, while the GI_{+1} considers leaf motion as well as possible dose rate fluctuations. Perhaps, for this reason correlation between fluence map conversion accuracy and fluence map delivery was demonstrated, whereas such correlation for leaf motion precision was not proven.

To obtain a complete view of this problem, an explanation has to be provided that the correlation is not shown because the position of the leaves is averaged from thousands of numbers during a relative integral calculation. Therefore,

isolated local leaf position distortions can go unreported, as average values do not fully illustrate whole movement features. But such a small imprecision in leaf movement can be illustrated on a fluence map and measured by GI_{+1}. However, the leaf motion inaccuracy clearly depends on beam rate. It rises as beam rate increases. It is coherent with the result of another study of Stell et al.[22] It should be also emphasized that detected discrepancies occurring in the course of treatment do not exceed tolerance values defined in limits for leaf parameters.[23] Otherwise, treatment delivery would be interrupted. Further investigation of MLCtracker outcomes is planned by the authors. However, it can be stated that this software has a practical application in daily quality assurance carried out for dynamic techniques. Its implementation allows to read out of leaf motion accuracy and compare it with the calculated one.

6. Conclusion

Beam rate analysis can help yield new insights into the discussion on treatment planning and treatment delivery quality assurance (QA). Applying different beam rates, one can obtain different levels of dose distribution and treatment precision. However, these differences are minor. The only parameter reflecting the benefits of a higher beam rate is treatment time, i.e. treatment session duration. The rest of the analyzed factors show superiority of a lower beam rate, which, however, does not have a significant impact on differences in treatment accuracy. In the future, the impact of intrafraction movements of the patient, caused by long treatment duration, on treatment precision can be considered.

Lastly, it should be mentioned that the above discussion concerns physical doses only. Possible influence of beam rate on biological effects remains to be an open issue.

Conflict of interest

None declared.

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