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Comparison of treatment plans calculated by Ray Tracing and Monte Carlo algorithms for head and thorax radiotherapy with Cyberknife

Abstract: This study investigates differences between treatment plans generated by Ray Tracing (RT) and Monte Carlo (MC) calculation algorithms in homogeneous and heterogeneous body regions. Particularly, we focus on the head and on the thorax, respectively, for robotic stereotactic radiotherapy and radiosurgery with Cyberknife. Radiation plans for tumors located in the head and in the thorax region have been calculated and compared to each other in 47 cases and several tumor types.

Assuming MC as the algorithm of highest accuracy it is shown that based on selected dose parameters, RT slightly underestimates the dose in homogeneous regions and overestimates in heterogeneous regions. In addition, deviations occur due to tumor size rendering large differences for small tumors. We conclude that dose prescriptions for radiotherapy treatments should differentiate between RT and MC calculation algorithm. This is especially important for small tumors in heterogeneous body regions.

Keywords: Treatment plans, Monte Carlo, Ray Tracing, Cyberknife, Tumour size and volume, dose prescription.

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1 Introduction

The exact calculation of local dose deposition in human tissue is of crucial importance for the result of radiotherapy. Any radiation planning system is based on various algorithms to calculate the interactions between radiation and tissue. For example, within the Multiplan®, an irradiation planning system from Accuray®, the Ray Tracing and the Monte Carlo algorithm are available. By using these algorithms, the modelling of interactions as well as the subsequent calculation of dose deposition and dose distribution in tissue may considerably differ. Ray Tracing algorithm, for instance, uses the electron density relative to water for all voxels found on beam trajectory on the computer tomography (CT) image used for treatment planning. On the other hand, a MC code uses the mass density of CT-voxels located at the trajectory of the beam. Additionally, in a MC scheme all interactions of primary, secondary and tertiary particles are pursued with appearance probability models to determine dose depositions of all interactions.

While some aspects related to the differences between these two particular algorithms has been already published [1,2,3,4], this study presents and spots new quantitative and qualitative aspects particularly focussing at small tumour lesions in various tissue environments.

2 Materials and methods

In this comparative study, treatment plans in the head and in the lung area are evaluated. These plans have been previously applied with Cyberknife (Accuracy, Sunnyvale, CA, Version: 10.5). Cyberknife is a linear accelerator system for robotic radiotherapy. By choosing one or even more of all twelve available fixed cones characterized by diameters between 5mm and 60mm, the irradiation can be applied from, at about, 150 irradiation positions.

Five patients were treated in head regions with homogeneous tissue. Acoustic neurinoma received 13Gy in

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one fraction to the enclosing 80% isodose. The volume of the lesion was 1.18-3.25cm^3. Five patients with cerebral metastases from lung cancer (n=3), breast cancer (n=1) and malignant melanoma (n=1) received 18Gy in one fraction to the enclosing 80% isodose. The lesion size was 1.54-2.28cm^3.

In total 37 patients with primary lung cancer (n=20), as well as patients with lung metastases from rectum cancer (n=12), endometrial cancer (n=1), larynx cancer (n=1), sarcoma (n=1), prostate cancer (n=1) and pancreas cancer (n=1) were treated. Planning Target Volume (PTV) in heterogeneous tissue of the lung was between 0.73-64.98cm^3. The dose of 37.5Gy has been delivered in three fractions, enclosing 65% isodose. All treatment plans have been created with treatment planning software Multiplan® (Accuray, Sunnyvale, CA, V.5.2.1) and are recalculated with the MC algorithm without change of planning parameters and optimization.

For every RT and MC treatment plan the following irradiation parameters are calculated: minimum dose (D_{min}), mean dose (D_{mean}), maximum dose (D_{max}), dose value received by 2% and 98%, of the target volume (*D2*, *D98*) and coverage (*Cov*) of the PTV, i.e. ratio of tumor volume and volume receiving the prescribed isodose. In addition, in case of lung lesions the dose parameters D_{min}, D_{mean}, D_{max} of the gross tumour volume (GTV) and its coverage are calculated.

For every singular irradiation parameter, the differences between the RT and MC algorithms are characterized by the minimum, maximum and mean value. For instance, the minimum and maximum value of absolute differences of D_{mean} are denoted by d_{mean}^{min} and d_{mean}^{max}, while a bar denotes the average value, e.g. $\overline{d}_{mean}$. Similar notation is used for dose differences of all above-mentioned parameters throughout this paper.

A simple calculation demonstrate that the average difference, e.g. $\overline{d}_{mean}$, equals the difference of average values of any particular dose parameters:

$$\overline{d}_{mean} = \overline{D}_{mean}^{MC} - \overline{D}_{mean}^{RT} . \qquad (1)$$

The percentage difference, if specified, is normalized by the value of the RT dose parameter, for example the mean value:

$$\overline{d}_{mean} = 100\ \% \cdot \frac{\overline{D}_{mean}^{MC} - \overline{D}_{mean}^{RT}}{\overline{D}_{mean}^{RT}} . \qquad (2)$$

3 Results

After recalculation of RT Plans, without being optimized, a divergence between irradiations in homogeneous and heterogeneous areas of the body is discernible (Fig.1). In the homogeneous head area a slight increase in dose is observed. For acoustic neurinoma the mean dose increases by $\overline{d}_{mean} = 2{,}99\%$ with a minimum and maximum of $d_{mean}^{min} = 2{,}36\%$, and $d_{mean}^{max} = 3{,}49\%$. The mean values of *D2* and *D98* increase by $\overline{d}_{D2} = 3.29\%$ and $\overline{d}_{D98} = 2.31\%$. The mean value of the coverage falls by $\overline{Cov} = -2{,}33\ \%$ from $\overline{d}_{Cov}^{RT} = 99.80\%$ using RT compared to $\overline{d}_{Cov}^{MC} = 96.50\%$ using MC. For brain metastases D_{mean} increases on average by 2.46% ($d_{mean}^{min} = 1{,}33\%$, $d_{mean}^{max} = 3{,}34\%$). An increase by 2.78% of $\overline{d}_{D2}$ and by 2.21% of $\overline{d}_{D98}$ is observed. Again, *Cov* shows a drop of $\overline{Cov} = -1{,}51\%$, i.e 99.16% using RT in comparison to 97.67% using MC.

In heterogeneous thoracic region, on the other hand, a drop in D_{mean} of the PTVs by $\overline{d}_{mean} = -16{,}73\%$ with a minimum deviation of $d_{mean}^{min} = -4{,}08\%$ and a maximum deviation of $d_{mean}^{max} = -39{,}15\%$ is noticed. A lower decrease of the GTV by $\overline{d}_{mean} = -11.77\%$ ($d_{mean}^{min} = -4{,}28\%$, $d_{mean}^{max} = -29{,}42\%$) is to be noted. A decrease of $\overline{d}_{D2}$ and $\overline{d}_{D98}$ of the PTVs by -12.42% and -22.98%, respectively, is also observed. The $\overline{Cov}$ of the GTV dropped from 99.86% to 97.77% less (-2.09%) than the $\overline{Cov}$ of the PTV, which dropped from 99.14% by using RT to 84.39% by using MC (decrease of -14.79%).

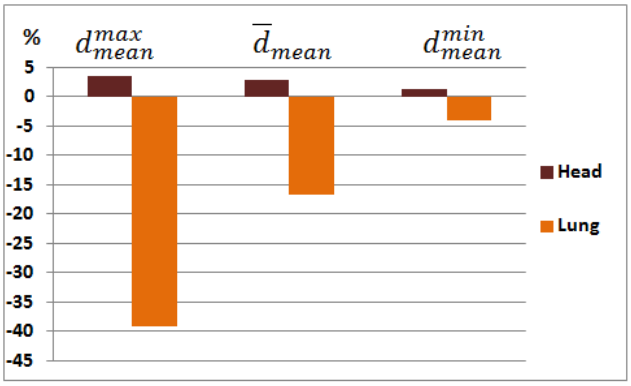

Figure 1: Comparison of RT and MC shows higher dose differences of D_{mean} in heterogeneous lung area.

Figure 2 displays the dose dependency on the target volume. A higher dose deviation in D_{min}, D_{mean} and D_{max} between RT and MC is recognized in the thorax for small target volume sizes below 30cm³. This result has been found within the parameters *D2*, *D98* and *Cov* of the PTV, too.

All lung lesions have been classified into two volume-subgroups: (A) 0-30cm³ and (B) 30-65cm³ is showed in Figure 3. Differences between the PTVs below and above 30cm³ are clearly visible. In group A the difference in D_{max} is twice as high with $\overline{d}_{max}(A) = -12{,}53\% = -7{,}21Gy$ as in Group B, which shows $\overline{d}_{max}(B) = -7.45\% = -4.30Gy$. The parameter D_{min} in group A shows a maximum difference of $d_{min}^{max} = -47{,}41\%$, which corresponds to a dose difference of -18.23Gy after MC recalculation. For D_{max} the maximum difference $d_{max}^{max} = -29{,}49\% = -17{,}02Gy$ have been evaluated. In group A, the D_{mean} difference of $\overline{d}_{mean}(A) = -18.11\% = -8.42Gy$ is also twice as high as in group B with $\overline{d}_{mean}(B) = -9.25\% = -4.23Gy$ as displayed in Fig. 3.

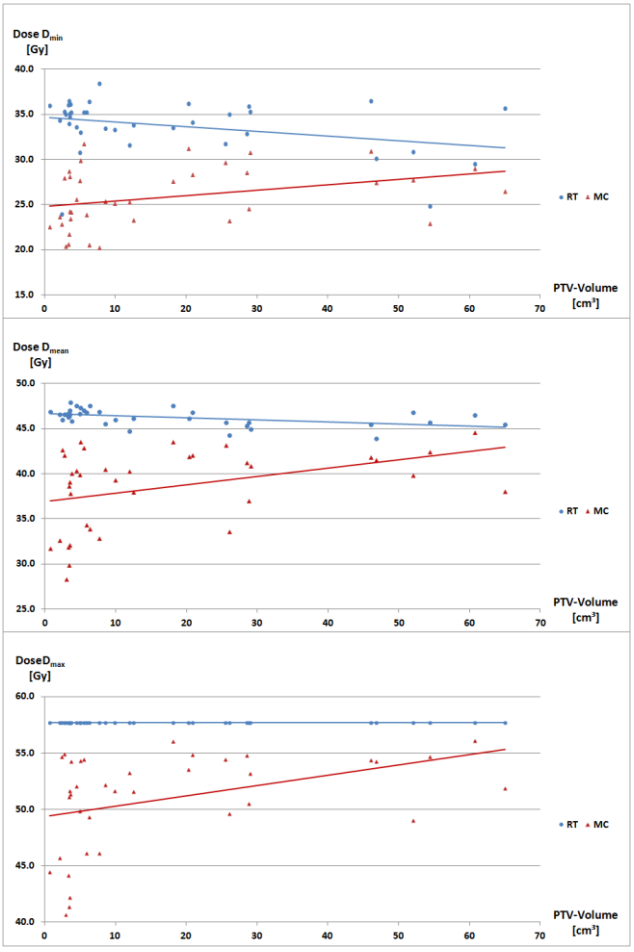

Figure 2: Dependence of tumor volume for D_{min} (top), D_{mean} (middle) and D_{max} (bottom). Small volume of less than 30cm³ results in higher differences between MC and RT.

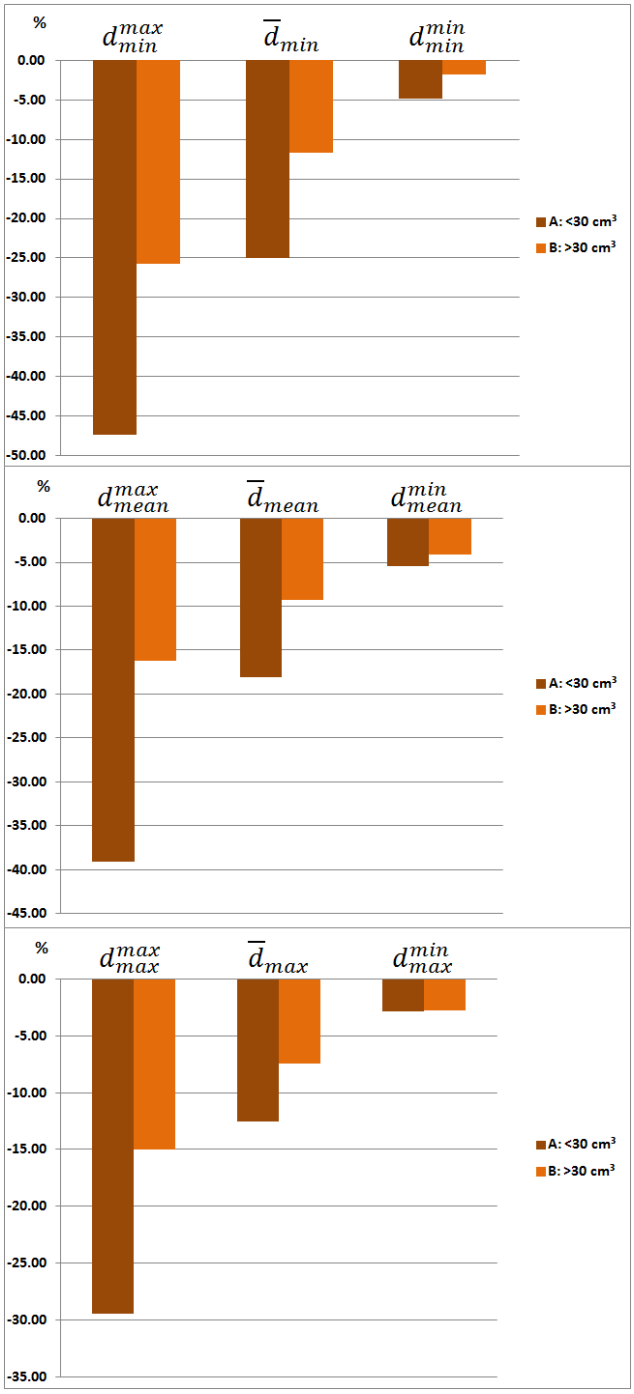

Figure 3: Percentage differences between RT and MC planning parameters D_{min} (top), D_{mean} (middle) and D_{max} (bottom) are higher in small PTVs below 30cm³. Highest differences occur for the maximum values while the differences of corresponding minimum values are small, i.e. less than 5%.

4 Discussion and conclusion

Dose calculations in irradiation planning systems are of crucial importance for the outcome of radiotherapy. Wilcox, Daskalov, and Lincoln [1] showed that a deviation of D_{max} and *Cov* in the pelvis, spine and head correlates, results in a maximum of 5% when comparing RT to MC. It is shown that the calculation algorithms RT and MC are equivalent in homogeneous body regions within 4% dose deviation. Thus, the use of RT in homogeneous body regions is to be regarded as sufficient and appropriate [1].

In heterogeneous areas of the body, such as the thorax, however, a clear difference in the dose distribution between the RT and MC algorithm is detected. On average, a drop of $\overline{d}_{mean} = -16{,}73\%$ (-4.08% till -39,15%) was found. Van der Voort et al [2] evaluated a dose drop of 17% in tumors with a diameter of less than 3cm, 13% in tumors between 3cm and 5cm, and 8% drop in tumors larger than 5cm. The PTV volume had an effect on dose deviations. PTV sizes of 0-30 cm³ showed an $\overline{d}_{mean} = -18.11\%$, sizes of 30 to 65cm³ a $\overline{d}_{mean} = -9.25\%$. The difference between D_{max} and *D2* of the PTV is -11.68% and -12.35%, respectively. For the parameters D_{mean}, D_{min} and *D98* the differences are higher with -16.68%, -22.86% and -21.94%. This can be explained by the different depth-dose profile of both algorithms. In the case of RT the curve is normally continued in the lung, whereas in MC it is flattened due to the associated interactions with the lung tissue. The fact that D_{min} and D_{mean} show higher differences between both algorithms is due to the fact that MC also calculates the dose depositions in the lung. Accordingly, the dose D_{min} arriving at the PTV is by use of MC less than the D_{min} for RT, and consequently the D_{mean}. After the irradiation enters the tumor the depth-dose-profile decreases further at RT, while MC produces a kind of second build-up effect. Thus, the deviation of maxima of the PTVs between RT and MC are lower than deviations in minima.

The D_{min} and *D2* of the PTV are an important parameter to avoid under-supply of the lesion. There, however, the highest dose decrease is recorded after recalculation with MC of $d_{min}^{max} = -47{,}41\%$ with -18.23Gy.

Sharma et al. showed that the *Cov* of the PTV was even reduced to 69.2% by MC [3]. It turned out that the *Cov* of the GTV dropped by 99.86% to 97.7% by the MC less compared to the decrease of *Cov* of the PTV from 98.14% to 84.39%. An adjustment of the previous fractionation scheme should be attempted on the base of this result. Lacornerie et al. [4] suggest that 22 different treatment regimens for the MC algorithm (15-72.5Gy in 1 to 12 fractions) were used in 45 studies. Differences in clinical outcomes may result from (i) whether the dose is prescribed for the GTV or PTV, (ii) to prescribed isodose and (iii) the fractionation scheme.

In summary, the discrepancy between treatment plans calculated by RT and MC algorithm is larger in magnitude in heterogeneous body regions. In the assumption that MC is the algorithm of highest accuracy it is shown that RT slightly underestimates the dose in homogeneous regions and overestimates in heterogeneous regions. In addition, percentage deviation differs according to tumor size. In conclusion, different dose prescriptions for RT and MC calculation algorithm are desirable, especially for small tumors in heterogeneous regions.

Author's Statement

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