The influence of air cavities within the PTV on Monte Carlo-based IMRT optimization

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Abstract Integrating Monte Carlo calculated dose distributions into an iterative aperture-based IMRT optimization process can improve the final treatment plan. However, the influence of large air cavities in the planning target volume (PTV) on the outcome of the optimization process should not be underestimated. To study this influence, the treatment plan of an ethmoid sinus cancer patient, which has large air cavities included in the PTV, is iteratively optimized in two different situations, namely when the large air cavities are included in the PTV and when these air cavities are excluded from the PTV. Two optimization methods were applied to integrate the Monte Carlo calculated dose distributions into the optimization process, namely the ‘Correction – method’ and the ‘Per Segment – method’. The ‘Correction – method’ takes the Monte Carlo calculated global dose distribution into account in the optimization process by means of a correction matrix, which is in fact a dose distribution that is equal to the difference between the Monte Carlo calculated global dose distribution and the global dose distribution calculated by a conventional dose calculation algorithm. The ‘Per Segment – method’ uses directly the Monte Carlo calculated dose distributions of the individual segments in the optimization process. Both methods tend to converge whether or not large air cavities are excluded from the PTV during the optimization process. However, the ‘Per Segment – method’ performs better than the ‘Correction – method’ in both situations and the ‘Per Segment – method’ in the case where the large air cavities are excluded from the PTV leads to a better treatment plan then when these air cavities are included. Therefore we advise to exclude large air cavities and to apply the ‘Per Segment – method’ to integrate the Monte Carlo dose calculations into an iterative aperture-based optimization process. Nevertheless, the ‘Correction – method’ provides a good alternative in the case when the external dose engine is not able to generate individual dose distributions for the individual segments.

1. Introduction

In the standard approach of intensity modulated radiotherapy (IMRT) treatment plan optimization, the intensity pattern for each IMRT beam is modelled as a 2D map of energy fluence incident on a patient. This intensity pattern is divided into discrete uniform beam elements (beamlets or bixels) and an inverse planning or automated optimization system is then used to generate a set of beamlets that will produce, as closely as possible, the desired dose distributions.

To produce practically deliverable treatment fields, these elementary beamlets are regrouped into larger fields during a process called ‘leaf sequencing’. However, the obtained treatment fields are only an approximation of the ideal intensity distribution and this usually leads to a reduced quality of the treatment plan. Nevertheless, there are several approaches to overcome the sequencer problems in IMRT optimization (Alber and Nüsslin 2001, Litzenberg et al 2002, Siebers et al 2002) and one of these approaches is the method of aperture-based optimization. Aperture-based optimization (Shepard et al 2002, De Gersem et al 2001) is a technique for IMRT that is designed to reduce the complexity of intensity modulated treatment plans and to facilitate the application of IMRT in clinical practice. This is achieved by avoiding the optimization of intensity maps. Instead, the planning process is based on a small, preset number of multileaf collimator (MLC) shapes (apertures or segments) per beam direction. The optimization is then either limited to calculate optimal weights for predefined apertures (which can be, for example, derived from the patient’s anatomy), or it can be extended to a simultaneous optimization of the shapes and weights of the apertures.
The aim of this work is to investigate whether the final treatment plan obtained by an iterative aperture-based optimization process that incorporates a conventional dose calculation algorithm could be improved by integrating Monte Carlo calculated dose distributions into this optimization process and to illustrate the influence of large air cavities on the outcome of the optimization process. Two alternative methods are examined to integrate these Monte Carlo calculated dose distributions into the aperture-based optimization process applied at Ghent University Hospital (GUH).

2. Methods and materials

2.1. IMRT optimization system

At GUH, a segmentation-based inverse planning approach is used to create IMRT treatment plans for step-and-shoot delivery with a MLC. Starting from an initial set of beam segments, as illustrated in figure 1, the corresponding set of segment dose distributions is calculated by an external dose engine.

![Diagram](image)

Figure 1. Overview of the iterative optimization cycle and the different optimization algorithms used at Ghent University Hospital.

Generally the differential scatter-air ratio dose calculation algorithm of GRATIS (Sherouse et al 1989) is used. As illustrated in a recent paper (Paelinck et al 2006) the accuracy of this system cannot be guaranteed, as for individual cases deviations above 10% were obtained when comparing GRATIS DVHs to MCDE results. During the optimization process, a bio-physical objective function is maximized starting with the in-house developed Segment Weight Optimization Tool (SWOT) cycle, which only optimizes the weights of the beam segments and leaves all segment shapes unchanged. After the first SWOT cycle, the Segment Outline and Weight Adapting Tool (SOWAT) optimizes the MLC settings and weights of these segments (De Gersem et al 2001) and an additional SWOT cycle is performed. When the plan acceptance criteria are not fulfilled, a new optimization cycle is performed (SOWAT + SWOT). This is repeated until the plan acceptance criteria are fulfilled. The aim of our study was to investigate whether the final treatment plan could be improved by integrating our Monte Carlo Dose Engine MCDE (Reynaert et al 2004) into the iterative optimization process and to illustrate the influence of large air cavities on the outcome of this optimization process.

2.2. Dose computation method: ‘Correction – method’

The initial treatment plan calculated with GRATIS (providing a global dose distribution $D_{\text{GRATIS}}$) is recalculated with MCDE resulting in a global dose distribution $D_{\text{MCDE}}$. The values of the voxels in the
correction matrix \( R \) are determined by \( R = D_{\text{MCDE}} - D_{\text{GRATIS}} \), which results in a dose distribution that is equal to the difference between the global GRATIS and MCDE results.

To take this correction matrix into account during the optimization process, an additional beam (‘patch-beam’) was created of which the weight (set to unity) and MLC settings were locked. Both SOWAT and SWOT cycles used the GRATIS dose distributions of the individual segments, plus the dose distribution of this ‘patch-beam’ to evaluate the outcome of the treatment plan.

It can be expected that this method will introduce small systematic errors during the optimization process, because the correction matrix \( R \) (and inherently the dose distribution of the ‘patch-beam’) remains constant, while the GRATIS results for the individual beam segments are modified during an optimization iteration (as the MLC settings and weights of the individual segments are changed). Nevertheless, the ‘Correction – method’ is very useful if the Monte Carlo dose engine that has to be integrated into the optimization software is only capable of delivering a global dose distribution.

2.3. Dose computation method: ‘Per Segment – method’

With the ‘Per Segment – method’, the Monte Carlo calculated dose distributions of the individual segments are used directly by the SOWAT and SWOT algorithms instead of the GRATIS dose distributions. No ‘patch-beam’ has to be created. It is therefore a more accurate method of integrating Monte Carlo results into the optimization process. However, this method requires a Monte Carlo dose engine to be capable of delivering the dose distributions of the individual segments.

2.4. Clinical case

An ethmoid sinus cancer patient case was studied with large air cavities present in the planning target volume (PTV). The patient was treated with 42 6 MV beam segments impinging from 9 different directions. Starting from the initial plan generated by the GRATIS dose calculation algorithm, five additional optimization cycles (SOWAT and SWOT) were performed. Before the start of each cycle, a MCDE calculation was performed for both the ‘Correction – method’ and the ‘Per Segment – method’, thus providing a global dose distribution and a set of dose distributions of the individual segments.

To determine the influence of the air cavities, both methods were applied while including/excluding the large air cavities from the original PTV. This allows the study of the influence of statistical noise from the MCDE calculations on the optimization process. The exclusion of the air cavities of the PTV leads to a newly defined structure and is accomplished by delineating these air cavities in the PTV and by subtracting these air cavities from the original PTV using in-house developed software.

Treatment plans were compared by means of dose volume histograms (DVHs) and their corresponding values of the objective function are used to illustrate the convergence of the iterative optimization process.

3. Results and discussion

3.1. Calculation times

The MCDE calculation times of the treatment plans obtained in the iterative optimization cycles with the ‘Per Segment – method’ and the ‘Correction – method’ were almost identical, namely 4 hours on a cluster consisting of 34 2.4 GHz Xeon processors.

However, to obtain the correction matrix (‘patch-beam’) for the ‘Correction – method’, the individual dose distributions of the different beam segments had to be calculated first by the GRATIS dose computation algorithm, which requires an additional calculation time of about half an hour before a new optimization cycle can be started.

With the ‘Per Segment – method’, there is no need for an extra dose calculation with GRATIS since these individual Monte Carlo calculated dose distributions are used directly in the optimization cycle.

3.2. Convergence of the value of the objective function

For the initial treatment plan, the values of the objective function for the dose distribution calculated by GRATIS were respectively -6.2 when including the large air cavities in the PTV and -6.8 when excluding these air cavities. A recalculation of this initial treatment plan with the Monte Carlo dose
engine MCDE provided a dose distribution from which the values of the objective function were equal to -14.9 and -12.6 respectively, as illustrated in figure 2. Both the ‘Correction – method’ and the ‘Per Segment – method’ tend to converge in both situations. However, when the air cavities are included in the PTV, the convergence isn’t obtained as fluently as in the situation without the air cavities as the values of the objective function don’t increase continuously.

![Graph showing convergence of the objective function](image)

Figure 2. Illustration of the convergence of the value of the objection function (OF) after five optimization cycles for both the ‘Correction – method’ and ‘Per Segment – method’ when applied in two situations: one situation in which the large air cavities are included in the PTV and the other situation in which these air cavities are excluded from the PTV.

Figure 2 also illustrates that the results obtained with both the ‘Correction – method’ as well as the ‘Per Segment – method’ are quite similar when the air cavities are included in the PTV. However, excluding the air cavities from the PTV clearly leads to a larger difference between both methods, which leads to the conclusion that a better treatment plan is obtained by applying the ‘Per Segment – method’.

3.3. Comparison of DVHs

As the quantitative values of the objective function strongly depend on the choice of this function, the quality of the resulting treatment plan was also evaluated by looking at the DVHs for both methods in both situations (inclusion or exclusion of the air cavities from the PTV).

A. Excluding the air cavities from the PTV.

Looking at the DVHs for both optimization methods in the situation where the air cavities are excluded from the PTV in figure 3, one can conclude that the initial treatment plan is improved by integrating Monte Carlo calculated dose distributions into the iterative aperture-based optimization process. Moreover, in accordance to the values of the objective function in figure 2, the ‘Per Segment – method’ provides a better treatment plan compared to the ‘Correction – method’ and is therefore a more favourable method of integrating Monte Carlo calculated dose distributions into the optimization process. Nevertheless, not all dose engines are able to produce dose distributions for the individual beam segments and therefore the ‘Correction – method’ provides a good alternative, especially in the case when the air cavities are excluded from the PTV.
Figure 3. Comparison between the ‘Correction – method’ and ‘Per Segment – method’ of the DVHs of the initial treatment plan and the treatment plan after the fifth optimization cycle obtained in the situation where the air cavities are excluded from the PTV.

B. Including the air cavities from the PTV.

Figure 4 shows the DVHs for the ‘Per Segment – method’ applied to both situations (including and excluding the air cavities from the PTV). It’s clear that the initial treatment plan is improved in both cases. However, excluding the air cavities from the PTV during the optimization process provides a
better treatment plan. This is mainly caused by the presence of high statistical noise on the Monte Carlo calculated dose in these air cavities, since relatively fewer particles will interact in air compared to the surrounding tissues.

If acceptable statistical uncertainties on the dose values in these air voxels are required, e.g. to compute the value of the objective function, the calculation time of the Monte Carlo dose engine
should be increased dramatically (by a factor of thousand) to compensate for the low density of air, which is not realistic at all. Denoising cannot solve this problem as the noise in the air cavities is too severe. Denoising techniques can decrease the calculation time by a factor of ten (Kawrakow 2002, El Naqa et al 2005), which is still not sufficient for the air voxels. Therefore each dose calculation algorithm will have to deal with the concept ‘dose to air’ in some way. There are several possible methods to achieve this. For instance, one can apply a KERMA approximation in the air voxels. Another possibility is to transport track-end electrons on straight lines by their range (Kawrakow and Fippel 2000) in these air regions, instead of locally depositing the track-end electrons, as is the case with EGS-based Monte Carlo dose calculation algorithms. However, lowering the ECUT value to 0.521 MeV in our patient calculations did not have a significant effect on the noise in these air voxels. In this paper, subtracting the volume of the air from the volume of the PTV (the volume of air measured 30% of the volume of the PTV) leads to a dose distribution in the PTV containing less statistical noise. An advantage of this method is that some commercially available treatment planning systems are provided with software to subtract structures. A disadvantage is that the delineation of all air cavities leads to a higher workload. However, one could question the subtraction of air cavities from the PTV on principle, as they are in fact part of the PTV. Nevertheless, we are interested in the dose to the tissue within the PTV and not in the dose to the air cavities. Another possible method is to adapt the DVH software and the calculation of the value of the objective function by the optimization software in such a manner that all voxels with a Hounsfield number less than, for instance, -500 Hounsfield units are neglected or are given a lower weight so they have less influence. The disadvantage of this method is that it is not always possible to manipulate commercially available DVH software or the optimization algorithm. Therefore, it is recommended that commercial treatment planning systems provide at least one of these aforementioned methods, especially those treatment planning systems that implement a Monte Carlo dose calculation algorithm.

4. Conclusions
By integrating Monte Carlo dose calculations into the IMRT optimization process the treatment plan can be further improved. Both the ‘Correction – method’ and ‘Per segment – method’ could be applied. However, the ‘Per Segment – method’ performed better than the ‘Correction – method’ when the air cavities are excluded from the PTV. When the air cavities are included, both methods converge to a similar treatment plan, which is indeed an improvement of the initial treatment plan, although not fully optimized. Therefore we advise to not include air cavities and to apply the ‘Per Segment – method’ to integrate the Monte Carlo dose calculations into the optimization process. However, the ‘Correction – method’ provides also a good alternative when the Monte Carlo dose engine is not able to generate individual dose distributions.

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