Impact of uncertainties in ion beam therapy on the optimality of irradiation condition and fractionation schedule

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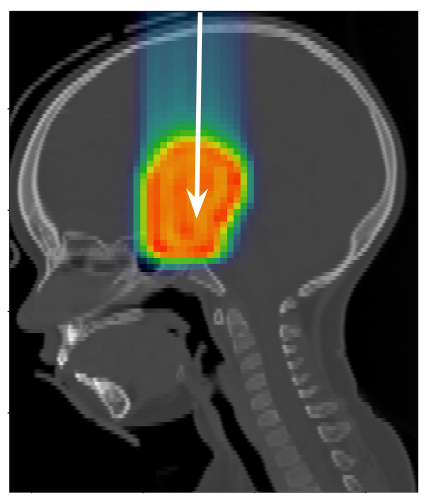
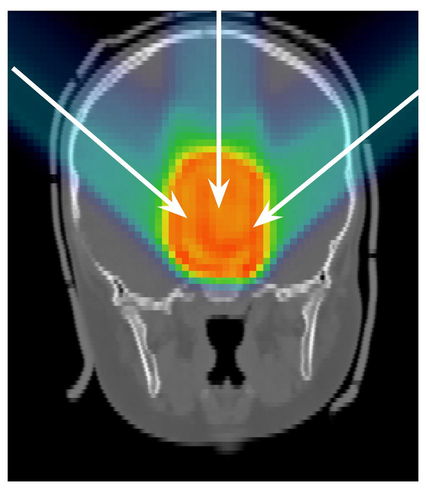
Purpose

The well-defined range of ions, enabling precise dose localization, makes them favorable for highly conformal treatments but also sensitive to uncertainties during planning and delivery. Standard approaches to manage these uncertainties include methods based on safety margins and worst-case optimizations [1], or, alternatively, on probabilistic algorithms [2]. However, all these methods are limited to finding optimal conditions for a single fraction, i.e. the overall effect in terms of tumor control has not been evaluated. In this work, a general probabilistic method to evaluate the optimality for the full fractionation schedule, by means of TPC/NTCP evaluations, was presented. The method was used to evaluate the effects of patient setup errors and CT stochastic noise, in the case of pediatric brain tumor.

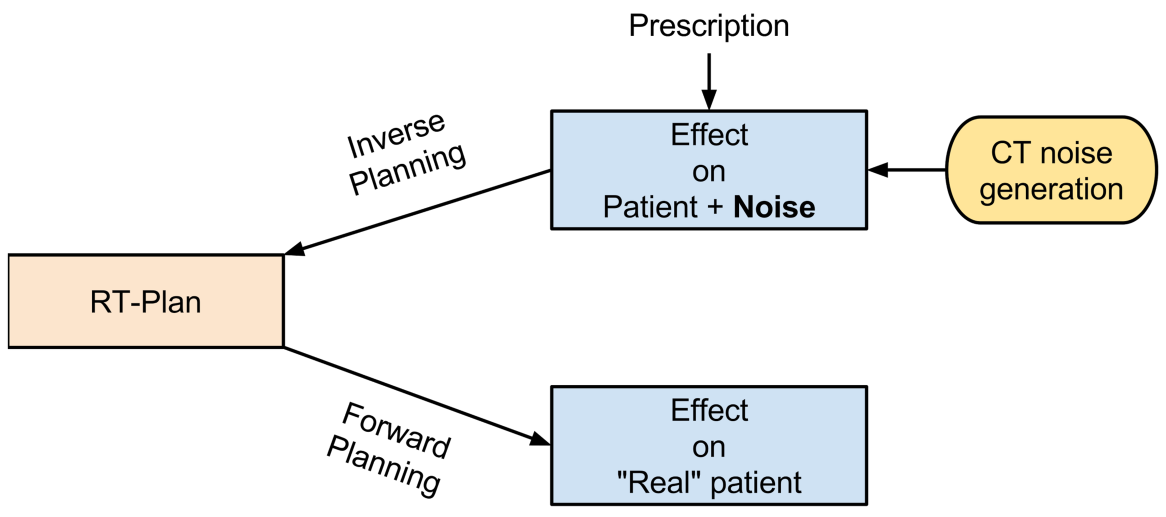




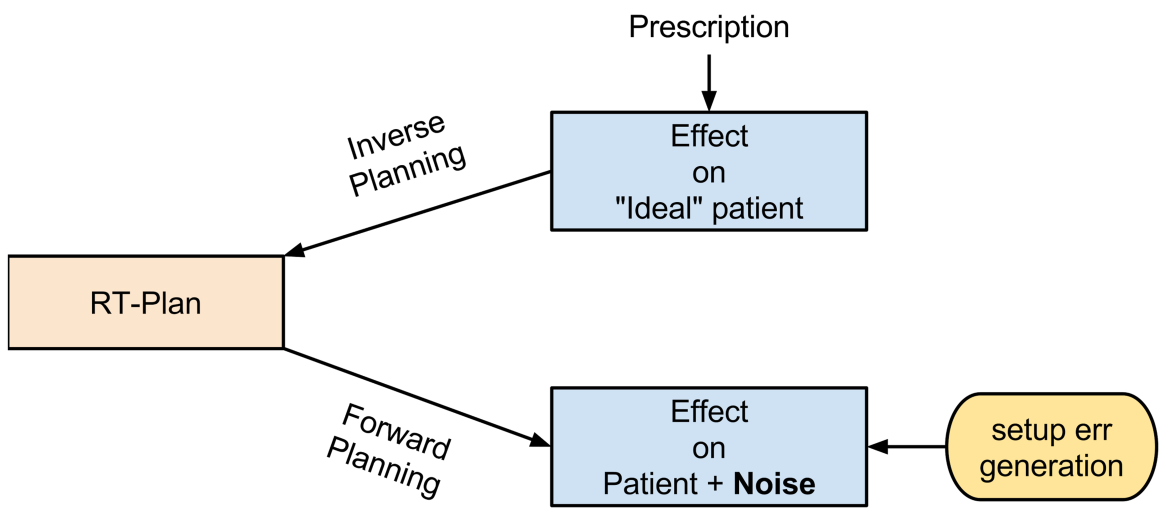
Materials/methods

The aim of the proposed method was to reproduce a realistic workflow of treatment planning and delivery. Two kinds of uncertainties were included:

1) in planning, due to erroneous input data such as noisy CT, resulting in a systematic error;

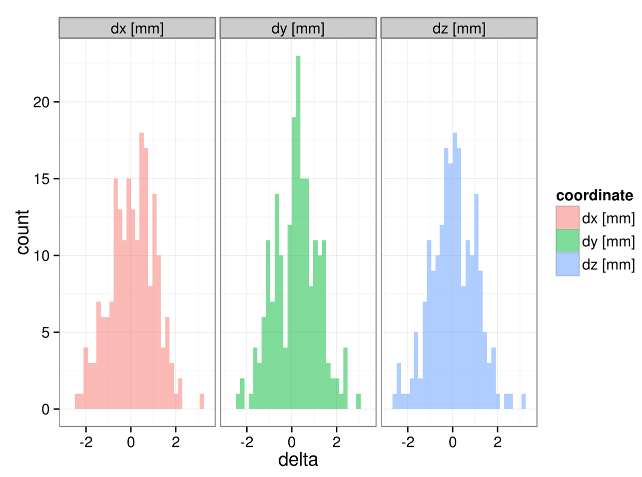


2) in delivery, due to patient setup errors, in which the effects for each fraction are mostly statistically independent.

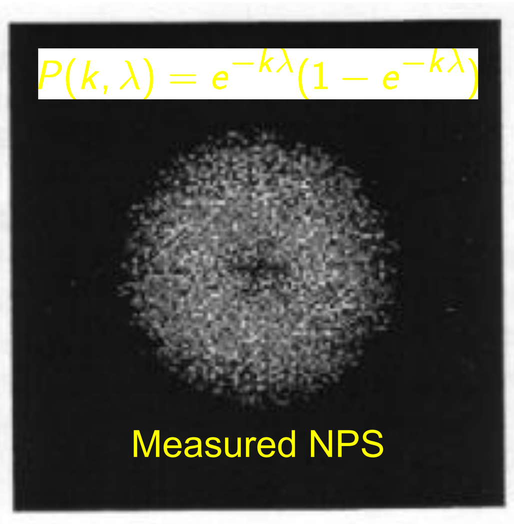


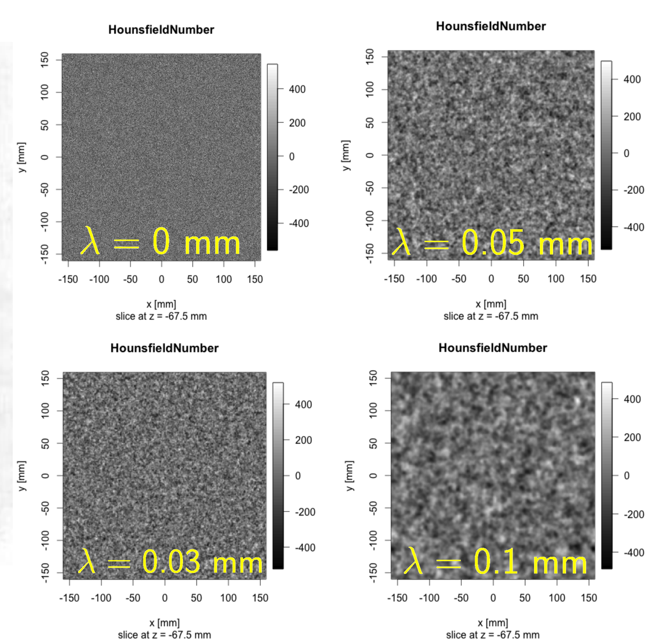
We performed a Monte Carlo/bootstrap sampling over treatment fraction simulations (400, with protons beams), aimed to model the full PDF of the treatment outcome. A case of pediatric brain tumor was simulated. The programmable TPS "PlanIT", based on the "PlanKIT" kernel [3] developed by INFN/IBA, was used to perform the inverse and forward planning simulations of the treatments.

Patient setup errors were included by applying to the isocenter random isotropic shifts, sampled from a Gaussian distribution with σ = 1, 2, 3 and 4 mm (PTV margin = 3 mm).



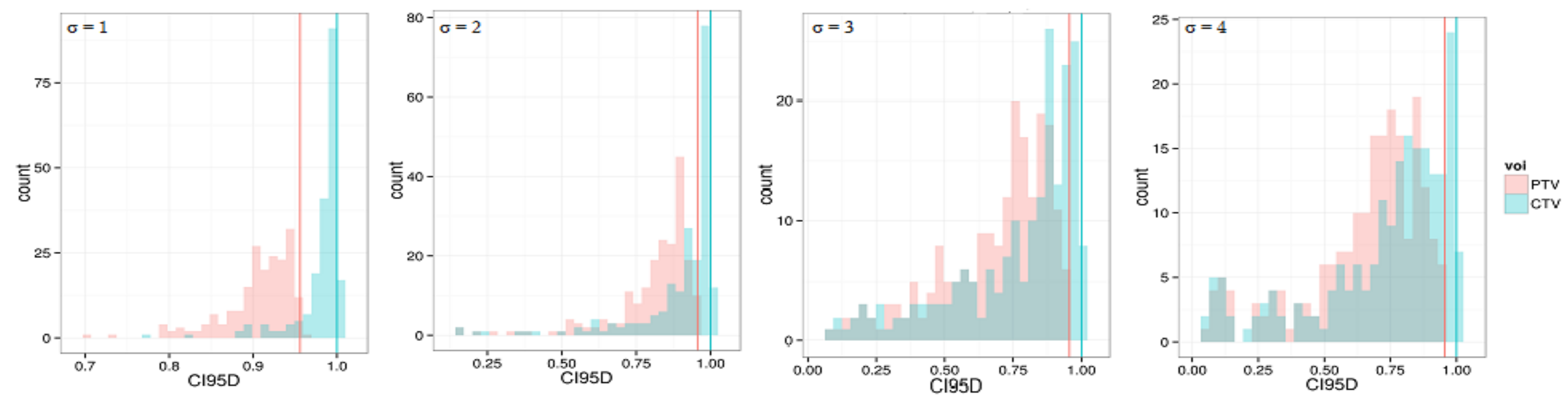
CT spatially correlated noise was generated from a measured noise power spectrum and then applied on the reference CT.

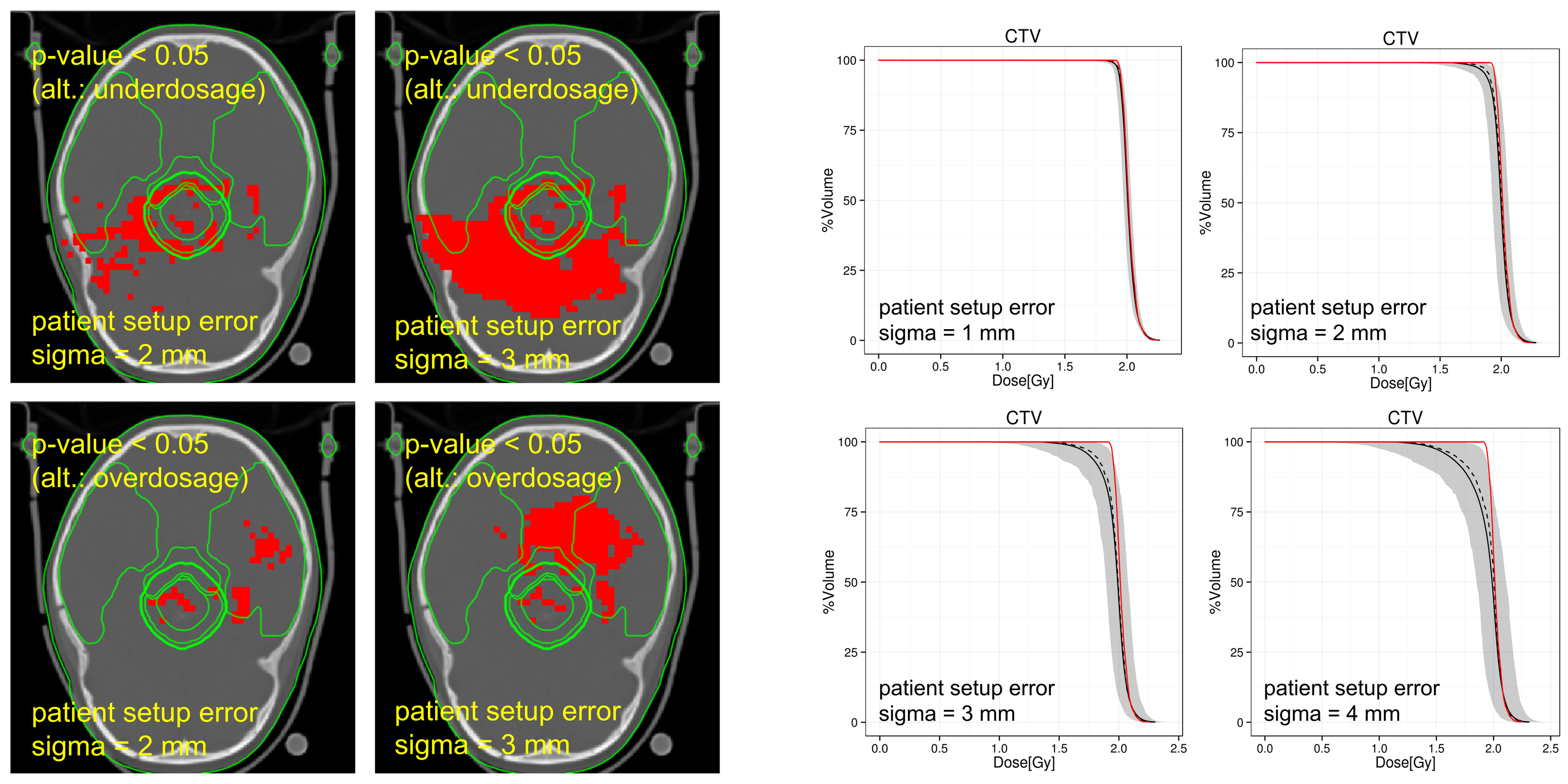




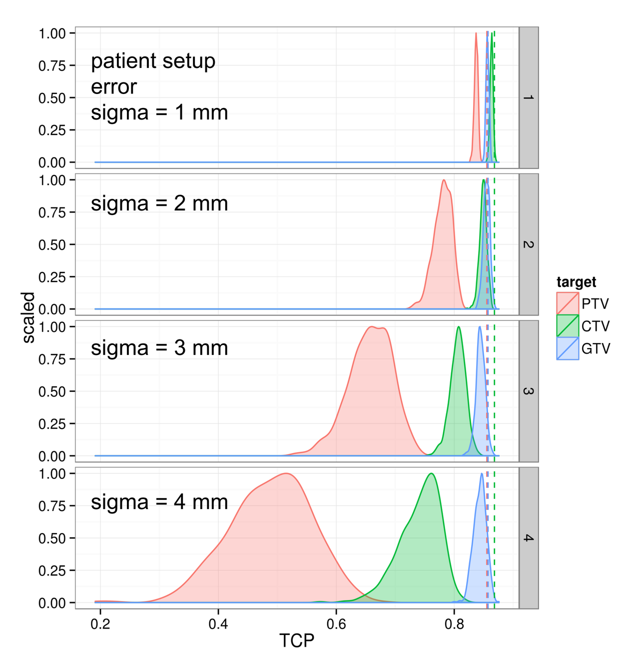
Results

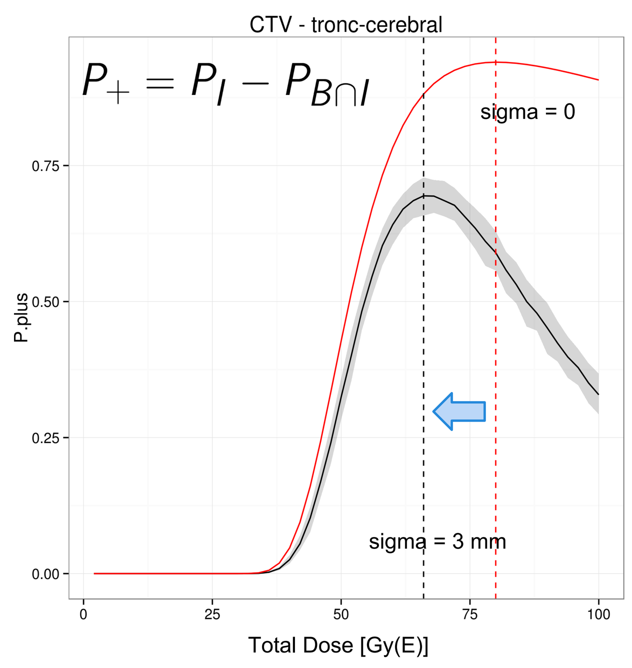
The PDFs of several quality indexes, such as conformity (CI95), homogeneity (HI95), and DVHs, were evaluated. P-value 3D maps for over/underdosage probabilities were also derived (see following figures).





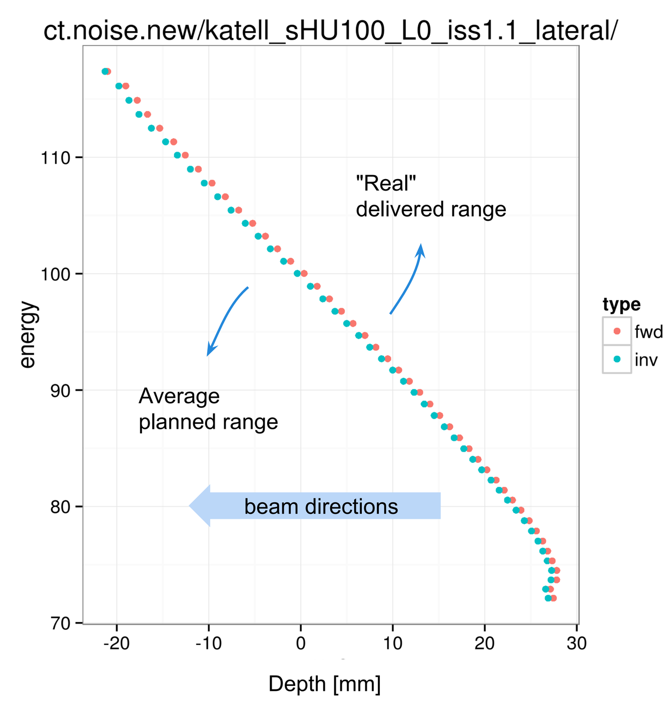
A generalization of the TCP/NTCP models (based on the Poissonian and Relative Seriality models respectively) were introduced to estimate the full treatment effect as a function of number of fractions and dose per fraction, accounting for interfraction dose variability and biological effect fluctuations.





We found that treatments with σ>2 mm could produce a TCP reduced by 10% or more with respect to the treatment without errors. Also, the optimality of the treatment, quantified by the maximization of the probability of local control without complications (P+), is shifted towards different fractionation schedules.

A systematic overestimation of the range of particles (1-2 mm), due to the noise in CT images, was also found. Interestingly, this deviation has the same order of magnitude, but different sign, as the correction to the effective proton range due to the variable RBE (the "biological range").



Conclusions

A method was implemented to estimate the effects of stochastic uncertainties on treatment optimality for the full fractionation schedule in ion beam therapy. The method could be used in a treatment procedure to perform robust planning, including also the optimization in fractionation schedule.

References

1. Pflugfelder D et al., Phys Med Biol, 53 (2008)
2. Unkelbach J et al., Med Phys, 36 (2009)
3. See Poster "*Pre-clinical validation of a beam model designed for treatment planning computation of active proton and carbon ion beams*"