The technical implementation of an IMPT system for research purpose

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Abstract. Because of their superior distribution, proton beams is the state-of-the-art modality in radiation therapy. There is a variety of researchers about proton therapy to utilize it. In this paper, we introduce a Matlab-based platform to develop and prototype proton treatment planning using LAP and CERR. Planning workflow to make an IMPT plan is described in details and demonstrated by a prostate case. The results showed that most of the dose criteria are satisfied, except for bladder and rectum, 2% of the volume of each organ receiving the least dose of 77.5 Gy (RBE) instead of 76 Gy(RBE) as dose requirements suggested by ICRU 78. As a result, planners absolutely can implement Intensity Modulated Proton Therapy plans by LAP and CERR for research purpose.

1. Introduction
Proton therapy has advantages over conventional radiation therapy using photon beams because of the capability of confirming the planned dose more closely to the specified target volume. In this work, we introduce a Matlab-based platform to develop and prototype proton treatment planning using CERR [1] and LAP [2]. CERR, the abbreviation for The Computational Environment for Radiotherapy Research, has been applied to a variety of purpose such as dose distribution modeling and treatment planning optimization [1]. The Laser Accelerated Particle (LAP), an extension for CERR was developed to provide the possibility to make the dose optimization easier and to provide the possibility to calculate doses for particle therapy (protons, carbons) as well [2]. The objective presented here is how to technical implementing of an Intensity Modulated Proton Therapy (IMPT) system for research purpose. The particular application for making IMPT plans in case of prostate cancer is used for workflow demonstration purpose.

2. Methods

2.1. Planning workflow
The overall process to make an IMPT plan is briefly described here. After importing CT data from a patient into CERR, all initial information of IMPT plan of the patient is archived in planC. To set up the parameters for the dose calculation process using IMRTP GUI. The optimized variables in LAP and CERR are weights of pencil beams. Before the optimization, the objective function is chosen to satisfy the plan requirements, specified by physicians. In CERR, the objective function is based on dose criteria. At each iteration, the computer changes the weight of each pencil beam to reach the stopping criteria. The optimization stops when no further significant improvement in objective
function is found. After the optimization process, planners use treatment plan analysis such as Dose Volume Histogram DVH to evaluate the plan. If the dose distribution is unacceptable, planners may adjust the specification of constraints and objectives saved in Matlab file \textit{readSettingsPatient.m} to improve the plan.

2.2. \textit{Dose calculation algorithm}

The dose calculation algorithm used in the programs is the pencil beam. The pencil beam is a beam with the infinitesimal cross area, and an incident beam of the larger cross-sectional area or irregular shape is modelled using some closely spaced finite pencil beams.

\textit{The dose delivered by each pencil beam having mono-energy E in the water to each voxel}

During interacting with material along the beam path, two physical effects dominate proton behavior: the energy loss due to Coulomb interaction with the atomic electrons of target material lead to the characteristic depth dose curve including the Bragg peak and the multiple Coulomb scattering with the target atoms result in the spreading of the beam (Figure 1). These two effects are almost independent so that the dose of each pencil beam \( D(\vec{r}, z, E) \) is separated into a central axis depth dose \( D(z, E_0) \) and a lateral dose \( L(\vec{r}, z, E) \) \cite{3, 4, 5}.

\[
D(\vec{r}, z, E) = c \cdot D(z, E_0) \cdot L(\vec{r}, z, E) \tag{1}
\]

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Illustrating the position of calculated voxel}
\end{figure}

with \( c \) is the correction factor due to inverse square law, calculated by

\[
c = \left( \frac{d_s}{d_p} \right)^2 \tag{2}
\]

Where \( d_s \) is the distance from the source to isocenter and \( d_p \) is the distance from the source to the calculated point. The lateral dose \( L(\vec{r}, z, E) \) can be estimated to the first order by a Gaussian distribution suggested by Moliere as following

\[
L(\vec{r}, z, E) = \frac{1}{2\pi\sigma^2(z, E)} \exp \left( -\frac{(r_0^2 - r_0^2)}{2\sigma^2(z, E)} \right) \tag{3}
\]

where \( r_0 \) is the position of the central beamlet axis and \( \sigma^2(d, E) \) is the standard deviation of the Gaussian distribution depending on the depth \( z \) in the material and the initial energy \( E \) of the proton beam. The standard deviation \( \sigma^2(d, E) \) is calculated by adding in quadrature the standard deviation due to the beginning size of the pencil beam and the multiple Coulomb scattering from the water.

\[
\sigma^2 = \sigma_a^2 + \sigma_b^2 \tag{4}
\]

Because the beam delivery is spot scanning method, \( \sigma_a \) is about 0.025 cm. \( \sigma_b^2 \) called lateral Spread Square is the standard deviation due to multiple Coulomb scattering in the lateral direction in the water phantom. \( D(z, E) \) in formula (1) and \( \sigma_b \) are estimated by the tabulated approach from depth dose curve and lateral spread square. This database has been compiled by Monte Carlo simulation.

\textit{Integrating the effect of all pencil beams}

The dose for the point of interest at \( \vec{r} \) is the sum of the doses of all pencils

\[
D(\vec{r}) = \sum_i D(\vec{r}_i, z_i, E_i) = \sum_i c_i \cdot D(z_i, E_i) \cdot L(\vec{r}_i, z_i, E_i) \tag{5}
\]
Heterogeneity correction

In CERR and LAP, to account for heterogeneity of tissues in patients, the depth of proton is corrected by the ratio of water CT number to body CT number. This will be explained as following in details.

![Diagram of proton pencil beam with sample points](image)

**Figure 2.** Illustrating the proton pencil beam with four sample points A, B, C, D

In Figure 2, A, B, C and D is the sample points on the central axis of pencil beam to calculate equivalent water depth. Because the dose database is calculated in water, the depth of proton in patients is replaced by equivalent water depth to calculate depth dose. For example, the equivalent water depth at B $z_{\text{effB}}$ equals to

$$z_{\text{effB}} = \frac{AB}{\text{Water CT Number}}$$

here $AB$ is the geometrical distance from A to B, CTNumber$_B$ is the CT number at voxel B, and Water CT Number equals to 1000.

The energy spectrum of laser-accelerated proton beam

The combination of LAP and CERR is used for treatment planning in case of proton beam accelerated by laser. One typical property of laser-accelerated proton beam is wide energy spread. To calculate dose delivered to each voxel in the patient for laser-accelerated proton beam, the spectra are decomposed into monoenergetic beams that can be simulated with the help of lookup tables containing dose database. There are five lookup tables for five parameters that are energy, depth, range, depth dose curve and the lateral spread square. To be able to cure deep tumors, the energy is required from 50 MeV up to 250 MeV with a step of 10 MeV. The width of each energy is 6 MeV. The energy solution of the initial particle fluence spectrum is 0.1 MeV. Therefore, at each energy, there are 61 energy values. Depth is from 0 cm to 55 cm with a step of 0.01 cm to resolve Bragg peak.

2.3. Dose optimization algorithm

Objective function

The objective function based on the dose criteria. In CERR, the dose constraints for organs at risk is set equal to zero, and the total objective function is given as following

$$\text{OF} = \sum_{n=1}^{N} \omega_{nT} \sum_{i=1}^{N_n} (D_{iT} - D_{nT})^2 + \sum_{m=1}^{M} \omega_{mOAR} \sum_{j=1}^{N_m} (D_{jOAR} - D_{mOAR})^2$$

The term $(D_{iT} - D_{nT})^2$, $(D_{jOAR} - D_{mOAR})^2$ means there is no difference between an underdosed point and overdosed point as long as their deviation to the prescribed dose is the same. $\omega_{nT}$, $\omega_{mOAR}$ are the important factors for the $n^{th}$ target volume and the $m^{th}$ organ volume respectively. The $D_{iT}$ and $D_{nT}$ are the calculated doses of the $i^{th}$ voxel and the prescribed dose in the $n^{th}$ target, $D_{jOAR}$ and $D_{mOAR}$ that are the calculated dose of the $j^{th}$ voxel and the dose constraints in the $m^{th}$ organ at risk. The $N$ and $M$ are the total number of targets and organs at risk respectively. The $N_n$ and $N_m$ are the total numbers of voxels in the $n^{th}$ target and the $m^{th}$ organ at risk.
Optimization algorithm
Optimization algorithm in CERR is Newton method with diagonal Hessian approximation and performed by function quadprog in Matlab.

2.4. Treatment plan analysis: Dose Volume Histogram DVH
Dose Volume Histogram–DVH is the most basic tool to look inside the dose distribution of tumor and organs at risk and used popularly in treatment planning.

3. Result and Discussion
A case of prostate cancer is selected to utilize IMPT system of CERR and LAP. Treatment prescription: \(D_{RBE} = 76\ \text{Gy}\) with Relative Biological Effectiveness (RBE) = 1.1 [6, 7]. The dose everywhere within the Planning Target Volume (PTV) be within 5 and 7 percent of the prescribed dose. Dose constraints: the least dose received by 2% volume of both Rectum and Bladder is smaller than 76 Gy (RBE).

Here, we also used the dose constraints of RTOG 0126 to evaluate the dose distribution of bladder and rectum more details (Table 1).

| Dose Constraints | Rectum | Bladder |
|------------------|--------|---------|
| \(V_{80\ \text{Gy (RBE)}}\) | 15% | |
| \(V_{75\ \text{Gy (RBE)}}\) | 25% | 25% |
| \(V_{70\ \text{Gy (RBE)}}\) | 35% | 35% |
| \(V_{65\ \text{Gy (RBE)}}\) | 50% | 50% |
| \(V_{60\ \text{Gy (RBE)}}\) | 50% | |

For femur heads, we use the recommendation of RTOG 0822: \(V_{40\ \text{Gy (RBE)}} \leq 40\%\) (RBE) [9]. \(V_{40\ \text{Gy (RBE)}}\) is the maximum volume receiving the dose of 40 Gy (RBE). Treatment planning: two beam orientations are 180 and 270 degrees. The margin between PTV and GTV is 12 mm. The margin between PRV and OAR including rectum, bladder and femur head is 6 mm. These margins are larger than of Thomas [10] to get the good coverage. Delivery technique: laser-accelerated proton beam with spot scanning [11]. Energy from 60 MeV to 260 MeV with step of 10 MeV. The width of each energy is 6 MeV. The energy solution of the initial particle fluency spectrum is 0.1 MeV.

Figure 3 shows the DVHs of Gross Tumor Volume (GTV) and PTV.

![Figure 3. The dose volume histograms of GTV and PTV](null)
The min dose and max dose of PTV is 97.5% and 107.5% respectively, satisfying the prescribed dose (see Figure 3). Especially, the dose to GTV is a uniform dose of 102.5%. That is the goal whichever radiation therapy desires to achieve.

![Figure 4. Dose-volume histograms of rectum and bladder](image)

![Figure 5. Dose-volume histograms of left Femur and right femur](image)

The maximum dose to rectum and bladder are the same value of 77.9 Gy (RBE). The maximum dose to right femur and left femur are the same value of 40 Gy (RBE). That means a small volume of them is receiving the dose of 40 Gy (RBE). The minimum doses to 2% volume of the rectum, bladder are both 77.5 Gy (RBE). Comparison with the dose constraints suggested by ICRU 78, both rectum and bladder receive little higher doses than dose constraints of 76 Gy (RBE). The reason is that a small volume of them being in the PTV (Figure 4 and Figure 5). Both rectum and bladder satisfied the dose requirements listed in Table 2.

4. Conclusion
A good IMPT plan in case of prostate cancer was performed. The PTV received the adequate dose from 97.5% to 107.5% of prescribed dose. All of the dose constraints of OARs satisfied the recommendations of RTOG 0126 and RTOG 0822. However, according to dose requirements of ICRU 78, most of the dose criteria are satisfied, except for bladder and rectum, the minimum dose to 2% of each OARs-rectum and bladder is 77.5 Gy (RBE) instead of 76 Gy (RBE). As a result, planners absolutely can implement IMPT plans by CERR and LAP for research purpose.

Acknowledgments
We thank Stefan Schell for helpful conversations about CERR and LAP features. This work was partially supported by Grant T2017-12 from the VNUHCM-University of Science, Ho Chi Minh City, Vietnam.
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