matRad – a multi-modality open source 3D treatment planning toolkit

E. Cisternas[1,6], A. Mairani[2,5], P. Ziegenhein[3], O. Jäkel[1,4,5] and M. Bangert[1]

[1]German Cancer Research Center DKFZ, Department of Medical Physics in Radiation Oncology, Heidelberg, Germany
[2]Centro Nazionale di Adroterapia Oncologica, Pavia, Italy
[3]Joint Department of Physics, The Institute of Cancer Research and The Royal Marsden NHS Foundation Trust, London, UK
[4]Heidelberg University Hospital, Heidelberg, Germany
[5]Heidelberg Ion Therapy Center,Heidelberg, Germany
[6]Instituto de Física, Facultad de Física, Pontificia Universidad Católica de Chile, Santiago, Chile

Abstract— **We present matRad, an open source software for three-dimensional radiation treatment planning of intensity-modulated photon, proton, and carbon ion therapy. matRad is developed for educational and research purposes; it is entirely written in MATLAB. A first beta release is available for download[1]. The toolkit features a highly modular design with a set of individual functions modeling the entire treatment planning workflow based on a segmented patient CT. All algorithms, e.g. for ray tracing, photon/proton/carbon dose calculation, fluence optimization, and multileaf collimator sequencing, follow well-established approaches and operate on clinically adequate voxel and bixel resolution. Patient data as well as base data for all required computations is included in matRad. We achieve computation times of 60-100s (60-400s) for realistic patient cases including photon (particle) dose calculation and fluence optimization. Memory consumption ranges between 0.2GB and 2.2GB. Dose distributions of a treatment planning study for a phantom and prostate patient case considering multiple radiation modalities are shown. Both the computational and dosimetric results encourage a future use of matRad in an educational and scientific setting.**

Keywords— **Radiation therapy, particle therapy, treatment planning, open source software.**

I. Introduction

Medical physics in general and radiation therapy planning in particular are specialties that heavily rely on the use of dedicated software. Due to the involvement of commercial enterprises and high safety requirements in medical applications, however, treatment planning systems usually come with a closed architecture. This compromises both the broad availability of radiation treatment planning software for educational purposes and the flexibility regarding custom developments in an academic setting.

Consequently, some research centers maintain highly specialized research treatment planning systems for custom developments. While most of these solutions are only available to a limited number of cooperators [1, 2] some solutions are/will be made available to the general public [3, 4].

[1] http://e0404.github.io/matRad/

With this paper we describe the implementation of the first beta release of matRad, an open source treatment planning system[2] supporting intensity-modulated photon, proton and carbon ion radiation therapy. matRad is entirely implemented in MATLAB[3]. It is developed for educational and research purposes. The code features high modularity and consequently flexibility. At the same time, matRad allows for an efficient workflow considering realistic patient cases. It comprises educational visualizations of the underlying physical aspects. Besides the source code itself, matRad also includes example patient data and the appropriate base data for photon, proton, and carbon ion irradiation.

Section II details the physics and optimization algorithms used by matRad, it explains how to obtain the source code and how to contribute to its development. Computation times as well as results of a first treatment planning study are shown in section III. A discussion and conclusion in sections IV and V conclude the paper.

II. Methods

A. matRad modules

```
% load patient data
[ct,cst] = matRad_load('patient.mat');
% set plan parameters
pln = ...
% determine beam geometry
stf = matRad_generateStf(ct,cst,pln);
% dose calculation
dij = matRad_calcDose(ct,stf,pln,cst);
% inverse planning
[wOpt,dOpt] = matRad_inversePlanning(dij,cst);
% analysis
matRad_calcDVH(dOpt,cst);
matRad_visCtDose(dOpt,cst,pln,ct);
```

Fig. 1: Pseudocode overview of the matRad workflow.

[2] matRad is published under the GNU General Public License v3.0
[3] http://www.mathworks.com/products/matlab

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Table 1: Computational efficiency of selected treatment planning scenarios for the TG119 phantom [5]: The number of non-zero D_{ij} elements corresponds to the total number of dose deposition elements which are pre-calculated during dose calculation and subsequently used during optimization. The photon treatment plans apply a 5×5mm² bixel resolution; the particle treatment plans apply 3mm spot spacing. The voxel resolution is 3.0×3.0×2.5mm³.

modality	# beams	# bixels	# non-zero D_{ij}	$T_{dose\ calc}$ [s]	$T_{fluence\ opt}$ [s]	memory [GB]
photons	5	1164	$14.4 \cdot 10^6$	52.1	11.4	0.2
photons	7	1556	$18.7 \cdot 10^6$	71.7	20.5	0.3
photons	9	1841	$21.6 \cdot 10^6$	81.4	21.8	0.3
protons	1	6334	$11.4 \cdot 10^6$	29.8	26.2	0.2
protons	2	12770	$41.9 \cdot 10^6$	55.1	53.8	0.6
protons	3	19187	$72.2 \cdot 10^6$	81.4	125.9	1.1
carbon ions	1	9806	$33.4 \cdot 10^6$	38.0	23.6	0.5
carbon ions	2	19438	$91.0 \cdot 10^6$	73.1	99.7	1.4
carbon ions	3	29122	$148.6 \cdot 10^6$	112.7	272.4	2.2

Figure 1 illustrates the most important steps of the treatment planning workflow in matRad. After the patient data comprising a CT dataset (ct) and a corresponding segmentation (cst) have been loaded (compare sections II.B and IV) the user has to specify a treatment plan (pln). Among others, this step includes setting the beam orientations and the radiation modality. Next the beam geometry, i.e. is the bixel grid for photon treatments and the spot placement for particle therapy, is automatically determined [6]. The resulting file (stf) is required for the subsequent photon, proton, or carbon ion dose calculation. For photons, matRad uses a singular value decomposed pencil beam algorithm [6,7]. For particles, a pencil beam algorithm facilitating a single Gaussian to approximate the lateral dose profile is applied [6,8]. The dose computation for all modalities applies an exact three-dimensional ray tracing algorithm for the computation of radiological distances [9]. Base data for the dose calculation algorithms is obtained by measurement at the German Cancer Research Center (photons), analytical computation [10, 11] (protons), and Monte Carlo simulations (carbon ions). Fluence optimization using the pre-computed dose influence data (dij) is performed through minimization of the standard piece-wise quadratic objective function [12]. Convenient tweaking of maximum dose constraints and optimization penalties of the objective function is possible through via MATLAB's built-in variable editor (cst). For photon IMRT, we implemented a multileaf collimator sequencing algorithm [13] to translate the continuously optimized fluence (wOpt) into deliverable segments. The result of matRad's treatment planning workflow, namely the optimized dose (dOpt), can be visualized via dose volume histograms and two-dimensional dose distributions overlaying the patient CT.

As depicted in figure 1, all modules correspond to individual MATLAB functions. They can be called as part of a MATLAB script or individually from MATLAB'S command prompt. Most functions feature a visualization of the underlying algorithm for educational purposes (not shown).

B. Patient data

The matRad toolkit comes with MATLAB workspace files of the CORT dataset [14] comprising CT images and segmentations for three patient cases and AAPM's TG119 phantom case [5]. Users can directly experiment with this freely available data.

C. Source code

The matRad source code is provided via an online Git repository at http://e0404.github.io/matRad. Users can either download the entire source code as compressed archive or make direct use of the functionalities of the Git repository[4] to obtain the code and contribute to its development. Via GitHub it is possible to file bug reports and feature requests. Furthermore, the open Git repository enables everybody to submit code modifications to the matRad development team. In the future we are going to extend the representation of matRad on GitHub to include dedicated wiki documentation.

III. Results

A. Computational efficiency

Table 1 lists the computation time of the dose calculation and the fluence optimization as well as the memory consumption of matRad during treatment planning for AAPM's

[4] https://github.com/e0404/matRad

TG119 phantom [5] for different irradiation scenarios. Note that we are operating at a clinically realistic resolution.

B. Treatment planning study

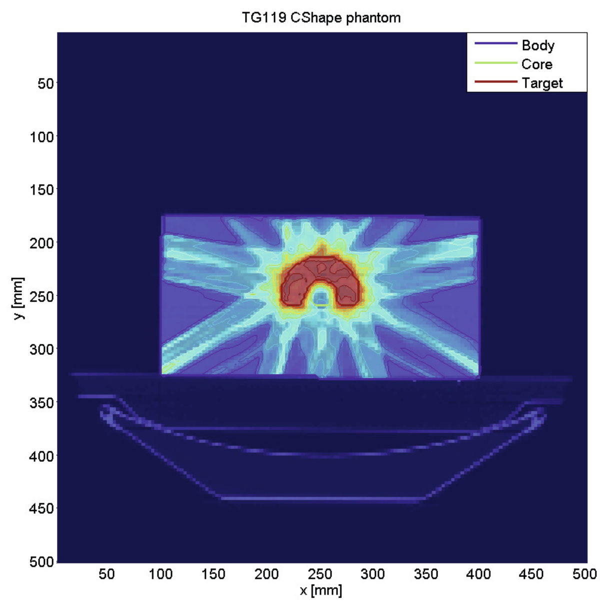

Fig. 2: Transversal dose distribution of a photon IMRT treatment plan applying nine equi-distant coplanar beams on the TG119 phantom [5]. The transparent dose colorwash on the CT is overlaid by isodose contours in 10 Gy increments.

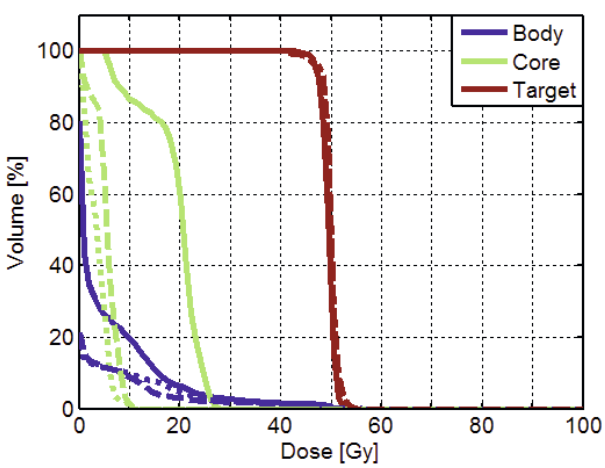

Fig. 3: Dose volume histograms of a photon IMRT treatment plan applying nine equi-distant coplanar beams (solid lines), an intensity-modulated proton therapy treatment plan applying three fields at gantry angles 0°, 90°, and 270° (dotted lines), and an intensity-modulated carbon ion therapy treatment plan applying three fields at gantry angles 0°, 90°, and 270° (dashed lines) for the TG119 phantom [14].

Figures 2 and 3 show results of a first treatment planning study for the TG119 phantom [14]. Using matRad, it was possible to generate a photon treatment plan fulfilling the clinical goals specified in [5]. For demonstration purposes, figure 3 also includes dose volume histograms for proton and carbon ions; figure 4 shows a transversal dose distribution of a proton treatment plan applying two intensity-modulated fields. Note that we only consider physical dose for both protons and carbon ions. As the radiobiological effectiveness is not yet taken into account by matRad, the numbers have to be interpreted with care – especially for carbon ions.

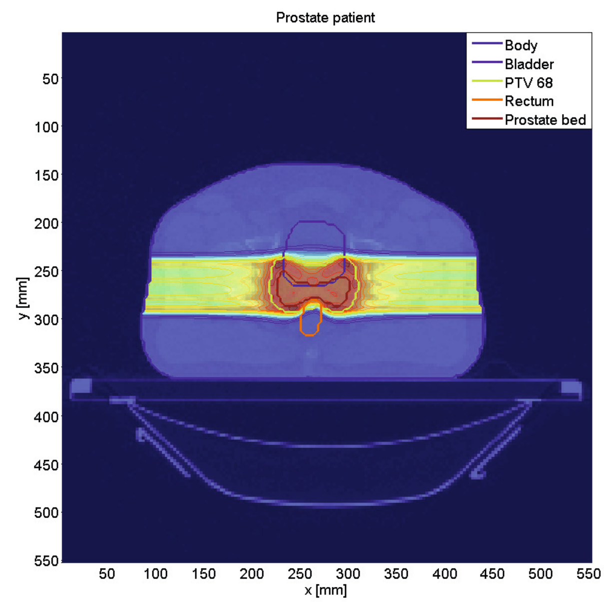

Fig. 4: An intensity-modulated proton therapy treatment plan applying two fields at gantry angles 90°, and 270° on the prostate patient data included in the CORT dataset. The transparent dose colorwash on the CT is overlaid by isodose contours in 10 Gy increments.

IV. Discussion

We present the first open source toolkit for multi-modality radiation treatment planning. We choose the proprietary scientific programming environment MATLAB for development as it is ubiquitous at universities and in the medical physics community. MATLAB enables highly efficient prototyping. It combines a variety of built-in functions, versatile visualization possibilities and comprehensive debugging functionalities. Even though MATLAB uses an interpreter programming language which does not require compilation it allows for the development of efficient code.

matRad complements other open source MATLAB software in the field of radiotherapy. In the future easy interfacing to CERR[5], a MATLAB platform for developing and sharing research results in radiation therapy treatment planning [1], and to FoCa[6], an open MATLAB treatment planning system for passive scattering and pencil beam scanning proton therapy [2], might be possible. Nevertheless, we also want to maintain a clear form of matRad in future releases. Potential overhead necessary for clinical validation (as performed for FoCa) and/or a sophisticated graphical user interface (as implemented for CERR) may conflict with a concise implementation of the underlying algorithms, which is desired for both educational and research purposes.

In order to maximize usability of matRad for the entire medical physics community, the next step is the development of an adequate online documentation through dedicated personnel. Among others, we want to include functionalities for DICOM import of patient data, direct aperture optimization for IMRT/VMAT, more sophisticated objective functions for inverse planning, and radiobiological effectiveness models for particle therapy treatment planning in future releases. matRad might also be a suited platform to showcase novel work in robust optimization [15].

V. Conclusions

matRad is the first open source toolkit supporting treatment planning for intensity-modulated photon, proton, and carbon ion therapy. It includes efficient MATLAB implementations of well-established algorithms modeling the entire radiation treatment planning workflow. Besides the actual treatment planning system, matRad also includes example patient data as well as base data for all supported radiation modalities. The presented MATLAB implementation yields competitive computation times for realistic planning scenarios and its modular design provides high flexibility. In the future we envisage manifold beneficial applications of matRad both in an educational and research setting.

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Conflict of Interest

The authors declare that they have no conflict of interest.

[5] http://www.cerr.info/

[6] FoCa is currently being tested at the University of Pennsilvania; it is not yet available for public download.

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Author: Dr. Mark Bangert

Institute: German Cancer Research Center DKFZ
Street: Im Neuenheimer Feld 280
City: 69120 Heidelberg
Country: Germany
Email: m.bangert@dkfz.de