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To cite this article: J C L Chow and M K K Leung 2008 J. Phys.: Conf. Ser. 102 012003

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A graphical user interface for calculation of 3D dose distribution using Monte Carlo simulations

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Abstract. A software graphical user interface (GUI) for calculation of 3D dose distribution using Monte Carlo (MC) simulation is developed using MATLAB. This GUI (DOSCTP) provides a user-friendly platform for DICOM CT-based dose calculation using EGSnrcMP-based DOSXYZnrc code. It offers numerous features not found in DOSXYZnrc, such as the ability to use multiple beams from different phase-space files, and has built-in dose analysis and visualization tools. DOSCTP is written completely in MATLAB, with integrated access to DOSXYZnrc and CTCREATE. The program function may be divided into four subgroups, namely, beam placement, MC simulation with DOSXYZnrc, dose visualization, and export. Each is controlled by separate routines. The verification of DOSCTP was carried out by comparing plans with different beam arrangements (multi-beam/photon arc) on an inhomogeneous phantom as well as patient CT between the GUI and Pinnacle 3. DOSCTP was developed and verified with the following features: (1) a built-in voxel editor to modify CT-based DOSXYZnrc phantoms for research purposes; (2) multi-beam placement is possible, which cannot be achieved using the current DOSXYZnrc code; (3) the treatment plan, including the dose distributions, contours and image set can be exported to a commercial treatment planning system such as Pinnacle 3 or to CERR using RTOG format for plan evaluation and comparison; (4) a built-in RTOG-compatible dose reviewer for dose visualization and analysis such as finding the volume of hot/cold spots in the 3D dose distributions based on a user threshold. DOSCTP greatly simplifies the use of DOSXYZnrc and CTCREATE, and offers numerous features that not found in the original user-code. Moreover, since phase-space beams can be defined and generated by the user, it is a particularly useful tool to carry out plans using specifically designed irradiators/accelerators that cannot be found in the Linac library of commercial treatment planning systems.

1. Introduction
The introduction of newer technology in radiotherapy prompts the need for more accurate dose calculation, which is important especially when the target volume is associated with inhomogeneous medium such as lung. Monte Carlo dose calculation method, such as EGSnrc-based DOSXYZnrc code, is well known as a benchmark tool to calculate dose distributions with inhomogeneities. Given the popularity of DOSXYZnrc as a simulation code, it is coupled with a routine called CTCREATE, which is able to convert a DICOM/RTOG/Pinnacle-formatted CT image dataset into a 3D DOSXYZnrc phantom for Monte Carlo simulation. However, the CTCREATE routine functions through a command line interface and the existing DOSXYZnrc graphical user interface (GUI) has no visualization tool to view and position beams within a CT phantom. Furthermore, there is only limited support in DOSXYZnrc to view and analyse the calculated doses after simulation conveniently. A GUI called DOSCTP, for
calculation of 3D dose distribution using Monte Carlo simulation was therefore developed to provide a user-friendly human-computer interface for non-IMRT treatment plans using EGSnrc/DOSXYZnrc as a dose calculation engine.

2. Methods
DOSCTP is written using MATLAB and its Image Processing Toolbox. MATLAB is chosen because it is a numerical computing environment that features an extensive library. The code can be freely modified and does not need to be compiled. Moreover, MATLAB can be run on various platforms such as Linux, MS-Window and Mac OS X. Figure 1 shows the flowchart of the DOSCTP program. The GUI contains four main components, namely, Treatment Planning, Monte Carlo Simulation with DOSXYZnrc, Dose Visualization and Export. The MATLAB routines associated with each step in the flowchart are also displayed. In the Treatment Planning block, the user loads a DICOM image set or DOSXYZnrc phantom into the system to initiate a plan. This is followed by definition of the isocenter coordinates and beam(s) placement. If the image source is DICOM, it is converted into a DOSXYZnrc phantom based on user-selected voxel numbers or dimensions. The user is then given a chance to edit the phantom. After the DOSXYZnrc phantom is set up, the GUI performs Monte Carlo Simulation with DOSXYZnrc. The user may adjust a set of DOSXYZnrc simulation parameters within the DOSCTP GUI. The program then automatically generates the input file(s), one for each beam, and performs dose calculation with DOSXYZnrc. To view the isodose lines, the Dose Visualization block is executed to import and display the calculated doses. Finally in the Export block, information relevant to the plan can be exported to a text file in the form of a report, while the treatment plan can be exported as RTOG. The DOSXYZnrc phantom can also be exported in DICOM format for import into commercial treatment planning systems.

3. Features of DOSCTP
3.1. CT image visualization and beam placement
Figure 2 shows the front-end window of DOSCTP with an imported CT image of a mouse to be irradiated with a 4-beam conformal plan (beam angles = 115, 180, 270 and 330 deg; field diameters = 5 mm). A panel (top left) manages the beam configurations. There, phase-space beams (P.S. Beam) generated by the user in BEAMnrc can be selected from a user-built library and added to the plan. Alternatively, the user
has the option of using monoenergetic parallel rectangular beams (P.R. Beam), which do not require phase-space files. To set up photon/electron phase-space beams in the GUI, the user can create a library of phase-space sources, which are stored in the GUI database. Beams in the library can be added, deleted and acquired from the user’s phase-space files at any time through the GUI for planning.

The contour panel (middle left) assists the user in adding and editing contours. Contour can be added, edited and removed through the contour panel. Contour created by DOSCTP can be exported in RTOG format and import into external treatment planning system or CERR.\(^8\)

The isocenter panel (bottom left) permits definition of the isocenter coordinates. The isocenter position is by default defined at the center of the slice closest to the z-axis origin of the coordinate system of the image set. It can be redefined by the mouse pointer or entered through the keyboard from the isocenter panel.

A tools panel is located at the top of the GUI to provide additional features for navigating CT images, selecting a point of interest for the isocenter, orienting beams, or drawing contours. To the right of the tools panel, is a set of control used for the display of relative isodose lines and selection of a normalization point from the user.

![Figure 2](image-url) The front-end window of DOSCTP showing an imported mouse CT image dataset with a 4-beam conformal plan at the right lung.

### 3.2. Dose calculation using EGSnrc/DOSXYZnrc

Dose calculation in DOSCTP is performed by the DOSXYZnrc code through the EGSnrcMP system. When the DICOM image set is converted into DOSXYZnrc format by DOSCTP, the user can edit the phantom pixel-by-pixel using the phantom editor as shown in Fig. 3. When the user is finished with the plan, a set of simulation parameters, such as number of histories, maximum CPU time, ECUT, PCUT and
others required by DOSXYZnrc may be edited. Input file(s) are then generated to perform Monte Carlo simulation. After all input parameters, beams and phantom have been defined by the user, DOSXYZnrc proceeds with the dose calculation automatically. The calculated doses are stored in the default .3DDOSE file output. If there is more than one .3DDOSE file as a result of multiple beams included in the plan, the .3DDOSE files are automatically merged.

![Figure 3 A slice of the mouse CT shown in the DOSXYZnrc phantom editor.](image)

### 3.3. Calculated dose visualization

When Monte Carlo simulation is complete, the dose can be displayed on top of the CT images. The sample dose distribution is displayed as shown in Fig. 4 for a mouse irradiated by a 4-beam conformal plan of 225 kVp photon beam. Isodose lines are always displayed in terms of relative doses in percentage with respect to a normalization point. Moreover, the dose information panel in Fig. 4 (under the transverse CT image window) shows the value of the relative dose of a voxel selected by the mouse pointer from the user. The user can define the appearance of the isodose lines, such as the spacing, font size, colour of the relative dose labels, and the isodose levels to be displayed and their line width.

### 3.4. Plan saving and loading

All existing plan configuration can be saved as .PLN file and loaded for calculation at a later time. The images displayed on the transverse, sagittal and coronal window can be exported as graphic files in BMP or JPEG format. Apart from viewing the dose distributions on the GUI, the .3DDOSE data file can be displayed using an external DOSXYZnrc/RTOG-compatible dose viewer.

### 4. Results and discussion

#### 4.1. CT number / density-material conversion ramp

Each voxel in a DOSXYZnrc phantom is associated with a material and density; in a DICOM image, it is described by a CT number. The conversion from a CT number to material/density is determined by a user-specified ramp that can be modified in the *user_parameters.m* option file. The conversion is based on the following two formulas using linear interpolation: (i) Conversion from CT number to density:
Figure 4 The dose distribution of a mouse irradiated by a 4-beam conformal plan of 225 kVp shown in DOSCTP.

\[
rhor_{i,j,k} = \text{material}_{-\text{density}}_{-\text{lower}}_{-\text{bound}}_{-\text{material}} + \\
\left(\frac{\text{material}_{-\text{density}}_{-\text{upper}}_{-\text{bound}}_{-\text{material}} - \text{material}_{-\text{density}}_{-\text{lower}}_{-\text{bound}}_{-\text{material}}}{\text{material}_{-\text{ct}}_{-\text{upper}}_{-\text{bound}}_{-\text{material}} - \text{material}_{-\text{ct}}_{-\text{upper}}_{-\text{bound}}_{-\text{material}} - 1}\right) \\
\times \left(\text{CT}_{i,j,k} - \text{material}_{-\text{ct}}_{-\text{upper}}_{-\text{bound}}_{-\text{material}}\right)
\]

(1),

and (ii) Conversion from density to CT number:

\[
\text{CT}_{i,j,k} = \text{material}_{-\text{ct}}_{-\text{upper}}_{-\text{bound}}_{-\text{material}} + \\
\left(\frac{\text{material}_{-\text{ct}}_{-\text{upper}}_{-\text{bound}}_{-\text{material}} - \text{material}_{-\text{ct}}_{-\text{upper}}_{-\text{bound}}_{-\text{material}} - 1}{\text{material}_{-\text{density}}_{-\text{upper}}_{-\text{bound}}_{-\text{material}} - \text{material}_{-\text{density}}_{-\text{lower}}_{-\text{bound}}_{-\text{material}} - 1}\right) \\
\times \left(\text{rhor}_{i,j,k} - \text{material}_{-\text{density}}_{-\text{lower}}_{-\text{bound}}_{-\text{material}}\right)
\]

(2),

where CT_{i,j,k} and rhor_{i,j,k} are the CT number and density of a voxel at coordinate (i, j, k) respectively. It is important to note that for dose calculation comparison between the commercial treatment planning system and Monte Carlo simulation, the CT number conversion ramp used in the treatment planning system clinically must equal the ramp used in DOSCTP in order to keep the material and density in the voxel interpreted correctly. To implement a new user-defined CT number conversion ramp other than that of the default, the user may edit the ramp defined in the user_parameters.m option file. The conversion ramp is also important when the user wants to edit the phantom voxels through the phantom editor. The ramp defined in user_parameters.m should be the same as the ramp used to create the phantom file through CTCREATE. Otherwise, an incorrect material may be attributed to the modified voxels in the edited...
phantom. A built-in check ensures that the materials stated in the .EGSPHANT file is the same as that defined in the DOSCTP ramp.

4.2. RTOG/DICOM export and import
DOSCTP includes a phantom editor for clinical research. The modified phantom can be converted into a DICOM CT dataset and imported into a treatment planning system for planning. In addition, the completed plan, dose distributions and contours from DOSCTP can be converted to RTOG format for import into a treatment planning system for more detailed plan investigation and evaluation. Conversely, the doses from a plan performed by a commercial treatment planning system can be imported into DOSCTP for dose viewing, analyses and normalization. By allowing plans to be imported and exported to, and from DOSCTP and external treatment planning systems through RTOG, it is possible to investigate the dose distributions calculated by Monte Carlo simulation in great details. The export feature allows plan evaluation using dose volume histogram and calculations of radiobiological parameters such as tumour control probability and normal tissue complication probability from the dose distributions calculated in DOSCTP.

5. Conclusion
A GUI, DOSCTP, is developed for calculation of 3D dose distribution using Monte Carlo simulations. DOSCTP greatly simplifies the use of DOSXYZnrc and CTCREATE, and in addition, offers numerous features that are not found in the original user-code. The GUI supports both the CT DICOM image sets and user-created phantoms in DOSXYZnrc format. Phantom can be graphically edited pixel-by-pixel before simulation, and later exported into a DICOM image set that can be imported by treatment planning systems such as Pinnacle3 or CERR. Integrating DOSCTP within CERR is a future work in this project. Moreover, since this GUI uses phase-space beam defined and generated by the user, it is particularly useful to carry out dose calculation using a specifically designed irradiator/accelerator that cannot be found in the Linac library of commercial treatment planning systems. This GUI can be requested from the authors.

Acknowledgement
Authors would like to thank Dr David Jaffray at the Princess Margaret Hospital to provide the mouse CT image dataset and to support this project.

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