TREATMENT PLANNING SYSTEMS FOR BNCT: REQUIREMENTS AND PECULIARITIES

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SUMMARY

The main requirements and peculiarities expected from the BNCT-oriented treatment planning system (TPS) are summarized in this paper. The TPS is a software, which can be integrated or composed by several auxiliary programs. It plays important roles inside the whole treatment planning of the patient's organ in BNCT. However, the main goal is the simulation of the irradiation, in order to obtain the optimal configuration, in terms of neutron spectrum, patient positioning and dose distribution in the tumour and healthy tissues.

The presence of neutrons increases the level of complexity, because much more nuclear reactions need to be monitored and properly calculated during the simulation of the patient's treatment. To this purposes several 3D geometry reconstruction techniques, generally based on the CT scanning data, are implemented and Monte Carlo codes are normally used.

The TPSs are expected to show also the results (basically doses and fluences) in a proper format, such as isocurves (or isosurfaces) along the CT scanning planes or graphs along a user-defined axis.

The most used BNCT-dedicated TPSs have been briefly described in this paper: NCTPlan and SERA. Also the main characteristics of BDTPS are reported. This TPS has been thought with the aim of properly coupling the real ^{10}B macroscopic distribution, obtained via PET scanning of the patient's organ, to the 3D and Monte Carlo modelling.

Introduction

The Treatment Planning (TP) is the process, which leads to the definition of the best irradiation modality, in terms of the optimal dose distribution in the tumour and healthy tissue. Since this decision process takes place before the patient's irradiation, it constitutes a crucial point in respect to the success of the Boron Neutron Capture Therapy (BNCT).

Several parameters should be taken into account during this decision process:

- the irradiation geometry (relative positioning between the patient and the source);
- the number of irradiation fields;
- the quality of the irradiation beams (neutron spectrum tailoring, etc.);
- the duration of the irradiation.

Besides, a peculiar aspect of BNCT is the presence of neutrons, which provide several nuclear reactions, each one characterized by its own physical and biological dose. All these doses must be taken into account in such a way that the healthy tissue undertakes the minimum possible damage after the irradiation, while the tumour tissue receives the lethal dose.

Therefore, the Treatment Planning is characterized in this case by very complex and delicate peculiarities, which must be properly addressed.

Materials and methods

The irradiation is only the last step of a toilsome process, which involves all the persons that take care of the therapy preparation in function of the patient's requirements. The main goal of this phase is the optimisation of all the parameters in order to release the maximum dose to the tumour tissue, maintaining at the same time the dose to the healthy tissue at a reasonable level.

Just to give an example, the irradiation protocol adopted at Studsvik Medical AB (Nyköping, Sweden) foresees the following reference parameters: peak dose (in 1 cm^3 volume) equal to 15 RBE-Gy and a mean dose of 6 RBE-Gy to the healthy tissue. The limiting dose is calculated into the normal tissue, because of two reasons:

1. there are radiation components which diffuse into all the tissues. Of course, the normal tissue should be protected from an over-exposure.
2. the unavailability of a proper knowledge related to the micro-distribution of the boron nuclei into the tumour.

In fact, the fission fragments of the boron capture reaction (α and ^7Li) are characterized by a high LET. In other words they loose their energy in a very short range (about 10 μm, which is almost equal to the mean cellular diameter). Therefore, the accurate definition of the boron distribution at cellular and sub-cellular level is necessary in order to evaluate the relative biological effectiveness of the secondary particles emitted during the irradiation [1]. For this reason, it has been decided to fix the tolerance level on the healthy tissue, assuming that this dose implies the maximum possible dose to the tumour ("*Primum non nocere*")*.*

A typical TP is composed of the following phases [2]:

a) CT and/or MRI scanning of the patient;

b) Use of the medical images in the reconstruction of the anatomic-computational model of the specific patient. This model is necessary for a proper Monte Carlo simulation of the irradiation configurations.

c) Definition and positioning of the irradiation fields.

d) Doses calculation on the grounds of the Monte Carlo results.

e) Evaluations of the related isodose curves.

f) Simulation of the patient positioning in the irradiation room, based on the results of the calculations.

g) Evaluation of the "monitor units", which are parameters to take into account for the proper definition of the beam quality in respect to a reference configuration. This is justified by the variance of the neutron spectrum in a nuclear reactor (up to now, the most used neutron source in BNCT), especially if it is used for several purposes.

At the end of this procedure, it is possible to pass to the irradiation phase.

Considering that the irradiation beam connects directly the reactor core to the irradiation room, it is clear that this configuration limits the degrees of freedom in the patient's positioning. This is why *ad hoc* solutions should be adopted in terms of the patient's bed and similar devices.

Excluding the steps a) and g), all the others are performed through the use of suitable software applications, which are normally known as Treatment Planning Systems (TPSs).

Generally speaking, a TPS is composed by:

1) A module for the reconstruction of a 3D Model, which fully describes the anatomy of the patient's organ to be irradiated and the "regions of interests" (ROIs), which is composed of.

2) A module for the calculation of the radiation transport into the patient's tissue (Monte Carlo model).

3) A module for the analysis of the calculation results. These should be represented in a way that the treatment planner can easily identify the optimal irradiation configuration.

The module 1) permits the analysis of the CT or MRI images in order to identify the ROIs (generally the skin, skull, healthy and tumour tissue are the main ones). Besides, the "target volume" identifies the tumour (as it can be found in the MRI imaging), the surrounding oedema and a safety margin of 1-2 cm [3]. In this part, particular attention should be paid to the localization of the radiosensitive organs (i.e. retina, optic chiasm, ears, etc.). The 3D Model is constructed in a format, which can be utilized by the other modules.

The module 2) is used to make the calculations of the radiation transport in several configurations, changing the relative positioning between the patient and the source, the neutron and gamma fluence, the duration of the irradiation, etc.

At the end of the calculations, the module 3) shows the results or through monodimensional graphs, or using the isodose curves, superimposed on the medical images or through the dose-volume histograms.

All this issues are actually quite diffused in the standard TPS used in the conventional therapies. The exception is given by the use of Monte Carlo codes for the radiation transport (module 2). This feature is almost an obliged choice, due to the complex 3-dimensionality of the problem and the presence of neutrons, whose physics is definitely more complicated than that of the photons.

In particular, in BNCT several nuclear reactions appear during the irradiation, but especially four of them contribute to the whole energy release:

- the reaction $^{10}B(n, \alpha)^{7}Li$;
- the reaction $^{14}N(n, p)^{14}C$;
- the reaction $^{1}H(n,n')^{1}H$, only in the case of epithermal flux;
- the reaction $^{1}H(n, \gamma)^{2}H$.

The contribution of these reactions to the total energy release during the irradiation should be simulated before the treatment by Monte Carlo codes in a complex geometry, which takes into account the anatomy of the patient's head (at least, in the treatment of the glioblastoma multiforme). Actually, also Discrete Ordinates codes [4] are available for these calculations, but still need further improvements.

From the technical point of view, three main features are necessary for a reliable simulation of the neutron transport:

a) definition of the geometry (i.e. patient's head). This is directly inherited from the module 1), previously described.

b) Materials and their nuclear properties. In BNCT a very important issue is the localization and quantification of the ^{10}B nuclei concentrations.

c) Neutron source characterization, in terms of angular and radial distribution.

The features a) and b) are really BNCT-related and requires a very precise definition of the material properties at the millimetre scale. In particular, the metabolism-dependent boron distribution requires its localization through a suitable diagnostic machine, able to follow the dynamics of the boron compound.

Recently, several studies suggested that Positron Emission Tomography (PET) can be the solution to this problem. In practice, the boron compound is labelled with a positron emitter (typically ^{18}F) and infused intra-veneously in the patient. The boron distribution is qualitatively and quantitatively determined using a patient-specific algorithm [5, 6]. This boron mapping can be used in the post-processing phase, when the transport code results (doses and fluences) are scaled on the grounds of the boron concentration values. However, to this purpose the 3D Model and the Monte Carlo Model should be directly connected to the Boron Model, before the radiation transport. This process needs

a reasonable match between the PET and CT images: the first gives the Boron Model, while the second gives the 3D Model and the Monte Carlo Model. This complex structure is integrated in an all-in-one TPS, called BDTPS (Boron Distribution Treatment Planning System) [7].

The most used TPSs in the BNCT Community are NCTPlan [8] and SERA [9] (called BNCT_rtpe in the previous version). They are different in the implementation, but follow the same basic structure, previously described. However, both of them have been implemented with the aim to consider the ^{10}B uniformly distributed in the ROIs. This choice has an historical reason; in fact, PET has been only recently exploited as a diagnostic machine in BNCT. However, studies have been performed in order to use SERA for a PET-based TPS, making use of auxiliary codes [10].

Finally, it should be worth to mention that among the various BNCT activities in Japan, also an independent treatment planning system has been developed in JAERI in 2001 (JCDS, JAERI Computational Dosimetry System [11]).

Results and Discussion

Due to space restrictions, in this paragraph the main properties of the main TPSs used in the BNCT Community (SERA and NCTPlan) are described. Additionally, a brief description of BDTPS is present. For further information on the remaining TPSs, it is suggested to follow the given references.

NCTPlan

NCTPlan has been designed and implemented at MIT (Massachussets Institute of Technology) and it is used inside the BNCT irradiation protocol followed by the Harvard-MIT group and in the Czech Republic.

This TPS has been actually upgraded and improved several times since its first conception. Initially, around 1990 it was called NCTPLAN [12] and was designed in order to optimise the beam configuration (dimensions, orientation, energy), making use of a brain-equivalent model, called NPBE (Neutron Photon Brain Equivalent). This model is made by two non-concentric ellipsoids. The elemental composition of this model is based on the average of the densities and percentages of each single element in the grey and white matter and in the skull. Table 1 shows the elements whose contribution to the total neutron scattering or capture cross section is equal at least to 1%.

Element percentage (in weight)										**Density**
Tissue	H	C	N	O	Ca	P	Cl	K	Na	(g/cc)
Brain	10.6	14.0	1.84	72.5	---	0.39	0.14	0.39	0.14	1.047
Skull	5.0	14.0	4.0	45.0	21.0	11.0	---	---	---	1.5

Table 1 – Elemental composition and density for the brain and skull in NPBE model

It is evident from this table that no boron has been considered during the neutron transport in NCTPLAN, because at that time the MIT BNCT experts thought that there should have been no influence on the neutron transport from such small boron concentrations, also taking into account the heterogeneous structure of the tumour tissue. However, following studies have demonstrated that, assuming for example a uniform boron concentration in the normal brain of 20 ppm, the neutron transport could be reduced by about 8%. The necessity of assigning a uniform averaged boron concentration to different tissues during the neutron transport came out also from the absence of knowledge, at that time, related to the macro-distribution of the boron compound.

The improvements in the computational studies induced the MIT scientists to develop in 1996 a new version of NCTPLAN. This version was developed for a Macintosh platform and written in Pascal. For this reason it was called MacNCTPlan [13].

According to the general scheme, described in the previous paragraph, MacNCTPlan contains a Part I, where the 3D mathematical model of the patient's head is created from a set of 2D images, making use of the *voxel reconstruction technique.* In this method, each plane of medical image data is partitioned into squares of regular size before being mathematically stacked to construct a large 3D array of 11,025 cells of 1 cm^3 volume. A material file should be prepared for the material assignment to each cell of the 3D model. To this purpose, two sets of 256x256x8 bits CT images are required. The first set is done without the iodinated contrast agent and is used to determine the tissue type that will make up the material of the 3D model for the Monte Carlo calculations. To this purpose, MCNP code [14] is used. The second set of images can also be used for identifying and locating the tumour and the oedema. Once the target region has been identified, the user should select with a proper pointing option the ROI, which contains the tumour. The ROI should include areas of soft (tumourous and healthy) tissue, skull and air. In fact, these are the four available elemental materials that fill the irradiation volume for the radiation transport calculations. The brain and the skull have been already defined in Table 1, where the brain is the basic material for both the cancerous and the healthy soft tissue. This material can change in the two regions only for the different presence of boron, which is assigned afterwards.

From the selection of a few CT images of properly chosen ROIs, it is possible to construct a diagram of the pixel number versus the Hounsfield number (H), where three peaks should appear: one for the soft tissue (cancerous or normal), one for the skull and one for the air. This way, each pixel in the CT stack is assigned its own material according to its corresponding H values.

The final 3D model is a parallelepiped 21x21x25 cm^3, containing 11,025 calculations cells. Each cell contains typically 500-1000 CT voxels. Therefore, the cell is assigned a material, which is the average between four basic materials, weighted on the number of voxels effectively pertaining to each basic material. MacNCTPlan contains a table of 56 possible material combinations.

Special care is taken when assigning the ^{10}B concentration to the normal and cancerous soft tissue. This operation is called "test-study" in the MIT-Harvard protocol, where tissue samples are taken one week before the BNCT and 2-3 h after the boron drug infusion. Venous blood samples are taken 10 times during 15 h after the infusion. The blood samples analysed through the PGRA, while the tissue samples are frozen in dry ice and analysed through the alpha particle autoradiography technique. Blood samples are also taken just prior and after the irradiation. This way, the ^{10}B concentrations in the soft tissues are assigned, assuming that no boron is going to concentrate in the bone and air.

Another important step in MacNCTPlan is the selection of the entrance and exit points of the beam central axis. Up to four beams can be determined as possible beam orientations. The selection of these parameters has been made easy by the simultaneous view of two orthogonal viewing planes through CT image data. As the beam orientation is changed, these viewing planes are graphically updated in real-time. In particular, the user can see the CT plane with superimposed three lines (the margins of the beam + centreline) in order to check how the beam interacts with the patient's model. The entry and exit points are really useful in the following patient positioning procedure. For example, these parameters are used at Petten to position the patient's mask using an *ad hoc* designed frame.

The source definition is quite simple, as it consists of a virtual plane source in a fixed position in reference to the 3D model. Therefore, once the user changes the orientation of the beam, the software supposes that the 3D model remains in the same position, while the source plane definition is going to be changed.

Once the 11025 cells model is created, a Fortran 77 program, called MPREP, provides the MCNP input deck from a series of files. These files contain all the information required for computing the doses in the irradiation volume such as the material file converted into a lattice, a material card, the spatial, angular and energy characteristics of the neutron and photon beams, the flux tallies and the flux-to-dose conversion factors (based on the neutron KERMA factors for normal brain) [15] for each desired dose component. In order to take into account the effect of the binding of individual nuclei on the interaction between thermal neutrons and the considered materials, $S(\alpha,\beta)$ tables evaluated at 300K for hydrogen in light water are included for all materials making up the patient's head model.

The Part II of MacNCTPlan provides the graphical environment for deriving the dose patterns from the results of the radiation transport calculations performed by MCNP and displaying the results in one- or two- or three-dimensional format.

In order to display RBE-dose isocontours, the user should provide the following information:

- the normalization factor (particles per unit time), which can be calculated, making use of the maximum RBE-dose measured in a reference phantom and calculated by the code.
- the RBE values for each radiation dose component and CBE values for each individual tissue type.
- Isodose contour selection.

The MacNCTPlan calculates the dose rate for the whole CT volume. A 3D interpolation process is used to interpolate the voxel-based rate to each pixel of the images, prior to any display. This is due to the fact that the 1 cm^3 resolution of the MCNP model is far from the about 1 mm^3 resolution of the MRI (or CT) scanning. In this phase, a Fourier Transformation and a ramp filter is applied to the 3D dose matrix, in order to reduce the spatial dose gradients due to the Monte Carlo statistic fluctuations. This adjustment process is quite diffused in the PET images processing.

Cumulative Dose-Volume Histograms (DVHs) for arbitrary tumour or normal tissue volumes can be generated as well. A cumulative dose volume histogram is the distribution of the percent of tissue volume exposed at or above a certain dose or dose rate within a region of interest.

MacNCTPlan provides also the effects of a multi-beam irradiation, linearly combining each individual beam according to its weight (generally defined in function of the difference in the beams irradiation time).

Recently a new PC-based version of MacNCTPlan, called again NCTPlan [8], has been developed in a joint effort by CNEA, Harvard Medical School and MIT. The necessity to integrate the entire process on one computing platform and requirements for upgrading the predecessor led to the development of this code. NCTPlan 1.0 is written in Microsoft Visual Basic™ 6.0 and runs under Windows 95/98/NT and 2000. The object-oriented programming offered several changes in the GUI (multiple windows for modelling analysis and dose displays, etc.). In view of the integration philosophy, MPREP has been integrated in NCTPlan. In addition, NCTPlan can superimpose isodose contours on two orthogonal planes of the CT volume and update these in real-time as the orientation of the plane changes.

Computational changes have been performed in the material assignment model, where the rounding procedure not always guarantees that the total percentage of each cell adds up to 100%. In these rare cases, MacNCTPlan assigns to the current cell the last admissible mixture calculated, while NCTPlan searches for the admissible mixture that minimizes the sum of the relative differences (in absolute values). If the minimum is not unique, the code selects the configuration that affects particle transport least.

Besides, since the image slices are 2 mm thick, 5 images comprise the material information in 1 cm^3. To assess which cells do not contain any tissue, MacNCTPlan analyses only the central image, while NCTPlan inspects all of them.

Also changes in the DVH calculating algorithm have been performed, especially in order to reduce the errors due to the interpolation method.

SERA

The SERA (Simulation Environment for Radiotherapy Applications) treatment planning system consists of seven modules that can be run independently. It has been developed at the Idaho National Engineering and Environmental Laboratory (INEEL), in collaboration with the University of Montana (MSU). The SERA package can be divided into three main parts, according to the general scheme previously described: the modelling of the patient's geometry, the transport modelling, contouring and display of the computed dose components.

The patient's modelling is performed through three modules: *seraImage* (for the conversion of the original medical images into the QSH internal format), *seraModel* (for the manual or semi-automatic creation of the ROIs) and *sera3d* (for the visualization of the patient's model in a 3D environment).

The reconstruction technique adopted is based on a pixel-by-pixel uniform volume element, named "univel". As with the B-spline method (used in the previous version, called BNCT_rtpe), construction of the patient geometry is independent of the medical image modality and field of view. The resolution of the model is therefore limited to that of the original medical image, allowing very accurate representation of the patient's geometry that usual analytical surface representations cannot afford. The ROIs are differentiated making use of different colours. The association *1 colour = 1 region* uniquely identifies the region itself.

A list of predefined bodies such as brain, skull, tumour, ventricles, etc. is available and refers to files that contain all the information required for radiation transport (elemental composition, RBE factors of the various dose components, etc.). Several editing modules are available in seraModel to make the completion of this task easier either manually or automatically.

When all the tasks for the creation of a 3D model of the patient's geometry have been completed, the program will save the user-defined regions in a uniform volume element format to describe both the geometry and the assignment of the physical properties of the univels. In particular, this is the step when the user defines the material to associate to each univel.

When all the bodies are created from the previous module, sera3d allows the user to visualize the rotating or static univel geometry with the assigned materials using various rendering algorithms such as the wireframe, the solid outline or the polygonal surfaces style. Sera3d also provides the tools for defining the beam orientation. Figure 1 represents a wireframe rendered model, while Figure 2 shows the same model represented with the "transparent regions" option. In the latter case, the outer regions can vary their opacity property giving the chance to see also the inner regions for better understanding the relative positioning in the whole model.

Amongst the numerous data display tools, two features allow the user to visualize the line of the beam orientation chosen. These are the body clipping tool and the slice-inlay tool. Two clipping planes can be moved interactively to cut away portions of selected bodies in three possible directions (axial, sagittal or coronal). When used in combination with the slice-inlay feature, it allows render the body modelling superimposed onto an original CT image, which facilitates the choice of the beam orientation.

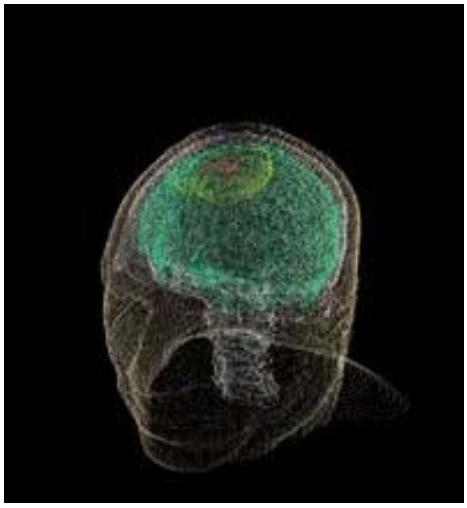

Figure 1 – Wireframe rendered 3D model

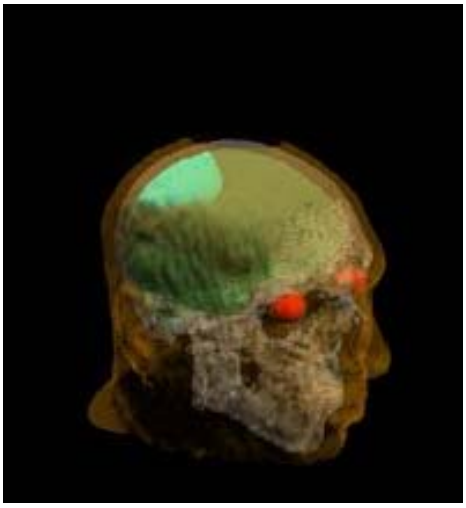

Figure 2 – Transparent regions in 3D model

The module *seraCalc* is devoted to the Monte Carlo (MC) input file preparation, while the MC engine is comprised into *seraMC*. The seraMC program has been developed by the INEEL, specifically towards the BNCT treatment planning application. Several reasons motivated this development:

- Existing Monte Carlo programs are targeted towards general purposes (such as MCNP) and are not made efficient for a medical application, especially from the calculation speed point of view.
- Most Monte Carlo programs provide volume edits and rarely point or surface edits.
- With millions of univels representing the patient's head, a rapid geometry ray-tracing technique was necessary.
- A general editing capability with the possibility to re-edit a previous run with new edit directives may be useful. This can be the case of changing just the multiplication factor for the tissue-to-blood ratio, if the boron concentration in the blood is changed compared to the value supposed during the initial treatment calculation.

Furthermore, the use of the integer arithmetic in the univels structure, compared to the floating arithmetic of the NURBS (in BNCT_rtpe) has shown an evident acceleration of the execution time for the transport calculations by a factor of between 5 and 10.

An interesting feature of seraCalc is the IOP, that is the automatic positioning of the surface source in respect to the target centre. This is based on the evaluation of the minimum distance between these two points, taking into account that the 3D model could have been rotated compared to the initial position (the patient is axially aligned to the source surface).

Finally, SERA offers the modules *seraPlan*, *seraDose* and *seraPlot* in the post-processing. SeraPlan is responsible for the statistical combination of up to four fields and/or up to six fractions from several independent seraMC calculations in order to produce single effective dose.

SeraDose is the dose contouring utility that displays the two-dimensional isodose curves edited by seraPlan superimposed over the original set of medical images. The isodose or isofluence curves can be normalized to three parameters:

1. Maximum of the thermal neutron fluence.
2. Maximum of the total gamma dose (sum of the contributions of the dose due to the gammas directly coming from reactor and the dose due to the gammas induced by the neutron interactions).

3. Maximum of the total dose.

Actually, this is a limitation in the dose representation, because the user cannot see the boron distribution normalized to the boron dose maximum. This is important especially in the case of a highly heterogeneous boron distribution, where there should be no coupling between the boron dose and thermal neutron fluence.

This feature and the fact that the isodose or isofluence curves are generated by SERA based on the raw calculation data (before executing seraPlan), are source of evident errors [7].

Finally, seraPlot provides integrated control of depth dose curves and dose-volumes histogram plotting utilities.

Recently, a new project has started joining the forces of INEEL, MSU and Lawrence Livermore National Laboratory (LLNL). The main goal of this project is the creation of a multi-modality treatment planning software system that will draw on the combined experience of the three institutions in their respective areas of interest. In particular, LLNL was mainly active in designing an improved Monte Carlo calculation engine fast enough for day-to-day external-beam photon-electron radiation therapy planning. This code is called PEREGRINE [16] and can be also applied to other types of radiotherapy, in a special version. Somehow, the PEREGRINE planning technique is quite similar to NCTPlan.

The integrated software system, previously mentioned, will combine the features of SERA and PEREGRINE, in order to be useful for all modern forms of radiotherapy. The new system will carry the name MINERVA (Modality-INclusive Environment for Radiotherapeutic Variable Analysis).

Several state of the art features will be incorporated in the new system. The incorporation of Java virtual machine gives a much greater portability among various computer hardware platforms. Besides, an open "plug-in" based interface environment is the key for tailoring the system to any radiotherapy modality.

The first version of MINERVA will include capabilities for external beam photon, electron and fast-neutron radiotherapy, neutron capture therapy, and molecular targeted radionuclide therapy. Other anticipated additions include new computational modules optimised for external-beam proton therapy, as well as for brachytherapy.

BDTPS

BDTPS is the result of the collaboration between the DIMNP (University of Pisa) and the JRC of the European Commission. The basic concept behind its implementation can be found into the feasibility study, which led to the development of a tool for integrating the real macroscopic boron distribution into the Monte Carlo calculations. This tool was named CARONTE [17, 18]. The geometry definition in CARONTE was based on two non-concentric ellipsoids, simulating the cranium. Inside this area several independent calculation cells are inserted, each one being characterized by its own ^{10}B concentration obtained through the PET scanning of the patient's head. This tool was not meant to be a TPS, but the main idea was inherited by the following BDTPS [7]. This has been thought to be an integrated TPS, containing the main features required to a BNCT-dedicated treatment planning system, such as the dose evaluation at the organs at risk and the fiducial markers positioning (for the patient's positioning procedure). In particular, the geometry is reconstructed using the "pixel-by-pixel method" (in the same way as SERA the ROIs are uniquely identified by their own colour). The added value is given by the automatic construction of the *Monte Carlo model* on the grounds of the *3D model*, coupled with the *Boron model*. This is a data structure containing the ^{10}B distribution into the 3D model, as it has been acquired through the PET scanning of the patient's head. In particular, the use of a third model (B model) constitutes the main difference between BDTPS and the other TPSs.

In this phase, particular attention should be paid in the co-registration of the PET and CT scanning, in order to have a perfect matching of the ^{10}B and anatomical information. To this purpose, the use of a CT-PET combined machine [19] could be definitely an advantage.

BDTPS makes use of the Monte Carlo code MCNP (and MCNPX); the parameterization of the geometry is based on the standard lattice tally (and the mesh tally). The ^{10}B distribution in the Monte Carlo model can be maintained uniformly constant to 1 ppm everywhere or each ROIs can be assigned its own ^{10}B concentration, in order to take into account the possible flux depression.

By contrary to what happens in SERA, the results are represented using isosurfaces, which are re-scaled on the grounds of the real ^{10}B concentrations. In fact, the whole 3D matrix is multiplied by the B model data structure. Besides, the isosurfaces are normalized in three ways:

1. maximum value of the parameter represented in the isosurfaces (i.e. ^{10}B dose).
2. the value of a parameter in a specific point.

The second method permits to represent the isosurfaces normalized to the max of thermal neutron fluence, once the DGIP (that is the point where this fluence is maximum) is found.

These features avoided clear discrepancies during the validation, which have been noted instead using SERA. The validation was performed using a special PMMA boron heterogeneous phantom, called HEBOM (HEterogeneous BOron phantoM), able to incorporate up to 64 vials, containing ^{18}F-BPA in different concentrations. In this case, the maximum of the thermal neutron fluence was registered in the center of the structure, where no boron was present. Therefore, according to the SERA algorithm, ^{10}B isodose curves were calculated even where there was no boron. Figure 3 shows the HEBOM vials structure as reconstructed by BDTPS.

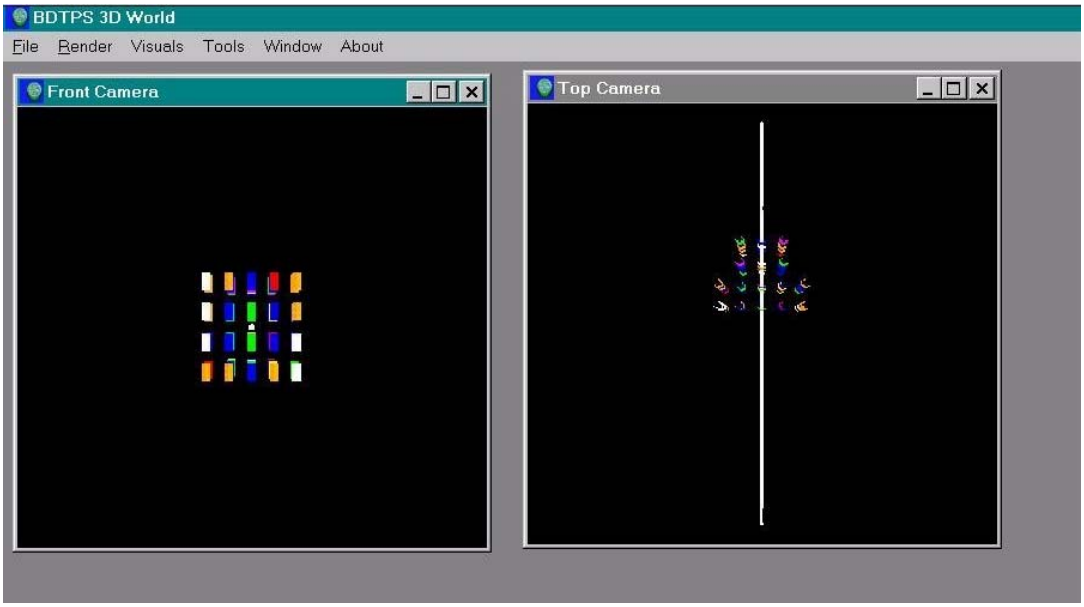

Fig.3. BDTPS 3D Model of HEBOM vials and its positioning in reference to the beam line

Conclusions

The main requirements and peculiarities expected from the BNCT-oriented treatment planning system have been reported in this paper. It is clear that the TPS plays an important role inside the whole treatment planning of the patient's organ. This is generally true in conventional radiotherapy, but in BNCT this role is particularly stressed by the presence of neutrons, which increase the level of complexity of the irradiation simulation.

As in the standard radiotherapy, the BNCT-dedicated TPS should be able to reconstruct the 3D geometry as much realistically as possible. This is basically obtained via a CT scanning and a

subsequent proper reconstruction of the 3D slices stack. This 3D model is coupled to a Monte Carlo model, mainly dedicated to the neutron transport simulation. Finally the results (generally doses and fluences) should be represented as using isocurves (isosurfaces) superimposed on the CT scanning planes as via graphs along a user-defined axis.

The most used TPSs in BNCT are NCTPlan and SERA (the new version of BNCT_rtpe). They contain all the required features for BNCT and differ especially for the Monte Carlo calculation engine. However, both of them do not consider expressly the real ^{10}B macroscopic distribution, which can be obtained via a PET scanning of the patient's organ. BDTPS is an integrated TPS, which contains all BNCT required main features and, additionally, has been thought to properly couple the CT anatomic data to the ^{10}B distribution PET data.

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