QUANTITATIVE STUDIES ON THE APPLICATION OF POSITRON EMISSION TOMOGRAPHY TO BNCT TREATMENT PLANNING

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ABSTRACT

The idea of embedding PET-derived information on the macroscopic distribution of boron into the Treatment Planning Software (TPS) in BNCT was proposed by the DIMNP research group in 1998, when the CARONTE code was presented [1]. At the basis of that preliminary study and subsequent research was the idea that inhomogeneities in the spatial distribution of boron nuclei within the patient's tissues can significantly affect the results of macro-dosimetric calculations. Such calculations are carried out in the treatment planning phase and determine a number of relevant irradiation parameters, therefore influencing the therapeutic efficacy.

This paper reviews how medical images were processed to prepare the input for Monte Carlo simulations of radiation transport and to process and present the results.

Introduction

Treatment Planning Systems (TPSs), by simulating the interaction of radiation with tissues, provide physicians and doctors with precious indications (e.g. optimal irradiation time and patient positioning) and are therefore essential to deliver appropriate therapeutic treatment, ensuring that the dose to healthy tissues will be within the allowed limits.

Present standard TP for glioblastoma multiforme (GBM - a kind of brain tumor), used in all BNCT trials, is based on the reconstruction (by CT and/or NMR images) of a 3D anatomical model of the patient head. This model, with the introduction of data on the boron distribution is implemented in a computer code which then simulates the interaction of radiation with tissues, computing the spatial distribution of the dose delivered to each anatomical structure.

A new trend in this research field is the attempt to include in the simulations data on the spatial distribution of boron nuclei in the patient's tissues obtained by means of PET scans, after labeling of the BPA molecule with F^{18} nuclei [1], [2], [3], [4]. This paper reviews the techniques employed to implement this approach at DIMNP, University of Pisa.

Methods

Positron Emission Tomography is a functional imaging technique which allows the "in vivo" investigation of metabolic processes. This can be done by linking a positron emitting nucleus to the molecule of the substance ("labeling") whose biological kinetics must be investigated. The substance (which in our case can be the boronated agent) is then infused into the patient, who later undergoes scanning. The PET scanner can detect the radiation emitted when a positron-electron annihilation reaction occurs and ascertain the location at which this reaction occurred.

A detailed explanation of how the PET scanner works is beyond the scopes of this paper, but it is worthwhile to provide a quick review of the basic concepts of digital images. Let us assume that the scanning of a cylindrical object has to be performed.

The sample is placed on the table (Fig.1) at the center of the circular gantry on which the detector arrays rotate during scanning. While the table is kept still, the detectors receive the gamma rays emitted by the annihilation reactions within the sample and add a "count" for each reaction in each location in space.

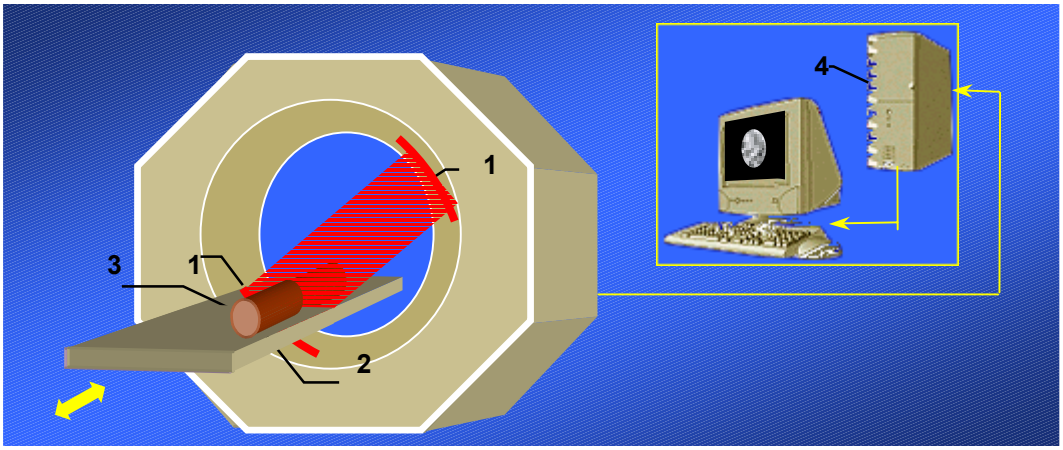

Fig.4. Schematic of a PET scanner. – **1** Detector arrays, **2** Micropositioning table, **3** Sample (to be scanned), **4** Computer. The semi-transparent rectangle between the detectors highlights the area from which gamma rays can be detected.

The region of space occupied by the sample is actually "logically subdivided" by the machine into a three-dimensional grid of parallelepiped volumes. Each picture shown on the computer monitor (hereafter also referred to as "slice") is "seen" by the machine as a matrix of voxels (i.e. volume elements, Fig.2), whose dimensions can be set by the user. Hence each voxel corresponds to a definite location in space within the volume being scanned.

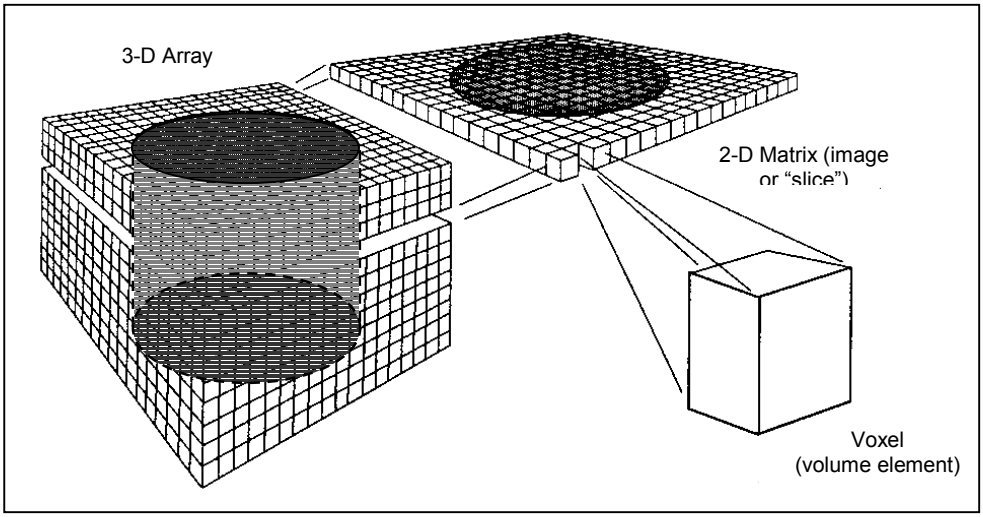

Fig.2. Visual representation of the logical concepts of voxel (volume element), matrix of voxels (image or "slice"), 3-D array (sequence of all the slices).

To obtain a three-dimensional map of the volume occupied by the sample, the micropositioning table is then moved in the axial direction to the location at which another "slice" will be taken. The results are usually shown as images reconstructed by assigning a shade of gray to each "counts" value in one slice, normally employing lighter tones for lower concentrations.

Some years ago a team of researchers in Japan developed a technique that, after labeling of BPA with F^{18}, allowed to obtain PET images whose "count" values could be related (through a semi-empirical model) to the boron concentration in each voxel [5]. The CARONTE system developed at DIMNP (Pisa) and based on the MCNP code [6] for the transport calculation proved the feasibility of a treatment planning approach based on the introduction of PET data on the boron distribution into the input for the computer simulations. Subsequent research was aimed at providing

quantitative evidence of the differences that arise when comparing a “traditional” treatment plan to this innovative technique.

To provide an example of how image processing techniques can fruitfully be employed to carry out a comparative study of this kind, Fig.3 shows the different steps of the procedure that was adopted to prepare the MCNP inputs for two simulations pertaining to the same glioblastoma case.

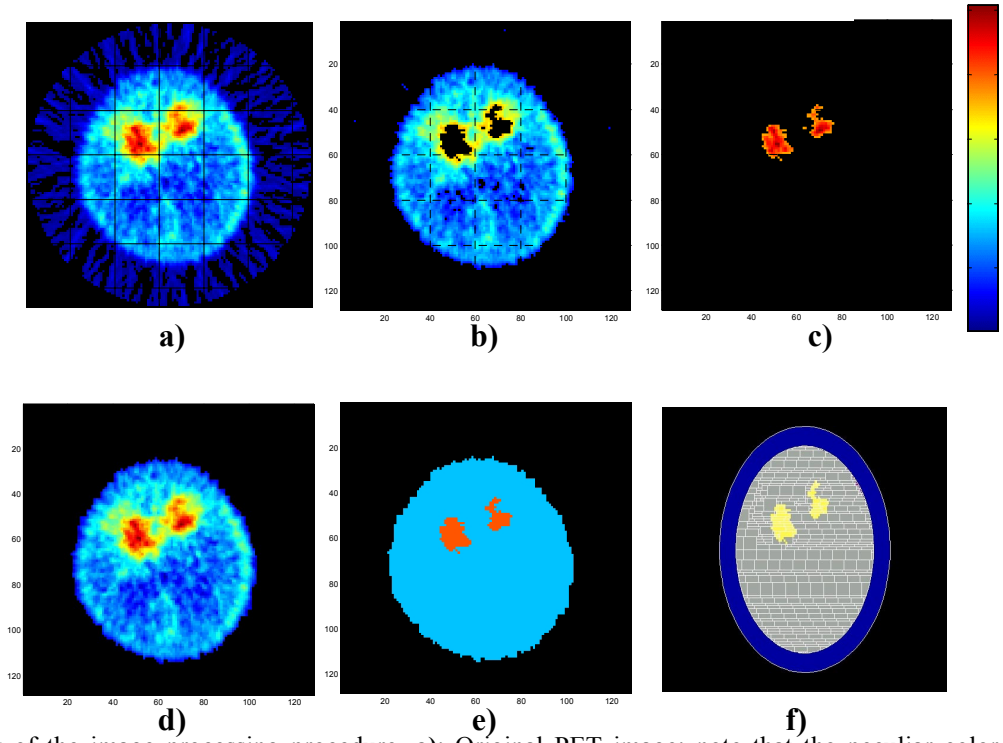

Fig.3. Steps of the image processing procedure. **a)**: Original PET image; note that the peculiar color scale adopted (instead of the “traditional” shades of gray) highlights the tumor zone. Correspondence between colors and relative B^{10} concentration values is shown in the color bar on the right. **b)** and **c)**: preliminary definition of “tumor” and “healthy tissue” zones by simple threshold criteria for the “traditional” approach simulation. **d)**: Suppression of the ring of “spurious counts around the patient’s head. This image is used as input for the “PET-based” calculation, which therefore takes the heterogeneous boron distribution into account. **e)**: “two zone” image for the “trditional” input and **f)** same input as plotted by MCNP.

Results

Fig.4 shows the computed dose-rate maps (for the same slice) obtained employing the “standard” approach (a) and the "PET based” approach (b) as implemented by CARONTE. The computed-dose spatial distributions appear to differ markedly in the two cases. Particularly, with the “standard” approach the isodose regions are much more regular in shape and higher dose-rate values are more strictly confined within the tumor.

In addition to these “qualitative” differences, the pixel-by-pixel difference in computed dose between the previous two images can be computed and plots of the spatial distribution of this parameter will be shown in the oral presentation. The results show that, in this particular case, at the tumor margin the “traditional” model significantly underestimates (up to 68% of the maximum computed dose value) the dose to healthy tissue with respect to the “PET based” model.

This technique has also been applied to the computational validation of the BDTPS code and the results pertaining to these calculations helped to point out several interesting questions in the comparison between the results obtained by this code and the SERA TPS as applied to the same in-phantom dose/flux calculations.

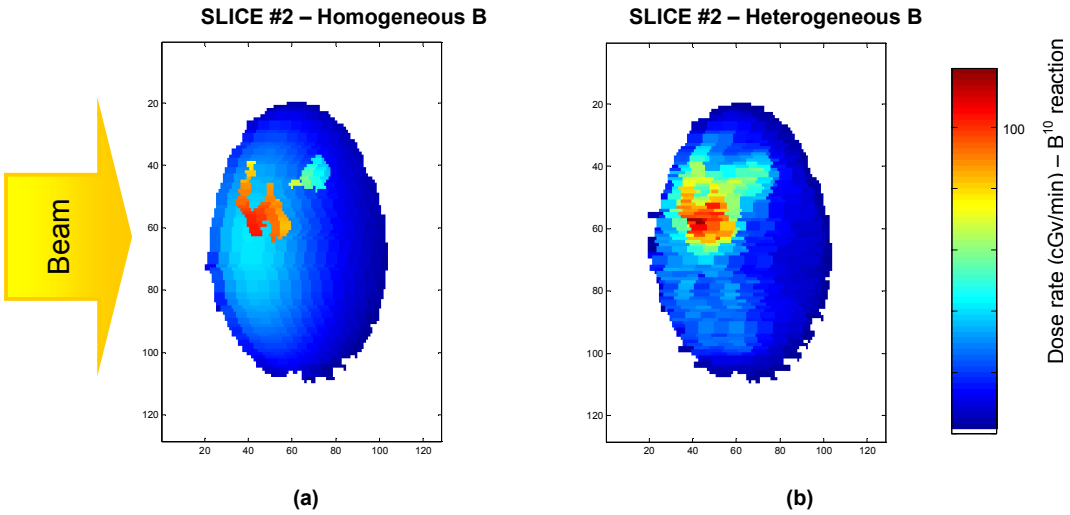

Fig.4. Distribution of the computed dose-rate values from the B^{10} reaction in the same slice as obtained by employing the "traditional" approach (a) and the "PET-based" approach.

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