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Software for radionuclide vertebroplasty

A.V. Levchenko[a,b,*], Yu.G. Zabaryansky[a,c], A.A. Golovin[a], N.K. Voznesensky[a], Yu.A. Kurachenko[a]

[a] *Obninsk Institute for Nuclear Power Engineering, National Research Nuclear University, "MEPhI" 1, Studgorodok, Kaluga Reg., Obninsk 249040 Russia*

[b] *Experimental Scientific-Research and Methodology Center "Simulation Systems" (SSL)., 133, Lenin Str., Kaluga Reg., Obninsk 249035 Russia*

[c] *State Scientific Center of the Russian Federation – Institute for Physics and Power, Engineering named after A.I. Leypunsky. 1, Bondarenko Sq., Kaluga Reg., Obninsk 249033 Russia*

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Abstract

The problem of the software support for radionuclide vertebroplasty has been considered in general. Requirements to systems of preoperative preparation and postoperative analysis are described. The subject area (the vertebra operated on and its vicinity) is modeled using CT scans: a) precisely, based on voxel representation and b) approximately, for use in online interactive calculations. The voxel model is made in two versions: for dose and temperature calculation. The MCNP code is used for dose calculation. The emitter radionuclides were selected in serial calculations; and the best "candidates" have been identified for application in this procedure based on a set of characteristics. A code was developed for solving online both the "direct" problem (dose field calculation in the vicinity of the bone cement delivered with the preset radionuclide activity) and the "inverse" problem (calculation of the required radionuclide activity to be delivered in a specific localization close to the cement "kernel"). The temperature fields caused by polymerization of the bone cement have been calculated by means of thermal-hydraulic codes used in nuclear reactor design; these codes have been adapted for use in vertebroplasty based on the conducted problem-oriented experiments. Using internationally adopted methodologies for assessing the synergistic effects of radiation and heating on tissue, beam impact "enhancement ratios" have been obtained, and areas of radical and palliative therapeutic effects for the given vertebroplasty conditions have been defined. A beta-version of the code for the radionuclide vertebroplasty planning has been created based on calculated and experimental data.

Keywords: Radionuclide vertebroplasty; Synergism of irradiation and heating at bone cement polymerization; Voxel models; Codes for dose and temperature computation; Radiation therapy planning.

Introduction

Vertebroplasty (VP) is a minimally invasive procedure to strengthen the spine affected by metastases or fractures [1]. This operation is needed by many oncologic patients who have lost mobility. Bone cement (polymethyl-methacrylate) is delivered into the metastatic cavities during the operation as the result of which the patient becomes capable to move again and has the quality of his life improved drastically. Radionuclide vertebroplasty (RNVP) suggests that a radionuclide is introduced into bone cement, which ensures that metastases are suppressed near the cement "kernel" and the pain syndrome is relieved. Besides, the synergism of irradiation and heating (when the cement is polymerized in the target vertebra) provides ground for reducing the activity delivered thus cutting the risks for the patient's critical organs and tissues and decreasing the exposure dose for personnel when RNVP is prepared for and administered.

For a number of years, an integrated research has been conducted on the basis of Simulation Systems Ltd., an experimental research and methodology center, to justify and

* Corresponding author at: Obninsk Institute for Nuclear Power Engineering, National Research Nuclear University, "MEPhI" 1, Studgorodok, Kaluga Reg., Obninsk 249040 Russia.

E-mail addresses: leva@ssl.obninsk.ru (A.V. Levchenko), chessmaster89@mail.ru (Yu.G. Zabaryansky), artem.golovin1@gmail.com (A.A. Golovin), nikwo@mail.ru (N.K. Voznesensky), ykurachenko@mail.ru (Yu.A. Kurachenko).

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practically implement this new oncologic disease treatment method. Concentration of expert efforts is required in the field of radiation physics, fluid hydraulics, chemistry, radiology, programming and, primarily, neurosurgery. The core of the team of experts is composed of highly professional staff and hopeful youngsters, including corresponding members of the Russian Academy of Sciences, three doctors of science, three candidates of science and two post-graduate students. The results of the team's work were published in science magazines and presented in reports at international and Russian conferences [2–5].

An essential component of the conducted research is to create, debug and test the software for the RNVP irradiation planning and dosimetric support.

Requirements to software

Software is an indispensible component of present-day devices and technologies for high-tech medical applications. The following major requirements to the RNVP software may be formulated based on the general philosophy of beam therapy and the peculiarities of this procedure. Implicitly, these requirements shape the tasks the software is expected to solve. With neurosurgical, orthopedic and other medical aspects of the VNRP problem taken out of the context, we shall focus on the existing radiation and thermal effects, on the synergism of these and on the issues of dosimetry. The program is expected to be capable to read and interpret CT files (preoperatively, the software reconstructs the 3D metastasis area and computes the needed quantity of cement to be delivered, and, postoperatively, it reconstructs the actually filled area and computes the actually delivered amount).

The preoperative support is based on a combination of two approaches:

- dose fields are calculated in the cement delivery area based on the preset activity of the radionuclide in the bone cement (a direct task);
- initial data for the operation are calculated based on the preset therapeutic dose in a particular localization in the vicinity of the delivered cement, including the cement amount delivered and the activity of the radionuclide (of a combination of radionuclides) with the effects on the surrounding healthy tissues, including critical organs, being at a tolerable level (an inverse task).

The postoperative support (the direct task) suggests that the effective dose field is calculated and the beam effects on the surrounding tissues and healthy organs are assessed with regard for the actually cement-filled area and the known amount of introduced activity.

Dose field calculation

Small optical dimensions of the subject area and a low density of its materials define the selection of the key code for the dose field calculation (MCNP [6]).

The subject domain's geometrical model is implemented in two versions: as a precision voxel model [4] (Fig. 1) and as a simplified basic-geometry model (in the form of a sphere or a cylinder). The precision model is intended largely for the postoperative dose field calculation and to assess the postoperative effects. The simplified model is used for the operational irradiation and dosimetry planning.

The efficient use of simplified geometrical models, instead of "expensive" voxel models, is pretty well justified by the specific nature of the task. The radionuclide is introduced into the bone cement for the purpose of injuring radiologically the metastatic cells in the immediate vicinity of the cement-filled "cavity" (the vertebral body region affected by metastases). Metastatic cells die when the dose is 60–100 Gy. But the affected region may be immediately adjacent to the spinal canal that contains the spinal cord, blood vessels, nervous roots, and fatty tissue. Despite the fact that these organs and tissues are rather highly radioresistant, the cement radionuclide radiation effects may be harmful.

The following solutions stem from this brief description of the task's specific features. A radionuclide (a low-energy β- or γ-emitter) shall be used that allows avoid overexposure of

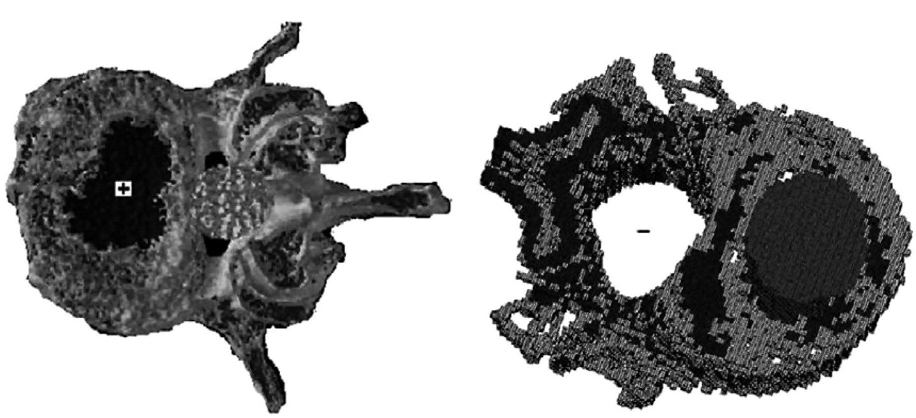

Fig. 1. A 3D reconstruction of the vertebra voxel models obtained based on CT files (left – for dose field calculation, right – for temperature field calculation); "+" – cement-filled "cavity" far from the spine column; "–" – unfilled cavity near the spine column.