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RESEARCH ARTICLE

Programming and computing suite for simulating the therapeutic absorbed dose in radiotherapy

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Abstract
Objectives. Simulation of the absorbed dose is an essential part of radiation therapeutic treatment, performed not only for its correct evaluation, but also for assuring quality control and retrospective evaluation of the provided cure. From the technological point of view, strict requirements are imposed on the software applications and hardware units that support a successful decision-making process before, during, or after the provided therapy. This paper reports an R&D project aimed at technological support of radiation treatment planning systems coupled with the creation of a mathematical framework for estimating the absorbed dose for radiobiological and medical therapeutic purposes.
Methods. A dedicated automated software suite for executing multipurpose Monte Carlo simulations was developed. The suite is backed up with virtualization techniques for structured hardware access, data intercommunication using diverse connection channels, various physical interaction engines, and coupled end-user software.
Results. The developed suite facilitates a wide array of tasks in the realm of radiobiological research conducted using radiation beams of different qualities. Additionally, it serves as a foundation toolkit for developing radiotherapy planning systems for both existing and new therapeutic facilities, as well as software packages for estimation of the long-term effects of the conducted radiotherapy.
Conclusions. The developed programming and computing suite is an effective tool for organizing a specialized environment for multipurpose estimation of the absorbed dose of radiation for therapeutic applications of radiation beams of different qualities. The suite can be updated and extended upon end-user needs and modified by skilled software developers for specific purposes.

Keywords: programming and computing suite, physics-based simulation, absorbed dose, radiotherapy, proton therapy, neutron therapy, Monte Carlo method

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НАУЧНАЯ СТАТЬЯ

Комплекс программно-вычислительных средств моделирования терапевтических величин поглощенных доз в задачах лучевой терапии

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Резюме
Цели. Моделирование поглощенных доз в радиотерапии является ключевым процессом в ходе лечения пациентов, а также выполняется с целью обеспечения гарантий качества терапии и ретроспективных оценок успешности проведенного лечения. С технической точки зрения предъявляемые требования к программному и аппаратному обеспечению весьма строгие для того, чтобы обеспечить успешный процесс принятия решения до, во время или после проведения терапии. Цель статьи – разработка и апробация технологического процесса обеспечения систем планирования лучевой терапии, а также создание расчетных модулей оценок поглощенных доз радиобиологического и терапевтического назначения.
Методы. Специализированное автоматизированное программное обеспечение, разработанное и поддерживаемое для обеспечения многоцелевых расчетов методом Монте-Карло, построено на основе технологий виртуализации для структурированного доступа к оборудованию, технологий передачи данных по разнородным каналам связи, различных физических моделей расчета взаимодействий излучения, которые совмещены в продукты для конечного пользователя.
Результаты. Комплекс позволяет решать широкий круг задач в интересах радиобиологических исследований, проводимых на пучках излучений разного качества, а также служить основой как для построения систем планирования лучевой терапии для действующих и вновь создаваемых установок, так и в интересах оценки отдаленных последствий действия терапевтического излучения.

Выводы. Разработанный комплекс программно-вычислительных средств является мощным инструментом, служащим для дальнейшего создания специализированных многоцелевых сред оценок поглощенных доз, необходимых для терапевтического применения широкого круга радиационных технологий. Комплекс может быть модернизирован под потребности пользователей, а также дорабатываться разработчиками программного обеспечения под собственные нужды.

Ключевые слова: программно-аппаратный комплекс, моделирование физических величин, поглощенная доза, лучевая терапия, протонная терапия, нейтронная терапия, метод Монте-Карло

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INTRODUCTION

The computational and mathematical problems that need to be solved within the framework of radiation therapy procedures can be conventionally divided into two main classes.

The problems of the first class include those of pretreatment patient preparation. At this stage, it is necessary to ensure the fulfillment of model therapeutic criteria of effectiveness and safety of the patient's treatment with the necessary accuracy and promptness for making a grounded medical decision. The resulting solution consists in the formation of recommendations about the admissibility of the course of therapy by the system supporting medical decision making.

The problems of the second class, conversely, are not directly linked to the decision to prescribe therapy to a particular patient; instead, they are aimed at verification and confirmation of the characteristics of the previously prescribed treatment scheme, including the criteria for the formation of early and late radiation complications, retrospective analysis of groups of treated patients in order to form a survival prognosis and assess the quality of the previously performed planning, or to form alternative scenarios for assessing the success of the therapy.

The systems that solve the first class of problems are conventionally referred to as treatment planning systems (TPS). Among them, commercially available systems include *Raystation*[1] by RaysearchLabs, *Eclipse*[2] by Varian (Germany), *Pinnacle*[3] by Philips (Netherlands), *One*[4] in *XiO* and *Monaco* versions by Elekta (Sweden); *PLANB*[5] complex by RT-7, *Amfora*[6] by Medico-Physical Center (Russia). As a general rule, the planning system is not a separate versatile product; rather, such a system is an element of the final physical installation, e.g., the planning system for the neutron therapy complex based on the NG-24MT generator (neutron generator based on the D(T, ^{4}He)n reaction, neutron energy 14 MeV) [1] and for the domestic 6 MeV conventional accelerator (electron drift tube with energy up to 6 MeV suited for medical application using a bremsstrahlung on a tungsten target) [2], *XiDose* for carbon therapy centers in Japan [3], *TRiP98* for carbon therapy centers in Darmstadt and Heidelberg, Germany [4], projects of *NCTPlan* use at Massachusetts Institute for neutron capture therapy at reactors of National Research Nuclear University "MEPhI" [5]. Specialized tools also include the *NeuCure* [6] and *NeuMANTA* [7] systems used for neutron capture therapy purposes.

In the classical scheme of radiation therapy, planning systems has the specific feature associated with the time of obtaining a solution to the dosimetric planning problem. Tasks related to the assessment of long-term (relative to the course of therapy) consequences of treatment and dosimetric features of dose formation are simulated, as a rule, using more conventional means and methods of Monte Carlo modeling of radiation interactions with matter, which include, e.g., *Geant4* [8], *FLUKA* [9], *MCNP* [10], *PHITS* [11], and *SHIELD-HIT* [12]. All these simulation tools have been approved by the world community as those intended for a reliably accurate prediction of, in particular, the values of absorbed doses in target media. Although the results of such models have proved useful in clinical and research practice, a number of issues remain to be resolved [13], primarily those related to elucidating the response of biological

[1] https://www.raysearchlabs.com/raystation/. Accessed May 19, 2025.

[2] https://www.varian.com/products/radiotherapy/treatment-planning/eclipse. Accessed May 19, 2025.

[3] https://www.usa.philips.com/healthcare/solutions/radiation-oncology/radiation-treatment-planning. Accessed May 19, 2025.

[4] https://www.elekta.com/products/oncology-informatics/elekta-one/treatment-applications/planning/. Accessed May 19, 2025.

[5] https://rt-7.ru/planb (in Russ.). Accessed May 19, 2025.

[6] http://mphc.ru/catalog/amphora/ (in Russ.). Accessed May 19, 2025.

systems with various levels of organization to complex mechanisms of radiation action on cell cultures [14–17]. Such systems are also used in *in vivo* studies [18, 19], for safety assessment of radioactive waste landfills [20] and space flights [21, 22], and for verifying the radiation safety for the personnel of the radiotherapy facilities [23].

In this paper, we set out to develop a versatile suite of computational tools capable of solving problems of both classes described above and having wide possibilities for interchangeability of components and their modernization. We also describe the characteristics and specific features of technological implementation of the developed suite for the tasks of pre-radiation preparation of radiobiological studies, dosimetric planning of radiation therapy, retrospective assessment of biological effects on the basis of equivalent precision calculation of absorbed doses, as well as for building predictive models to describe the damaging effects of radiation and present the results obtained in accordance with the international requirements of the IAEA[7] and ICRP[8] for specific types of radiation (ion radiation ICRU 93[9], neutron capture therapy CRCP/BOR/002[10]).

MATERIALS AND METHODS

For efficient operation of a hardware and software suite, which is capable of functioning in an automated mode, an integrative connectivity between its individual components, as well as the possibility of their controlled launch depending on the availability of relevant input data, should be ensured. Figure 1 presents the architecture of the developed suite and displays the interconnection between the components, as well as the roles and places of individual users. The solid lines show module affiliations; the dotted lines show communication links.

While developing the suite, the main requirement was related to the possibility of rapid deployment of its components on a new hardware platform, geographically separated from other components of the suite. At the same time, the initial construction of the software included in the suite and its implementation were carried out on a single hardware base represented by a means of high-performance computing, including a dual-processor system based on Intel Xeon Gold E5506 (Intel, USA) with 380 GB of connected random access memory (RAM), NVIDIA Tesla V100 graphics processor (NVIDIA, USA), and a data storage system based on server hard disk drives (HDD) manufactured by Toshiba (Japan). The platform is connected to the local area network of the experimental sector of the A. Tsyb MRRC[11] based on MikroTik switches (Latvia), providing bandwidth at a level of 1 Gbps. The external communication channel used during the testing of the software in a geographically distributed setup mode provided data transmission speeds of up to 70 Mbit/s. Terminal workplaces of the complex operators were connected both in the internal network mode with full capacity (1 Gbit/s) and in the modes of artificially limited typical network (100 Mbit/s) and remote network (Internet channel).

CONTROL ARCHITECTURE

Since the architecture under development was required to enable shared component work, and since the physical means for organizing server interaction was presented as a single entity, the main technological approach was the organization of virtualization. To that end, Proxmox[12] was used as the base operating system of the server. This distribution is based on Debian GNU/Linux, developed and supported by the Internet Foundation Austria. Initially, the Proxmox VE 6 version was developed followed by its modification to Proxmox VE 7.1-11. At present, a stable version of Proxmox VE 8.2 is available.

The system fast data storage (solid-state drive, SSD) is divided into the main sector (for installing the Proxmox base environment) and sectors of managed application servers. In this case, each storage is a separate disk space with the possibility of expanding the address space, including during physical migration of the storage medium. The long-term storage is organized by addressing the whole pool of disk space of physical devices of the system into the created Proxmox container managed by TrueNAS[13] operating system. On the basis of TrueNAS, a software RAID array of level 5 with access via CIFS[14], SSH[15], and NFS[16] protocols is organized.

[7] International Atomic Energy Agency. https://www.iaea.org. Accessed May 19, 2025.

[8] International Commission on Radiation Units and Measurements. https://www.icru.org/. Accessed May 19, 2025.

[9] ICRU Report 93: Prescribing, Recording, and Reporting Light Ion Beam Therapy. https://www.icru.org/report/icru-report-93-prescribing-recording-and-reporting-light-ion-beam-therapy/. Accessed May 19, 2025.

[10] IAEA. Advanced in Boron Neutron Capture Therapy. Non-serial Publication. https://www.iaea.org/publications/15339/advances-in-boron-neutron-capture-therapy. Accessed May 19, 2025.

[11] A. Tsyb Medical Radiological Research Center. https://new.nmicr.ru/en/mrrc/. Accessed May 19, 2025.

[12] https://www.proxmox.com/en/. Accessed May 19, 2025.

[13] http://www.truenas.com/. Accessed May 19, 2025.

[14] https://learn.microsoft.com/ru-ru/windows/win32/fileio/microsoft-smb-protocol-and-cifs-protocol-overview (in Russ.). Accessed May, 19, 2025.

[15] https://www.rfc-editor.org/info/rfc4251. Accessed May 19, 2025.

[16] https://www.rfc-editor.org/info/rfc3010. Accessed May 19, 2025.

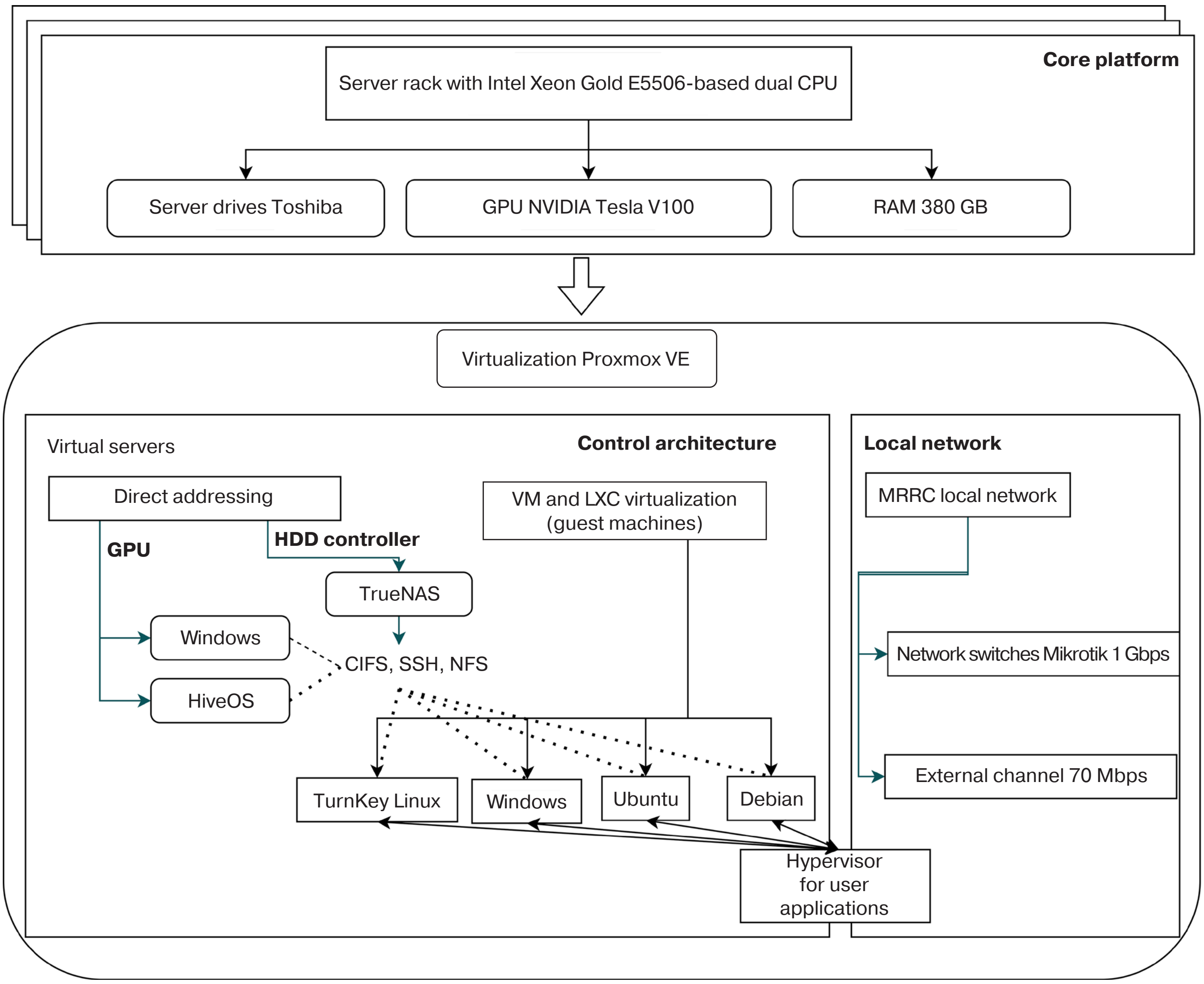


Fig. 1. Structural diagram of the software-computing complex. GPU—graphics processing unit, HDD—hard-disk drives, VM—virtual machine, LXC—simplified Linux containerization scheme

Support for iSCSI[17] in the implementation [1] is used only as part of the terminal equipment of automated workstations. Thus, it is assumed that all further created components of the server architecture use at least their address space of fast storage and have a common configurable access to the common file space of long-term storage.

RAM allocation for each of the subsequent managed servers in Proxmox virtualization is carried out at the stage of creation of a virtualization server, and, depending on specific needs, the parameters cannot always be dynamically expanded without recreating the server. In this regard, for each task solved by the server computers, an understanding of the actual resource consumption by the system architect and system programmer is needed. It should borne in mind that the tasks of modeling a direct radiation response (e.g., a tumor) and the entire therapy course with different variants of treatment responses are undoubtedly large-scale computing tasks. Thus, the task solved by a person when organizing the control level of the control architecture is, among other things, the choice of optimal parameters of the physical computing means.

Finally, a separate technological solution was developed as part of the solution to the problem of controlled, configurable launching of end-user applications on individual system servers. It represents its own hypervisor, launched by the command of the end-user tool, providing further automatic start, management, control, receipt, and transfer of the results of execution of computing tools on one target server. The target server can be any server running an *nix family of operating systems; connection and communication is performed via the secure SSH protocol. The configuration of managed applications is specified by a text file of JSON[18] syntax.

[17] https://www.rfc-editor.org/info/rfc7143. Accessed May 19, 2025.

[18] https://dx.doi.org/10.17487/RFC4627. Accessed May 19, 2025.

SERVER COMPUTING HARDWARE ARCHITECTURE

In the developed suite, all server computing facilities are divided into two classes. The first class includes systems that are deployed only within the Proxmox virtual environment, requiring no physical addressing of server devices. In general, this simply includes individual compute nodes for tasks that require only a central processing unit (CPU). The second class of systems are those that require the virtualization server administrator to configure physical addressing, which primarily refers to the graphics processing unit (GPU). The implementation of such means implies that at a particular moment in time, the access of such a system to the addressed physical entity is exclusive. Thus, e.g., all computational models and tools using a graphics card must either connect to the currently active server using the GPU or wait their turn for their server exclusive access to a physical resource on the host machine. When implementing system components outside of a virtualization environment, e.g., when there are separate physical compute machines and graphics card machines, such a task can be excluded from consideration.

The stages of deployment of server computing environment are built according to the classical scheme. First of all, after installing and assembling the operating system on the dedicated node and installing the appropriate updates, the target software of the node is assembled. For the computational nodes involved in the described suite for simulating the effects of ionizing radiation, the main package of computational software was *Geant4* [8] developed by CERN[19] (Switzerland), with versions from 4-9.5.0 (2016) to 4-11.2.2 (2024) being used during the period of the target use of the suite. One of the features of the package is the allocation of components of section libraries in separate downloadable files with the possibility of automatic linking at the stage of building the program. The *Geant4* build system is completely based on CMake[20], and versions from 4-10.0 can be built on any target platform compilers gcc, clang, and msvc, depending on the preferences of the developer. In this case, unlike the vast majority of similar Monte Carlo codes, *Geant4* is not a final executable file, but rather a set of libraries of dynamic or static linking for further creation of the programmer's own application. However, it should be noted that there are ready-made executables based on *Geant4*, which the user already manages only by providing input data, similar to other environments. Such solutions include *TOPAS*[21], *GATE*[22], and *GAMOS*[23]. The Table shows characteristic

[19] Conseil Européen pour la Recherche Nucléaire, CERN.
[20] https://cmake.org/. Accessed May 19, 2025.
[21] https://www.topasmc.org/. Accessed May 19, 2025.
[22] http://www.opengatecollaboration.org/. Accessed May 19, 2025.
[23] https://fismed.ciemat.es/GAMOS/. Accessed May 19, 2025.

Table. Performance evaluation of different *Geant4* versions

Geant4 version (*Geant4* year of issue)	Archive unpacking, ms	CMake configuration, ms	Make		
			1 thread, ms	16 threads, ms	32 threads, ms
9.6.4 (2016)	1392	6275	1321462	116047	85899
10.0.0 (2016)	1504	7737	1721182	106263	82304
10.3.0 (2016)	1760	5497	3124605	164876	127049
10.4.0 (2017)	1636	2911	3538766	179560	138334
10.5.0 (2018)	1764	1761	2814052	216675	163520
10.7.0 (2020)	1787	6147	3715283	239053	185224
10.7.4 (2022)	1708	3612	3057118	256715	201234
11.0.0 (2021)	1599	9720	6450537	277412	211570
11.1.0 (2022)	1745	6532	4831937	299245	238212
11.2.0 (2023)	1662	4732	5031802	306279	238548
11.2.2 (2024)	1688	8582	3813355	306803	246890

installation times of different *Geant4* versions on one of the currently functioning dedicated servers. All measurements were made in automatic mode by means of bash interpreter and *nix system time utility. The data is presented as a single measurement of calendar (wall time) time of the build procedure execution.

When implementing computational packages within the suite, one or another version of the software was used, depending on the specific task. For example, to solve the problem of dosimetric planning as part of the neutron therapy complex [1], the stable version 10.6.2 was used, which was not updated further. For a number of other tasks, in particular those described in [24], the then current version 10.3.1 was used. All routine simulations of the tasks arising in the course of the activities of the Department of Radiation Biophysics of the A. Tsyb MRRC are always performed on the latest stable version at the time of problem statement. It should be noted that backward compatibility of the user code is not always guaranteed by the developers of the *Geant4* environment, including compatibility with new versions of compilers. This is especially true in the case of explicit requirements for cross-platform end-applications.

It should be noted that the use of a specific tool for mathematical simulation of radiation action is not a limiting factor. It was earlier shown in [25] that heterogeneous tools can be used both in solving the task of radiation therapy planning and integrated under a common architecture of control commands. Thus, in the present work, the launch of the functionality executed on video cards can be performed both directly from the *Geant4* environment application and separately on a standalone virtual machine using the output of the *Geant4* application as its own input data transmitted via the previously described communication channels.

ARCHITECTURE OF A STANDARDIZED DATA TRANSMISSION FORMAT

In the presented suite, JSON is the main format of configuration files. This convenient format allows cross-platform transfer of “key-value” pairs, and the values can be both separate data types and lists and dictionaries of values. However, due to the specificity of user data, which are conventionally represented in such systems in the DICOM[24] industrial format, the internal format of data exchange in applications should effectively support the transfer of binary data. Thus, during the implementation of the project, it was decided to implement a separate format for storing user intermediate data. As the main format for such tasks, the protobuf[25] message transmission description by Google[26] was selected. After that, versatile tools for transforming tomographic images and associated contours [26], phase spaces for general-purpose Monte Carlo codes [27], and associated output formats were written. The format and the messages themselves are fully portable between operating systems, while message writing and reading functionality implemented for a vast amount of programming languages. The only limitation of the used solution consists in the maximum message size, which cannot be larger than 2.14 GB due to the addressing of the binary file in a 32-bit memory region. Such target files may occur, e.g., when working with tomographic images with the pixel number of 1024 × 1024 and the slice number of more than 200 and simultaneously with the associated number of contours more than 32. To solve this problem, a backup format based on serialization libraries in Boost[27] was implemented; however, the associated disadvantage involves the impossibility of transferring the final target files between Linux and Windows operating systems.

ARCHITECTURE OF END-USER TERMINAL FACILITIES

In contrast to server-based settlement tools, which should be deployed only on the basis of Linux or BSD operating systems, the requirements for endpoint workstations and client machines may be not as strict. In general, deployment should be available on any operating system, including Windows, Linux, and macOS. In addition, any endpoint user environment should be easily upgradeable. Thus, it was decided to use the Python[28] programming language for the work of creating the final user interface, and the final executable files were built for the specific operating system of the target endpoint using publicly available tools for building executable files (e.g., pyinstaller[29]). In this case, separate modules of the final software, which have their own separate input and output data, are realized as ready executable files, and integrative access is provided by means of the end environment file system and network file system, linked by servers according to the scheme described above. Some examples of this approach include specific modules for the pre-radiation preparation stage [28] and an external system for field optimization in the mode of 3D conformal radiation therapy [29].

[24] Digital Imaging and Communications in Medicine is a medical industry standard for creating, storing, transmitting, and visualizing digital medical images and documents of examined patients.

[25] https://protobuf.dev/reference/protobuf/edition-2023-spec/. Accessed May 19, 2025.

[26] https://about.google/. Accessed May 19, 2025.

[27] https://www.boost.org/. Accessed May 19, 2025.

[28] https://python.org/. Accessed May 19, 2025.

[29] https://pyinstaller.org/. Accessed May 19, 2025.

Figure 2 presents the architecture of using end-user tools as part of the considered suite when realized within the framework of neutron therapy tasks (variant 1), prospective planning tasks (variant 2), and related integration tasks (variant 3). The client application in C# language can call separate modules of Python language and executable files of additional applications (*NGPlan.Visual.Client* and *ROReview*); it also has interfaces of exchange with third-party services and tracking the progress of server tasks. Within the framework of providing data flows on the server, three variants of execution of Monte Carlo calculations are realized, the main technological components of which are presented in their order of invocation. Figure 3 shows a number of screenshots illustrating the appearance of the software products.

SUITE APPROBATION IN FIELD STUDIES

The primary evaluation of the technological connectivity of the components was carried out within the framework of related work on the assessment of the radiation hardening of products to heavy ions [30]. In the process of performing the simulations that serve as a basis for subsequent estimates of the values of linear energy transfer of various ions through scatterers and a low (10 torr) density atmosphere, the calculation server, deployed as described earlier, was used. The results obtained were automatically analyzed in the form of histograms in the *ROOT* package [31] developed by CERN. The communication mechanisms between the calculation server with *Geant4* and typical clients in the form of the Windows file system explorer and the root client application were tested.

One of the main applications of the suite software consists in obtaining comprehensive estimates of the values of biological effectiveness of radiation. Primary results related to the medical application of the suite were described in [32], where the components of the suite, including the GPU, were used in an automated mode to perform retrospective estimates of the contribution to the biological dose of the proton component in fast neutron irradiation.

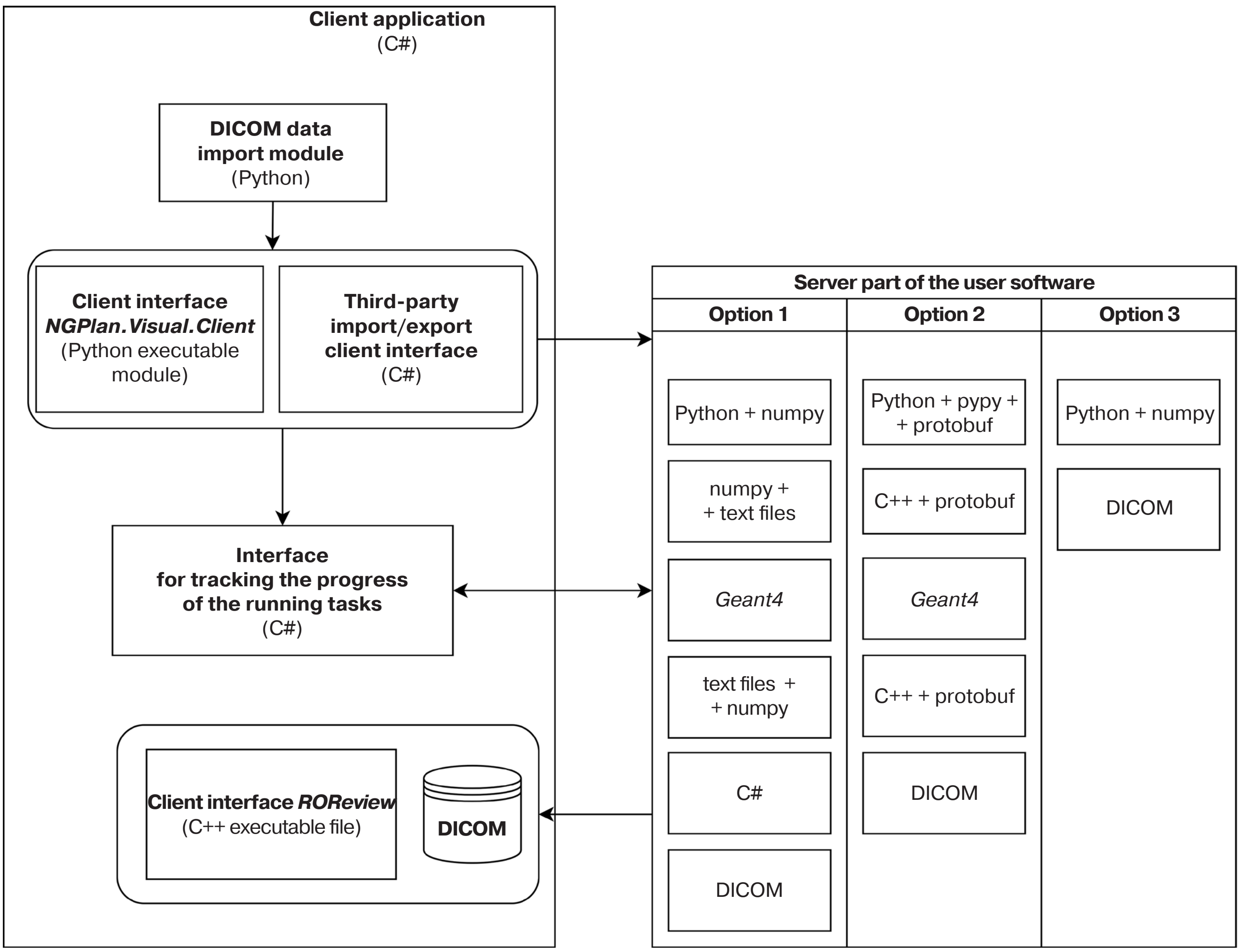
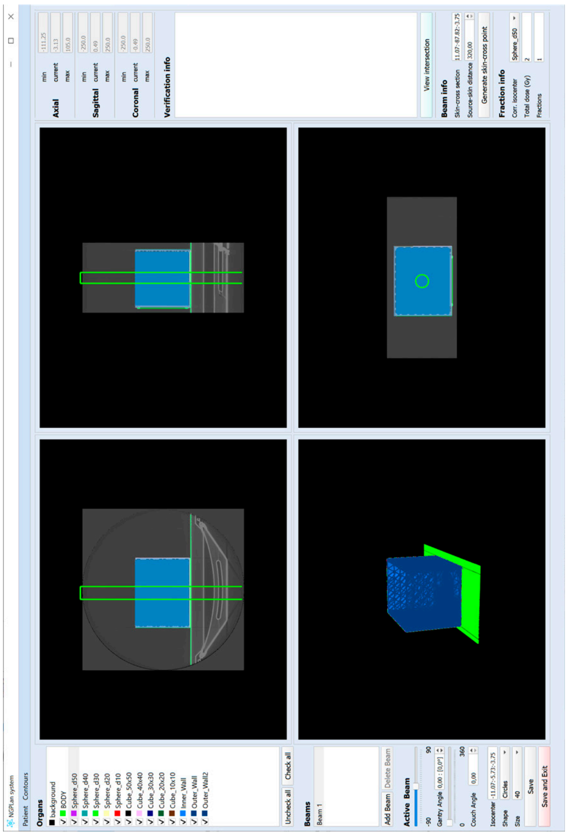
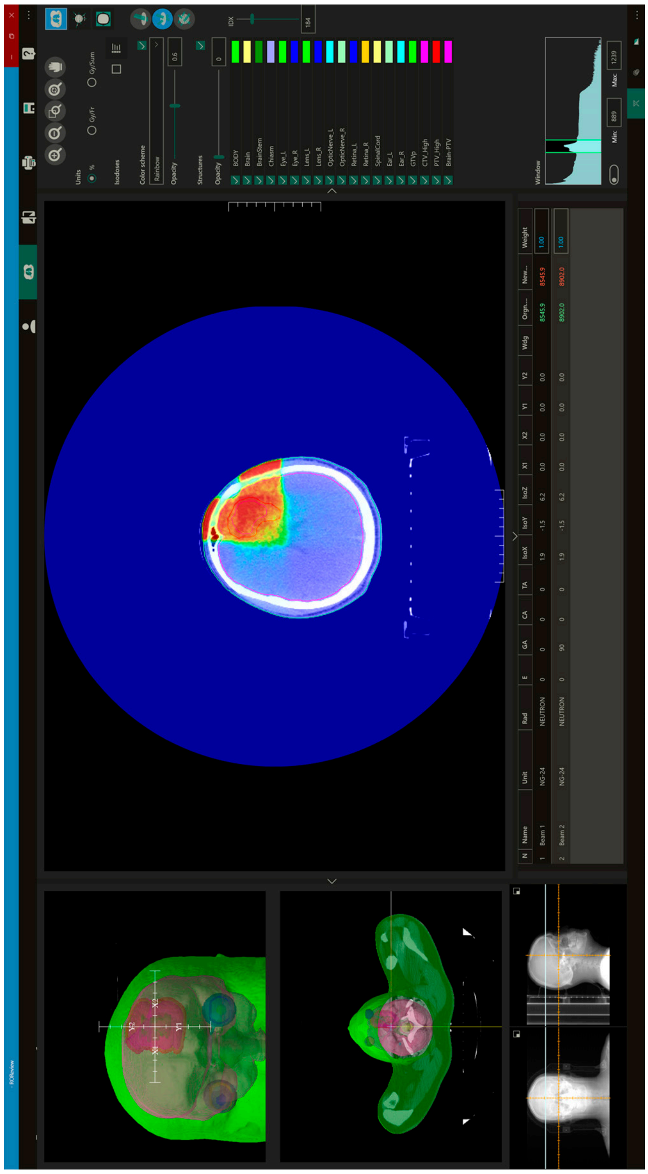


Fig. 2. Principal diagram of the end-user application organization



(a)

(b)



(c)

Fig. 3. Appearance of some software tools of the developed suite:
(a) *NGPlan.Visual.Client* interface for working with the irradiator location at the stage of pre-radiation preparation;
(b) interface of the third-party import/export utility;
(c) interface of the *ROReview* software package in the dose field display mode

A similar application domain[30] was the modification of the presented suite for the purposes of estimation of relative biological effectiveness (RBE) of proton radiation in comparison with the conventional RBE 1.1 used in routine clinical practice. When building such models, Hounsfield number transformations of the original tomograms based on the optimized model of material densities [33] were used, but all operations within the presented suite are configurable. Work is underway to create an ergonomic user interface for convenient data input at the commissioning stage of the planning systems implemented or intended to be implemented as part of the described suite.

The results of field testing of mathematical models for optimizing the dose deposit of a modified Bragg peak for protons in the form of a task file for the accelerator of the Prometheus proton therapeutic facility (Obninsk, Russia) were presented in [34]. The above-described approaches to mathematical simulation of proton radiation action were used to develop control commands, which were then transmitted to the control system of the accelerator [35]. A similar task of creating control commands was solved in [36] to detect morphological changes in tumor cells after implantation in a tumor-bearing animal. In general, such an approach to the automation of radiobiological studies shows its effectiveness and makes it possible to significantly reduce the time of preparation for the experiment by unifying typical solutions.

Finally, the computing and programming suite proved feasible in the tasks of experimental activities at the temporary radiobiological stand [37], and later—within the framework of the collective use center of the U-70 accelerator facility (CCU “RBS on U-70”[31]). When carrying out an initial assessment of the biological efficiency of carbon ion beams [38], data on the dose-averaged values of linear energy transfer calculated in a detailed model of the irradiated object for various experimental conditions were used. The approaches to the creation of means for passive modification of carbon radiation described earlier [39] and realized later as a software package as part of the described suite and directly fabricated ridge filters were used by other researchers [40, 41]. The operations of the radiobiological stand of the U-70 facility were described in [42]; approaches to the implementation of channels for medical and therapeutic purposes were reported in [43].

DISCUSSION

One essential aspect of radiotherapy planning systems in clinical practice involves the organization of data transfer between different systems and the connectivity of software components within the system. Thus, the work [44] showed that even when transferring the same DICOM-data set, different planning systems (in [44]—*MRIdian TPS* and *Eclipse*) differ significantly (up to 16%) in terms of interpretation of structure volumes and, consequently, dose-volume parameters. At the same time, taking into account the abundance of systems both available on the market and proprietary (in-house) systems of individual clinics [45–49], the question of ensuring coherence and equivalence of the reported clinical results remains relevant. As clinical practice shows, even in the same hospital, two [50] or more planning systems may be used for the same accelerator or treatment cabin, and the decision to prescribe therapy is achieved after all alternative proposed scenarios have been analyzed by the attending radiotherapist or a board of specialists.

The main direction in the development of calculation systems carrying out simulation of the absorbed dose of radiation therapy consists in a multiple increase of their calculation performance while maintaining the accuracy at the level of precision provided by Monte Carlo systems. In this context, calculations with the use of GPUs are increasingly attracting attention. GPUs have long been used for simulating radiobiological response at the DNA, cellular, and intercellular levels of matter organization, including water radiolysis [51, 52]. At the same time, simulations for the purposes of radiation therapy have emerged only in recent years. For example, the researchers in [53] developed *goCMC*, including the support of a computational module for carbon ion therapy, which allows a computational speed of one plan within 40 min. At the same time, the manufacturers enable the integration of their approach into the *Eclipse* commercial planning system. A similar problem, applied to intraoperative high-energy electron therapy, was solved in [54], with calculation speeds of up to 10 s on a video card. Earlier solutions, such as the one described for proton therapy in [55], become the basis for experimental validation of the approaches used, showing not only times of 3.5 to 11.5 s per beam versus 20 s for the CPU-based solution, but also excellent agreement with measured values according to gamma index criteria (more than 95% passing points according to the 3%/1 mm criterion). The *VQA Plan* [56] system by Hitachi, developed specifically for the ion center in Osaka (Japan), is another solution proposed for the operational calculation of scanning ion beams.

[30] Smyk D.I. *Proton therapy in re-irradiation of recurrent tumors of head and neck organs*. Thesis for a Candidate Degree in Medical Sciences. https://new.nmicr.ru/wp-content/uploads/2024/05/dissertacija-smyk.pdf (in Russ.).

[31] http://ihep.ru/pages/main/6580/8769/index.shtml (in Russ.). Accessed May 19, 2025.

According to the authors, the distinguishing feature of the presented system in comparison with the simplified analogs in *XiDose* and *RayStation* consists in the calculation of the biological component of the dose of carbon beams. The implementation of fast computational algorithms for such systems based on GPUs seems to be a challenging task, the solution of which requires the efforts of a wide range of specialists [57, 58].

CONCLUSIONS

Modern approaches to radiation therapy should not only meet the quality criteria of medical services, but also ensure the required safety of treatment. Organization of an effective software computing environment for a wide range of purposes facilitates, among other things, coordination of efforts of various medical specialists, software developers, radiation technologists. As part of promising development directions, mechanisms for the introduction of quantum computing and artificial intelligence technologies can be considered. Work on the mass-scale introduction of the developed technologies is underway.

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Authors' contributions

A.N. Solovev—writing the original draft, software, conceptualization, project administration, methodology, and investigation.

Ya.V. Kizilova—visualization, formal analysis, data curation, software, investigation, writing the review, and editing.

E.I. Kazakov—investigation, resources, validation, and methodology.

S.N. Koryakin—resources, supervision, validation, funding acquisition, writing the review, and editing.

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