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BIOPHYSICS AND MEDICAL PHYSICS

Radiation Technology in Medicine: Part 1. Medical Accelerators

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Abstract—Ionizing radiation is widely used in medicine today. Sources of ionizing radiation include X-ray tubes, natural and artificial isotopes, and accelerators [1, 2]. This review describes the role of accelerator technology and nuclear physics methods in cancer treatment. It presents an analysis of the data that have been published in scientific articles and reports, materials of the IAEA, and other places over the course of the past 5 decades.

Keywords: ionizing radiation, accelerators, medical physics, nuclear technology, linear accelerators.

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INTRODUCTION

Ionizing Radiation in Medicine

At the end of the 19th century, the study of the structure of matter led to the discovery of radiation that is capable of penetrating opaque mediums. In 1895, W. Röntgen discovered that cathode beams occur on an anode that result in X-radiation, or roentgen radiation. This is electromagnetic radiation with an energy of 30 to 250 keV. In 1896, A. Becquerel revealed radiation that is spontaneously emitted by uranium salts. Later, this phenomenon was called radioactivity. Exposure to both types of rays caused changes in the structure of matter.

Basically, since the moment of its discovery, ionizing radiation has been applied in various global industries, primarily, in medicine. The structure of the medical use of ionizing radiation rays is shown in Fig. 1. It includes several basic areas of focus: X-ray diagnostics and treatment, radiation therapy, and nuclear medicine.

In the area of medicine that is based on ionizing radiation, multiple kinds of high-technology radiation generating devices were created. There are over 110 000 such devices in the world (not including X-ray emitting units, of which there are several million). These include approximately 14 000 electron and proton accelerators, approximately 100 reactors, 1500 cobalt devices, 300 Gamma Knives, and 2200 brachytherapy devices. As well, there is medical diagnostic equipment: 30 000 MRI (magnetic resonance imaging) scanners, 40 000 CT (computed tomogra-

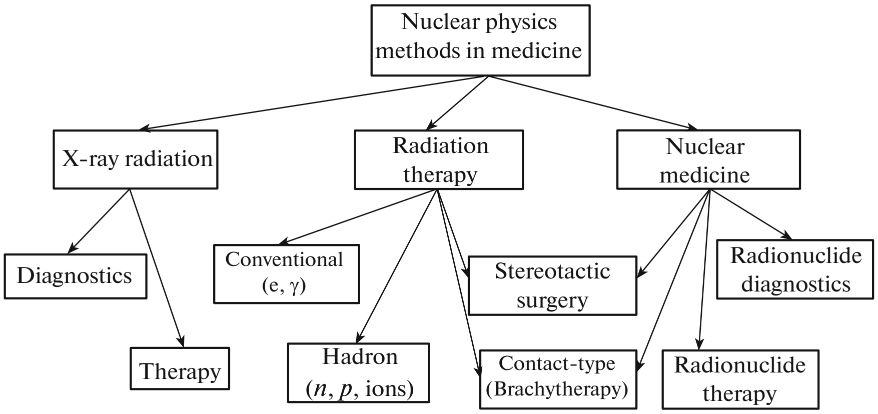

Fig. 1. The structure of the use of ionizing radiation in medicine.

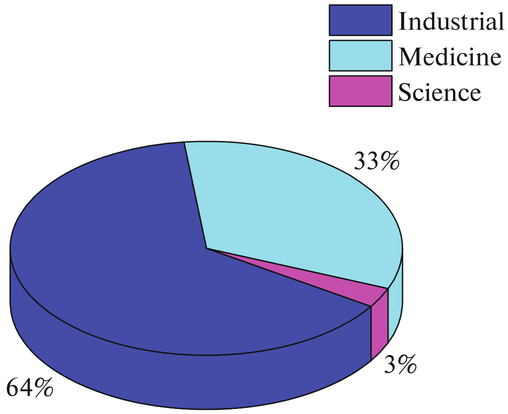

Fig. 2. Distribution of charged particle accelerators by fields of application.

phy) scanners, and 4000 PET (positron-emission tomography) scanners, which are installed in 600 PET centers.

Among the contemporary medical devices, charged particle accelerators play a great role, comprising 15% of the overall number of high-tech medical devices; their number grows yearly. Three-quarters of a century later, these devices are just as important as lasers, rockets, aircraft, and spacecraft, having become one of the brightest human achievements. Accelerators are essential not only as scientific tools: they have been successfully integrated into various areas, such as medicine, production, and agricultural industries [4]. Accelerators are becoming smaller and developing a wide range of properties that can be adjusted to a broader spectrum of problems and purposes [4].

In general, out of the 40 000 accelerators that operate in the world (Figure 2), approximately 25 000 work in industrial areas (including several hundred in the agricultural industry); 3% of the total quantity (approx. 1200 units) work in science, and approximately 35% are used in medicine [1, 2]. If the present trend of putting accelerators in operation remains at the current level, then by year 2020 their overall number can exceed 50 000.

According to statistical data [3] for the beginning of 2014, approximately 400 electron accelerators and 50 proton accelerators were used in Russia [3]. The accelerator distribution in the areas of the Russian national economy significantly differs from the global distribution. In Russia, approximately 20% of all accelerators are used in science, 43% are used in industrial areas, and 37% are used in medicine. A major part of the latter (approximately 90%) are utilized for radiation therapy, while the rest are used for charged-particle therapy and the production of radioactive isotopes for the purposes of diagnostics in the centers of positron emission tomography (PET Centers) [4–6] and nuclear medical technologies.

This article presents a review of the data on accelerator types that are applied in various areas of medicine.

1. THE PHYSICAL MECHANISMS OF THE EFFECTS OF IONIZING RADIATION ON BIOLOGICAL TISSUES

Exposure to ionizing radiation leads to the destruction of bonds between atoms and molecules that make up tissues. The sensitivity level of different tissues to radiation is not uniform. The high level of sensitivity to radiation that is shown in blood-making organs is the key to determining the nature of the acute radiation syndrome.

The fact that tumor cells are more affected by ionizing radiation than healthy body cells served as the foundation for the development of radiation therapy aimed at the treatment of cancerous diseases. This is based on exposing organs, body parts, and the whole body to radiation. Physicists and radiobiologists select the doses and types of radiation and its spatial distribution in order to achieve the best result. The main goal of physicists is to select the parameters of radiation for the best match of the volume of the body to be exposed (the target) and the area of maximum absorbed dose that is fatal to target cells. In this case, healthy cells and critical organs surrounding the target, which cannot endure high doses, receive a minimal absorbed dose that is not enough to inflict damage or cause their dysfunction. As well, the most important requirement is the equal distribution of the dose over the entire target volume.

At the molecular level, ionizing radiation damages molecules and atoms. From the physical point of view, this means breaking interatomic and intermolecular bonds and the formation of new bonds between atoms and molecules, as well as ionizing atoms and molecules. The effect of ionizing radiation on a cell is described through the number of ionization events that occur in various structures of the cell.

The following types of ionizing radiation are used for biological objects. Heavy charged particles are usually distinguished as protons, ions, and neutrons in order to compare their biological effects. These have a dense ionization nature. Beams of electrons, photons, and X-ray radiation have a sparse type of ionization. It should be noted that the path of neutral particles (photons and neutrons) between the events of the environmental interaction is significantly larger than the path of charged particles. At high values of the energies of these particles in tissues, the path can reach several centimeters. The effects of different types of ionizing radiation on biological tissues varies. The absorbed dose in biological tissues for different types of ionizing radiation depends significantly on linear energy transfer (LET) by particles.

At high energy levels of *protons* (150–250 MeV) that are used in radiation therapy, environment ionization processes are predominant and the energy that is absorbed is concentrated along proton tracks. As a result of ionization, secondary electrons occur; the majority of them have small energies (less than 100 eV). When, for example, a proton of 200 MeV energy passes through tissues, they are ionized down to the depth of 14–15 cm. A track appears with a surrounding "coat" of secondary electrons and a maximum level of ionization density at the end of the path, which is called the *Bragg peak*. Thus, as the particle decelerates, the ionization density reaches its maximum and then rapidly drops, which is suitable for treating tumors at a considerable depth and thus is used in proton radiation therapy.

The mechanism of the *heavy-particle* interaction with atoms and molecules in the body is not fundamentally different from the mechanism of protons as described above. The actual differences are due to the density of linear energy transfer (LET). The number of ion pairs that occur per unit length of the path is significantly higher for ions. The so-called "coat" of secondary electrons that occur around the track is denser for ions than it is for protons.

The passage of electrons through biological tissues is notably different from the passage of heavy ions. Electrons have a low mass and thus scatter intensely, thus increasing the volume of the tissues that are exposed to radiation. An unbound electron passes a specific distance through tissues and brings ionization events around its track; as well, part of the energy is spent on the excitation of atoms. Having used up all of its kinetic energy for ionization and excitation, the unbound electron decelerates to a speed that is comparable to bound electrons and is then captured by a neutral atom, which forms a negatively charged ion. As a result of the first and third of these processes, the energy of the ionizing particle is spent on forming a pair of ions. The primary beam of electrons can be accompanied by secondary electrons that have significantly lower energies and scatter in all directions relative to the primary beam. Electrons with energies less than 100 MeV pass several centimeters in tissues and have the maximum value of ionization density close to the surface of tissue–air boundary. This is the reason that electrons are used in the treatment of surface tumors.

Unlike electrons, *X-rays and gamma-rays* pass large distances in tissues and are used for treatment of deep-seated tumors. Photons, when passing through the biological environment, create an electron and photon shower, forming a flux of secondary electrons and photons, thus making is possible to destroy molecules that are far from the region of the initial ionization. Secondary electrons form an absorbed dose from a photon beam, while secondary photons increase the target volume of biological tissues; it is necessary to take this into account in planning radiation therapy.

Soft X-ray photons at an energy of 10 keV transfer approximately 9.5 keV to a photoelectron; the length of the path of such an electron in tissues amounts to 2.3 μm. X-rays at energies of up to 100 keV are absorbed in surface tissue layers, generally as a result of the photoelectric effect; the energy that is absorbed is transferred to photoelectrons that have paths no longer than 2 mm. The maximum absorbed energy of hard X-rays at photon energies of 300 keV occurs at the depth of approximately 1 centimeter. Photons that occur at the decay of ^{60}Co nuclei (1.18 and 1.33 MeV) are absorbed after passing 5–6 cm of tissue (approx. 60% of the entire primary beam energy is absorbed). High-energy photons of approximately 35 MeV, transfer most of their energy after passing 6–8 cm of tissue.

Unlike heavy particles such as α-particles that form multiple ionization events within the target, ionization caused by photons leads to the destruction of a great number of molecules and cells across the entire target volume.

Neutron beams that participate in nuclear reactions also form fluxes of various secondary particles with angle and energy distributions that are necessary to take into account during the calculation of the absorbed dose. During the interaction of neutrons and photons with the tissues ionization events are created over the entire target volume. As an example, when tissues are exposed to high-speed neutrons at an energy of 14 MeV energy, heavy recoil nuclei occur at a depth of 15 cm, with a LET of over 50 keV/μm. These provide 25% of the absorbed dose, while 70% is absorbed by recoil nuclei with a LET value of 16 keV/μm [7].

The type of ionizing radiation, the machine, and the beam parameters for the process of exposure are selected depending on the nature, volume, and depth of the tumor.

2. ACCELERATORS IN MEDICINE

Accelerators were created in order to study the structure of matter, as the energy and beam intensity of particles from natural isotopes are insufficient for this purpose.

In the late 1920s to early 1930s, the first accelerators were invented and used: the cascade accelerator (1929), the Van de Graaff (electrostatic) generator (1931), the cyclotron (1931), and the Widerøe linear-particle accelerator (1928) [7]. Accelerators started to be used in medicine less than 10 years after their invention. In 1937, an accelerator was successfully used in London to treat cancerous diseases [8]. In the 1950s, medical accelerators had their first rivals, machines that use the ^{60}Co isotope as a source of ionizing radiation (later these were called cobalt machines). The photon energy of these isotopes is ~1.3 MeV.

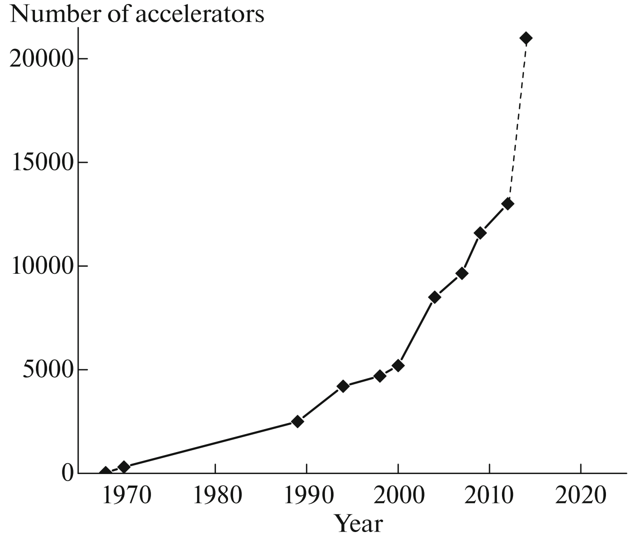

Fig. 3. Growth dynamics of medical accelerators in the world and the prognosis for the period until 2020.

In the early 1970s, over 300 accelerators of various types were in use in medicine (157 betatrons, 118 linear accelerators, 22 Van de Graaff generators, and 9 resonant transformers [9]). Moreover, proton accelerators had their first experimental use; four of these existed, two of which were in Russia.

Since the 1980s, linear electron accelerators have become smaller and easier to use in radiation therapy. This became possible after the sources of a high-frequency electromagnetic field that are used in them were improved. Betatrons and cobalt machines dominated in medicine until the 1970s; and since the 1980s, linear electron accelerators have been superior to cobalt machines and other types of accelerators.

By 2000, the number of linear electron accelerators in the world reached 5000 [10, 11]; based on the recent data, almost 14 000 of them are in use [2]. The growth of the number of linear electron accelerators in the world that are used for medical purposes since the 1960s can be approximated by a quadratic dependency (Figure 3). If this trend continues, by 2020, for example, the number of electron accelerators that are used in medicine may reach almost 21 000 units.

Medical accelerators are used in 117 countries. Table 1 displays information on the accelerator distribution for countries that use more than 100 units. Russia is in 12th place. According to Table 1, the 17 leading countries of the world use over 9000 medical accelerators, 9 European countries use approximately 2400 medical accelerators, and 31 more countries have 800 units.

Since the early 1990s, Varian, Elekta, IBA, and Siemens and Philips (until recently) have been the main manufacturers of accelerators. The rapid growth of the sales of medical accelerators has stimulated their total annual production rate, which is 700 to 1000 units per year.

Table 1. Medical accelerators in 117 countries

Country	Population per 1 accelerator, thousand people	Population of the country, million people	Amount, pcs
United States	80	308.7	~3818(5200)
China	1325	1400.0	~1017
Japan	140	128.1	~847
Germany	200	81.0	~514
France	168	70.0	~476
Italy	163	61.5	~376
Great Britain	200	59.5	~314
Brazil	936	199.0	~288
Canada	131	35.1	~267
Spain	228	47.2	~207
India	2300	1140.0	~176
RUSSIA	**1120**	**140.0**	**~150**
Turkey	540	76.2	~141
Australia	170	23.3	~137
Netherlands	131	16.8	~128
South Korea	402	48.7	~121
Poland	341	38.2	~112
TOTAL			~9068

Since the beginning of the 21st century, the number of medical accelerators in Russia has a linear growth (Fig. 1). In the last 15 years, over 120 new accelerators were installed in Russia. Today, approximately 150 accelerators are used; if this growth rate continues, their number may reach 300 by 2020, which is two times higher.

3. ACCELERATORS IN RADIATION THERAPY

Out of the total of 14 000 medical accelerators, linear electron accelerators make up more than 13 000. Approximately 1000 heavy charged particle (protons and ions) accelerators are used in medicine.

3.1 Electron Accelerators

Linear electron accelerators in medicine have completed the path from being experimental nuclear machines for medical purpose to becoming fully capable medical devices. Linear accelerators, as mentioned, have become the main tool of radiation therapy since the 1980s.

The progress in the application of medical linear accelerators has been driven by the improvement of the elements and systems that generate radiation and by the advancement of computer technologies, medical-imaging techniques, and methods of formation of the dose field. A number of unique computer technologies have been implemented for this purpose: *Intensity-Modulated Radiation Therapy* (IMRT) allows modeling of the beam intensity in specific small tumor volumes, which enhances the conformity of radiation; *Image-Guided Radiation Therapy* (IGRT) allows the formation of images during a session and within short time intervals, thus increasing accuracy when exposing tumors that occur in movable body parts to radiation [12–16].

Conventional Radiation Therapy. Various types of ionizing radiation can be used to produce effects on body tissues: X-ray radiation, high-energy bremsstrahlung, gamma-rays emitted by radionuclides, beta radiation, neutron radiation, and proton radiation. In the majority of cases, radiation therapy uses bremsstrahlung radiation photons. In this case, the energy of accelerated electrons that emit bremsstrahlung usually comprises 6–25 MeV.

One of the essential problems of radiation therapy is achieving the conformity of the radiation. For the best match of the region that is exposed to radiation and the boundary of the tumor volume, it is exposed to radiation from different sides at a varying intensity of the photon beam (IMRT method) with the use of multileaf collimators (MLC).

Electron beams are applied significantly less often. Recently, there have been suggestions to expose a target that is situated in a transverse or longitudinal magnetic field to electron beams of 20–70 MeV energies [17]. In actual practice, intraoperative radiation therapy devices have been implemented; their application has been expanding over the recent years.

Intraoperative Radiation Therapy. In order to destroy all of the possible remaining tumor cells in tissues after surgery, the tumor bed can be treated by electron beams. This method has been tested in approximately 200 oncology centers in the world, however its chances of success were viewed with skepticism, as surgery and further radiation therapy at a medical linear accelerator could be performed only in different rooms, viz. in the operating room and then in the accelerator room. The major efforts that are required to prevent contamination of a wound during transportation of a patient from the OR to the accelerator room and then back to the OR present a challenge. The possibility of a malfunction in the accelerator also poses a threat. In the 1990s, compact devices emerged that are suitable for this purpose that could be installed in an OR. The first device to pass all of the licensing processes that were required was an American device, the Mobetron.

There are also successful ventures for creating intraoperative radiation therapy devices in Russia. As an example, at Moscow State University, in cooperation with Universitat Politècnica de Catalunya, one of the devices was designed based on a slotted microtron with the electron beam energy of 4 to 12 MeV. The proposed accelerator is singular for its size, which allows placing it in a small container having the dimensions of $24 \times 13 \times 48$ cm^3. The weight of the microtron does not exceed 120 kg and its power consumption amounts to approximately 1 kW [18].

Ionizing radiation is a flux of electromagnetic radiation, elementary particles, and nuclear fission products that are capable of ionizing matter. As stated, the main type of ionizing radiation that is used in medicine is bremsstrahlung radiation. It is used not only in conventional radiation therapy, but also in stereotactic surgery (Cyber Knife devices, modified linear accelerators, and tomotherapy).

Stereotactic Surgery. In 1951, a famous neurosurgeon, Lars Leksell, suggested using a stereotactic frame during X-ray treatment of the basal ganglia of the brain. In this manner, stereotactic radiosurgery was born. Currently, stereotactic radiation localization is used to deliver a significantly larger dose to a small target area compared to the dose that is taken by the surrounding healthy tissues. As a rule, a high and lethal dose for tumor cells is delivered once. This type of radiation therapy enables one to treat small brain tumors that are located at a considerable depth, which was impossible until now.

Stereotactic radiosurgery devices are widely used in medical centers all over the world. Approximately 300 Gamma Knives and 300 Cyber Knives are currently used; more than half of these are used in the United States and Japan. Stereotactic radiosurgery in

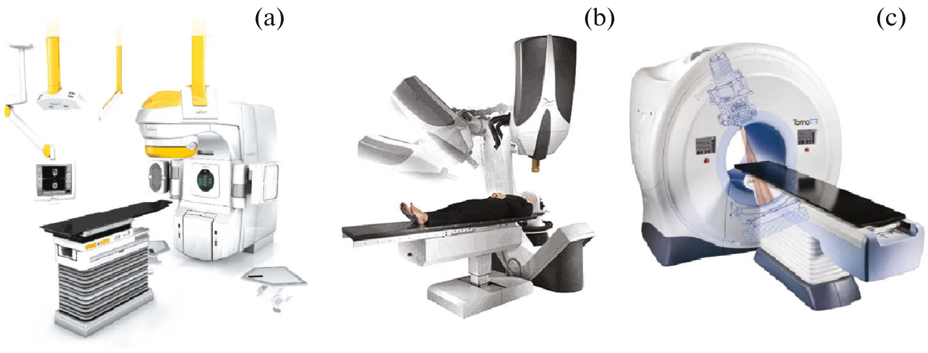

Fig. 4. The Linac modified medical accelerator (Varian, Novalic) (a), Cyber Knife device (b), tomotherapy device (c).

Russia has been rapidly developing for the last 3 to 4 years, moving the country from 30th to 40th places in the rating up to 10th place according to the number of such devices [19].

The first *Gamma Knife* device was designed and created by the Swedish neurosurgeon, Lars Lesksell in the 1950s and 1960s; 201 photon Co^{60} beams were directed towards one point. Thus, the dose that was delivered to the tumor exceeded the dose that was delivered to healthy tissues by many times. The accuracy of the dose delivery was over 0.3 mm. This allowed the surgeon to "burn the tumor out" in only one or several sessions.

In Argentina, the neurosurgeon O. Betti and engineer V. Derechinsky created a *modified medical accelerator* (Fig. 4a) in 1982, in which the stereotactic frame was fixed onto a special chair. This device is an alternative to Gamma Knives and one of the modern methods for using electron accelerators in radiation therapy. The goal of the creation of such devices was to replace the cobalt sources that are used in Gamma Knives, which present a constant radiation hazard, while accelerators are hazardous only when they are turned on. Such machines use a double arc: the accelerator rotates around the isocenter in the vertical plane, while the medical table rotates in the horizontal plane. The radiation dose distributions that are achieved in modified linear accelerators and Gamma Knives are comparable.

Another accelerating machine, which is an alternative to the Gamma Knife, is called the Cyber Knife. The device was created in 1992 at Stanford University under the direction of D. Adler; the first surgery with it was performed in 1999.

The device is comprised of two main elements: a light linear accelerator and a mobile computer-controlled robotic arm with six degrees of freedom (Fig. 4b). The computer-controlled accelerator can treat a tumor and multiple metastases with radiation during one session (from 1200 possible directions), which is impossible to achieve in a surgical operation. The energy of the electron accelerator of the device is based on levels from 4 to 6 MeV. The Cyber Knife enables non-isocentric radiation treatment of the target, as well as asymmetric and highly-conformal radiation of the target with an accuracy of up to 0.5 mm. Due to the fact that the photon beam in the device is directed from the robotic manipulator arm, it is possible to treat tumors that are located in different parts of a patient's body. For Gamma Knife devices, this level of maneuverability is impossible. The Cyber Knife is one of the brightest achievements in the area of medical accelerator devices.

In Moscow alone, 29 accelerators are used at 12 medical institutions for radiation therapy, including four Cyber Knives. In all of the sectors of the national economy, there are a total of 88 electron accelerators and nine proton accelerators.

Among the developments in the recent years, there are devices that enable the combination of radiation therapy and diagnostics methods. One of the methods that is being actively developed is called *tomotherapy*; it combines computed tomography scanner diagnostics options with radiosurgical destruction of cancerous sites by bremsstrahlung photons from an electron accelerator (which is used instead of the X-ray source that is applied in a CT scanner) (Fig. 4c).

3.2 Proton and Ion Accelerators

Since the late 1950s, physicists and health professionals have been cooperating on research using heavy charged particle accelerators, viz., protons, ions, and pions, in medicine. The main advantage of such devices is that the energy of the particles is transferred to matter at the end of their path, i.e., a so-called Bragg peak occurs in the depth distribution of the dose. At the proton energy of 200–250 MeV, the peak in biological tissues is located at a depth of 10–15 cm, which is suitable for radiation therapy. The beams of heavy charged particles also have many other advantages, for example, a low scattering angle compared to an electron beam.

Before the 1990s, there were 23 centers of proton and ion radiation therapy in the world based in research institutions, which used beams from research accelerators. They obtained clinical research results that proved the viability and competitiveness of this method of treatment. The first medical center where a heavy particle accelerator was used opened in Loma Linda University (United States) in 1990. Currently, there are 42 operating centers of proton radiation therapy in 19 countries, while 36 more centers are being constructed or designed [20]. Beams of carbon ions are used In seven centers; five more of these centers are under construction.

Out of 90 operating and designed centers of proton and ions radiation therapy [21], 6 are in Russia. Proton radiation therapy continues to develop in the Institute for Theoretical and Experimental Physics (Moscow), in the Joint Institute for Nuclear Research (Dubna), and in the Petersburg Nuclear Physics Institute (Gatchina). Centers of proton therapy are being created based on the nuclear centers of Troitsk and Dimitrovgrad and centers of carbon therapy in the Institute for High Energy Physics (Protvino). According to the number of patients who undergo proton radiation therapy, Russia takes fourth place after the United States, Japan, and France. In order to achieve the level of the world's leading countries. Russia must create 20 centers of proton radiation therapy and four centers of ion radiation therapy.

4. ACCELERATORS IN NUCLEAR MEDICINE

Nuclear medicine incorporates radionuclide diagnostics and therapy with the use of radioactive isotopes. For these purposes, natural and artificially created isotopes are used, which are obtained either during processing of natural materials or at accelerators and reactors. In radionuclide diagnostics, isotopes are used in research that occurs at gamma chambers, Single Photon Emission Computed Tomography (SPECT) units, and positron emission tomography (PET) units.

Radionuclide therapy involves methods of implantation of various isotopes to affected tissues: this includes brachytherapy and "burning a tumor out" using a Gamma Knife. In the first case, in order to treat cancerous diseases, isotopes are directly implanted into the body where they are localized in the affected tissues. Photons or charged particles emitted by the isotopes transfer most of their energy to the tumor and as a result of this exposure, tumor cells die.

Throughout the development of brachytherapy, approximately 150 radionuclides have been used [8–10]. Currently, only six are used. When applying this method, thin rods with isotopes are implanted into tissues or placed close to them. In order to create a dose field that circumscribes the tumor shape, rods are moved at different speeds that are set by the planning system.

In the worldwide practice of nuclear medicine, there are approximately 100 reactors that produce radionuclides (7 in Russia) and approximately 1000 charged particle accelerators (20 in Russia). Compact cyclotrons are generally used for these purposes. A number of methodologies have been recently developing that are aimed at obtaining isotopes in electron accelerators [21–26].

In total, 27 isotopes are used and studied in radionuclide diagnostics and 37 in radionuclide therapy. Based on these, there are over 200 radiopharmaceuticals. In Russia, 22 radiopharmaceuticals are used for computed diagnostics, 20 overseas sets are used for radioimmunology analysis; 6 are used in brachytherapy, and 4 are used for PET scanning. For nuclear medicine purposes, there are 18 types of isotopes that are developed in accelerators, while 28 are created in reactors. In this manner, for example, the artificial radionuclide ^{99m}Tc was synthesized in an accelerator for radionuclide therapy. The widest range of radionuclides for nuclear medicine purposes can be obtained in cyclotrons at an energy of 70 MeV [27].

As mentioned, the ^{11}C, ^{13}N, ^{15}O, and ^{18}F radionuclides, which emit positrons during their decay, are used in PET. Positrons pass a distance of 1 to 3 mm in tissues and lose their energy upon deceleration. At the moment that they stop, each of them annihilates upon meeting a local electron and turns into two photons at an energy of 0.511 MeV, that travel in opposite directions. The photons are registered by two counter-positioned scintillation detectors on crystals; the events that are associated with the synchronous occurrence of photons that occur as a result of one annihilation event are filtered out by a coincidence circuit.

The main component of a full PET center that incorporates several PET scanners is a proton accelerator (cyclotron). As a rule, in order to produce isotopes for PET scanners, cyclotrons with 7, 18, or 70 MeV energies are used. [28, 29]. Approximately 600 centers operate in the world, while there are only 7 in Russia. As an example, over 300 PET centers operate in the United States. The first Russian PET scanner was manufactured and is used in St. Petersburg.

CONCLUSIONS

Today's achievements in contemporary physics are widely applied in medical equipment. In total the high-technology medical equipment consists of more than 110 000 nuclear devices, excluding electron microscopes and X-ray machines [21]. Table 2 shows the basic types of physical devices that are used in cancer diagnostics and therapy.

As a result of the collaboration of physicists, engineers, and health professionals, combined tomogra-

Table 2. High-technology medical devices in Russia and abroad in 2012 [28–35]

Devices	In the world	In Russia
Accelerators	~14 000	~150
^{60}Co gamma-rays sources	~1500	~215
Gamma-ray chambers	~17 000	~240
Computed tomography scanners	~40 000	~100
MRI scanners	~30 000	~450
PET scanners	~4000	22
PET centers	~600	7
Gamma knife	~300	5
Cyber Knife	~300	7
Brachytherapy devices	~2200	~150
Proton and ion therapy devices	90	6
TOTAL	~110 000	~2300

phy scanner models have been currently introduced: PET + CT, MRI + CT, etc. This area of global industry is developing rapidly.

Accelerators comprise a rather significant proportion of the high-technology medical equipment, 15%, and are also the most expensive devices. In spite of this, their number is increasing. Russia is behind the developed countries of the world in terms of the use of accelerators for medical purposes. Only 30% of all patients undergo radiation therapy in Russia; there is one accelerator per more than a million people. In Europe, there is one accelerator per 100 000 to 200 000 people, while in the United States there is one per 70 000 people. In order to reach the Central European level, Russia needs to have approximately 1000 electron accelerators and 30 proton radiation therapy accelerators (for example, in Germany 20 such centers are currently planned) and 4 ion-radiation therapy centers. At least 100 positron emission tomography (PET) centers are also required. The trend of the development of medical accelerators in the 21st century can be described as follows:

- Rapid growth of the number of linear accelerators with energies up to 25 MeV for radiation therapy.
- The growth of the number of radiation therapy centers based on proton beams and carbon nuclei.
- Development of accelerators for stereotactic surgery (a decrease in their size and weight and an increase of their beam power.
- Construction of circular accelerators for nuclear medicine purposes (isotope production for radiation therapy and PET and SPECT diagnostics).
- Development of compact synchrotron radiation devices for medical purposes.

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