LINEAR ACCELERATORS IN TELERADIOTHERAPY

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ABSTRACT

Radiotherapy is a therapeutic method of local treatment of tumors and other types of diseases using high-energy ionizing radiation. Teleradiotherapy is a type of radiation in which the radioactive source is located inside the teleradiotherapy device. The devices used in teleradiotherapy are a linear accelerator and an almost abandoned cobalt unit. Accelerators are devices that, using electric and magnetic fields, accelerate charged particles to high speeds, sometimes even to speeds that are slightly less than the speed of light. Diagnosis and treatment of cancer are complex processes that require the knowledge and expertise of oncologists first, and then other members of the oncology team. The accelerated development of technology is proportional to the development of linear accelerators. Experts continuously work on improving them with the aim of using ionizing radiation as precisely and efficiently as possible for therapeutic purposes. Radiotherapy is a treatment method that implies precision in the deepest sense of the word. Precision must be present with the oncology team when creating the radiation plan, the medical radiology engineer when handling the linear accelerator and positioning the patient, as well as with the device itself. Accordingly, it is necessary to constantly carry out quality control of the linear accelerators themselves. Constant education of the oncology team, i.e. experts who perform radiotherapy using a linear accelerator, is extremely important in order to ensure the best possible care.

Key words: Linear accelerator, radiotherapy, teleradiotherapy

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INTRODUCTION

Radiotherapy is a therapeutic method of local treatment of tumors and other types of diseases using high-energy ionizing radiation by delivering the absorbed dose to the target volume with as little radiation as possible to the surrounding healthy tissue (1). Depending on the type of cancer and the stage of the disease, four types of radiotherapy can be distinguished: curative, neoadjuvant, adjuvant and palliative (2). Radiotherapy can be administered as a single treatment modality or can be combined with other treatment modalities such as chemotherapy, immunotherapy, hormonal therapy or surgery (3). The main mechanism of radiotherapy is to produce irreversible damage to the DNA molecule in malignant cells, using ionizing radiation (4). Radiotherapy is not only used in the treatment of malignant diseases, but also in the treatment of benign diseases such as: keloid scars, trigeminal neuralgia, acoustic schwannoma, pterygium, heterotopic ossification and arteriovenous malformation in the brain (5). It can be divided into teleradiotherapy (external radiation) and brachyradiotherapy (radioactive source is located in or on the patient's body) (6). Teleradiotherapy is performed with a radiation source that is far from the human body. As a source of external radiation, linear accelerators (7) are most often used. In teleradiotherapy, planning with computerized tomography - CT (*Computed tomography)* plays an important role, which provides a three-dimensional simulation of the patient's position. This enables determination of the best approach to the target volume, i.e. the tumor and its surrounding, healthy tissue. Before radiation with a linear accelerator, it is important to position the patient correctly every time in order to avoid errors in radiation and thereby increase therapeutic efficiency (8). The aim of this review paper is to analyze and explain the principle of operation and the application of linear accelerators in teleradiotherapy based on current knowledge.

GENERATIONS OF LINEAR ACCELERATORS

The accelerators that were first created were linear accelerators (LINAC), and the creator of the concept was Gustav Ising (1924). Over the past 40 years, medical linear accelerators have gone through five different generations in the following features:

- Low energy photons (4–8 MV): flat beam; fixed smoothing filter; external wedges; symmetrical jaws; single portable ionization chambers; isocentric assembly.
- Photons of medium energy (10–15 MV) and electrons: bent beam; moving target and smoothing filter; scattering foils; double transmission ionization chamber; electronic cones.
- High-energy photons (18–25 MV) and electrons: dual energy photons and multiple electron energies; achromatic bending magnet; dual foil scattering or electronic pen beam scanning; motorized wedge; asymmetric or independent collimator jaws.
- High energy photons and electrons: computer controlled operation; dynamic wedge; electronic portal imaging device; multi-lamellar collimator - MLC (*Multi-Leaf Collimator*).
- High energy photons and electrons: intensity modulation of the photon beam with MLCs; full dynamic conformal dose delivery with intensity modulated beam produced with MLC (9).

Chronologically, the first type of accelerator is the Cockroft-Walton accelerator. It consists of an accelerator tube in which acceleration is performed, a high voltage source that is connected in a special way to the system of accelerator electrodes and the detector system. The essence of this accelerator is a voltage source and a system of electrodes that accelerate ions. The high voltage generator consists of diodes and capacitors connected in a special way that enables a gradual increase in the voltage on the electrodes in the accelerator tube.

Another type of accelerator is the Van de Graaff accelerator, which is considered an electrostatic accelerator. The operation of this accelerator is based on the definition of the potential of a conductor, according to which the potential is the work that must be done to transfer a unit charge from the conductor to infinity. In this accelerator, the charge is transferred from the source to the moving insulating tape by means of a spike. Through this strip, the charge is transferred to the collecting electrode, which collects it and leads it to the hollow electrode. In this way, a very large potential difference can be achieved, which is later used to accelerate the particles (10).

WORK PRINCIPLES

Linear accelerators use only an electric field to accelerate particles. They consist of a vacuum tube and hollow cylindrical electrodes, through which it passes. The even electrodes are connected to one and the odd electrodes to the other pole of the high-frequency alternating voltage generator. There is a small space between the electrodes. At its beginning is the source of the particles, and at the end is the target. Today's linear accelerators are constructed in a slightly different way (11). In the vacuum tube, which can be several kilometers long, there are cylindrical electrodes that are connected to the poles of an alternating source of high-frequency voltage. At the beginning of the tube there is a source of particles to be accelerated, while the target is placed at the other end of the tube. As they move between the electrodes, an electric field acts on them and accelerates them. Let us assume that a positive ion is accelerated in such an accelerator. At the beginning, the first electrode is negative and attracts the ion, which starts to accelerate. When the ion enters the electrode cavity, the acceleration stops and it continues to move in a straight line, by inertia (12).

At the moment when it leaves the first electrode, the polarization of the electrodes changes and the first electrode becomes positive and the second negative. The process is repeated, the ion accelerates to the second electrode, enters it, moves by inertia and when leaving the electrode, the polarization changes again. The particle continues to accelerate towards the third electrode and the process continues. The frequency of the voltage is adjusted by changing the polarization and matching it with the exit of the particle from the electrodes. The length of the electrodes and the distance between adjacent electrodes increases uniformly. The speed and energy that the particle will have upon exiting the accelerator depends mostly on the length of the accelerator. A longer length of the accelerator implies a higher energy of the particles. In a linear accelerator, particles can be accelerated to relativistic speeds,so the relativistic effects of mass increase, length contraction and time dilation must be taken into account during their construction (13).

The goal of these devices is to achieve high accelerations of charged particles. They work on the principle of emission of charged particles at one end and gradual acceleration of these particles in a straight vacuum tube until they reach kinetic energy (14).

BASIC PARTS

Linear accelerators consist of multiple separate technological components that function as a single unit to accelerate electrons to high energies with high-frequency waves, striking a target and producing a photon beam, which is then aligned, shaped, and measured prior to clinical use (15). The main components of a linear accelerator are: accelerator tube, electron gun, accelerator waveguide, high-frequency wave source (klystron or magnetron), electron beam rotation magnet, accelerator head, therapy table, control panel, monitoring system (16) (Figure 1).

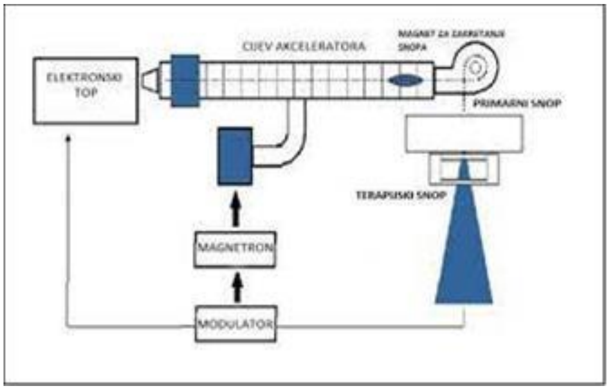

Figure 1. Schematic representation of the main components of the linear accelerator (17)

An accelerator tube can be thought of as a series of resonant cavities. It serves to accelerate the injected electrons from the electron gun to megavoltage kinetic energies using radiofrequency electromagnetic waves (18). The electron gun produces electrons and injects them into the waveguide. Triode guns (anode, cathode and grid) are most commonly used (19). A magnetron is a source of high-energy radio frequency field that accelerates electrons (20). After accelerating through the waveguide, the electrons reach the accelerator head, which houses the electron beam rotation magnet. It serves for energy filtering of accelerated electrons, which it then directs towards the radiation beam modifiers (21).

The accelerator head models the monoenergetic electron beam for therapeutic purposes and directs it towards the isocenter. It consists of primary and adjustable collimators, x-ray production targets, radiation beam straightening filters, ionization chamber, MLCs, light field indicators and wedge filters.

The therapy table consists of a base and a movable flat plate that has movements in three axes: left-right (x-axis), up-down (y-axis) and rotation around a vertical axis (z-axis) that passes through the isocenter of the apparatus. The movement of the therapeutic table enables the execution of several types of radiation techniques, and can also be used to adjust the patient's position in order to irradiate tumors as best as possible while protecting healthy tissue to the maximum extent possible. At the same time, the head of the device must not come into contact with the table or the base of the table, nor with the patient's body. The board of the therapy table is made of a material that minimally attenuates radiation (carbon fibers), which enables the production of good quality images during the verification of the accuracy of the patient's positioning.

The information system located in the accelerator room in front of the therapy bunker monitors all parameters of the accelerator's functioning, parameters of the plan for the application of therapy: angle of the collimator gantry, field size, positioning of the table, position of the lamellae of the multi-lamellar collimator, static or dynamic mode of operation, type and quality of radiation, applied dose, radiation beam intensity, etc. The command room is equipped with audiovisual monitoring of the patient in the therapy room (bunker).

The installation of such a medical linear accelerator requires special design of the premises in accordance with local and international recommendations for protection against ionizing radiation. The aforementioned implies placing the device in a room (bunker) with concrete walls of a certain thickness, in order to attenuate the primary beam of radiation and the secondary scattering of photons as much as possible (22).

METHODS OF APPLICATION OF TELERADIOTHERAPY

If it is planned to irradiate tumors located deep in the body, beams of nominal acceleration potentials above 10 MV are used. Such high-energy photons can interact with atomic nuclei, which will lead to the creation of an unwanted neutron flux in photonuclear reactions (23). The probability of neutron formation depends on the energy of the photon and the atomic number of the material on which the photon hits. With an increase in the atomic number, the probability of the occurrence of a neutron flux increases (24, 25). Such an isotronic neutron flow is dominated by neutrons with energies between 700 keV and 1 MeV (26). The described effect is extremely important for the radiological safety of staff and patients, especially in cases of application of modern radiotherapy techniques such as intensity-modulated radiotherapy - IMRT (*Intensity-Modulated Radiation Therapy*). Modern radiotherapy techniques use a large number of monitor units that represent the output measure of the linear accelerator. In advanced radiotherapy techniques, a large number of small beams are used for the most precise application of ionizing radiation for therapeutic purposes (27). In modern radiotherapy, such as IMRT in its various forms (step and shoot, sliding windows, volumetric modulated radiotherapy - VMAT (*Volumetric Modulated Arc Therapy*), tomotherapy), it is common to deliver 5 to 5 Gy to the target volume instead of 2 Gy. It is important to point out that each small photon beam is accompanied by neutron contamination approximately equal to the neutron contamination of the large beam. Since IMRT uses a series of small beams instead of one large beam for irradiation, the neutron contamination is increased several times (17, 28).

In radiology and radiotherapy, modern devices, including linear accelerators, apply artificial intelligence methods (machine and deep learning), although numerous studies indicate that there are numerous ethical problems in relation to its application (29). The development of computer software and technology has made it possible to image the human body in multiple dimensions (3D, 4D, 5D, 6D), which are used in various branches of medicine, such as interventional radiology in the display of intracranial aneurysms (30, 31), and radiotherapy in showing the position of anatomical structures in order to achieve the accuracy of the daily placement of the patient on the patient's table before the start of the radiation procedure with a linear accelerator (32). For this purpose, techniques for checking the positioning and geometry of radiotherapy have been developed, such as image-guided radiotherapy - IGRT (*Image Guided Radiotherapy*). The most commonly used IGRT equipment is EPID (*Electronic Portal Imaging Device*) and CBCT (*Cone Beam Computed Tomography*) (16).

Another very important modern teleradiotherapy method is robotic surgery (*Cyberknife*). It is a fully robotic non-invasive radiosurgical system that treats malignant as well as benign tumors anywhere in the body. The system includes a 6 MV x-ray linear accelerator and a collimator system with field sizes of 5 mm to 60 mm radius mounted inside the robotic arm. The system is fully automated and allows irradiation of diseased tissue from any position in 6 degrees of freedom, which enables maximum compliance with the radiotherapy principle of irradiating diseased tissue and protecting healthy tissue (16, 33).

Along with the application of photon therapy, there is a possibility of applying a therapeutic beam of neutrons, protons or some other heavy ions. This form of teleradiotherapy is called particle therapy. The most common clinical application of this method is proton therapy. With this type of therapy, a very high dose can be delivered to tumors at a certain depth, with maximum protection of the tissue located near the tumor on its painful side (34).

ROLES OF THE RADIOTHERAPY TEAM

Cancer diagnosis and treatment are complex processes that require the knowledge and expertise of medical staff. The purpose of the multidisciplinary team is to combine the professional knowledge, skills and experiences of each individual member of the team in order to ensure the best possible care. The radiotherapy team consists of: a clinical oncologist, a radiation physicist and a medical radiology engineer. Three-dimensional planning begins with a CT scan of the part of the body that is planned for irradiation. The medical radiology engineer contours the organs at risk, and the clinical oncologist outlines the area to be irradiated. The radiation physicist then creates a radiation plan that is usually further evaluated and improved in cooperation with the doctor.What is particularly important in 3D conformal radiotherapy and teleradiotherapy with variable radiation intensity is a strict, continuous, daily check of the quality of radiation, all components of the device and radiation beams (16).

When applying teleradiotherapy with a linear accelerator, it is extremely important for the medical radiology engineer to position the patient in the appropriate position that has been planned, and to ensure that the patient remains calm during the radiotherapy treatment with appropriate fixation devices. In order to achieve the above, communication between the medical radiology engineer and the patient is extremely important at the very first setting for the start of the radiotherapy treatment. This implies clear and comprehensible communication by conveying basic information about the radiotherapy treatment process to the patient. Most patients come to the start of radiation in a state of stress for various reasons. These reasons can be: facing the unknown, fear of a closed space (bunker), fear for one's own health and possible side effects caused by radiotherapy treatment (burns, difficulty swallowing, etc.). Explanation of the radiotherapy treatment procedure (positioning of the patient, gantry positions, usual duration and course of treatment, etc.) by the clinical oncologist and the medical radiology engineer is extremely important in order to obtain cooperation from the patient during the radiotherapy session. After the patient has been placed in the appropriate position for radiation using appropriate equipment for fixing body position and image checks (EPID, CBCT), teleradiotherapy is performed using a linear accelerator. It is extremely important to have a proper psychological approach to the patient, which includes and implies support and understanding by the medical radiology engineer for all the patient's questions before and after the radiotherapy session.Numerous studies indicate that the correct psychological approach of healthcare professionals significantly reduces the anxiety and fear of patients who have been prescribed an examination with magnetic resonance (35) or CT (36, 37), and this approach has also been noted to increase the level of resilience of patients treated with radiotherapy and oncology patients in general (38-40).

CONCLUSION

The use of linear accelerators in teleradiotherapy has progressed throughout history and they play an important role in cancer treatment. The development of technology and computer programs led to the modernization of linear accelerators, which resulted in an improvement in their precision, which reduced the irradiation of adjacent healthy tissues during treatment. The technical characteristics of linear accelerators enabled the generation of more energy of supervoltage radiation for beams of photons (X-rays) and electrons, and thus the effective application of teleradiotherapy for almost all tumor localizations.

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LINEARNI AKCELERATORI U TELERADIOTERAPIJI

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SAŽETAK

Radioterapija je terapijska metoda lokalnog liječenja tumora i drugih vrsta bolesti uporabom visokoenergijskog ionizirajućeg zračenja. Teleradioterapija je vrsta zračenja u kojoj se radioaktivni izvor nalazi unutar teleradioterapijskog uređaja. Uređaji koji se koriste u teleradioterapiji su linearni akcelerator i gotovo napuštena kobaltna jedinica. Akceleratori su uređaji koji, pomoću električnog i magnetskog polja, ubrzavaju nabijene čestice do velikih brzina, nekada čak i do brzina koje su nešto manje od brzine svjetlosti. Dijagnoza i liječenje raka složeni su procesi koji zahtijevaju znanje i stručnost ponajprije specijalista onkologa, a potom i ostalih članova onkološkog tima. Ubrzani razvoj tehnologije proporcionalan je s razvojem linearnih akceleratora. Stručnjaci neprekidno rade na njihovom usavršavanju s ciljem što preciznije i učinkovitije primjene ionizirajućeg zračenja u terapijske svrhe. Radioterapija je metoda liječenja koja podrazumijeva preciznost u najdubljem smislu te riječi. Preciznost mora biti prisutna kod onkološkog tima pri izradi plana zračenja, inženjera medicinske radiologije pri rukovanju s linearnim akceleratorom i namještanju bolesnika, kao i kod samog uređaja. U skladu s time, potrebno je neprestano provođenje kontrole kvalitete samih linearnih akceleratora. Iznimno je važna konstantna edukacija onkološkog tima, odnosno stručnjaka koji provode radioterapiju primjenom linearnog akceleratora kako bi se time osigurala najbolja moguća skrb.

Ključne riječi: Linearni akcelerator, radioterapija, teleradioterapija

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