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Radiation therapy systems using linear accelerator, importance of its components and their development

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Abstract

Given the importance of devices used in the field of medicine in terms of diagnosis and treatment, and the great importance of this topic in accelerating early diagnosis and saving the lives of the largest possible number of people, we decided to study one of these devices to better define its components and review some of the difficulties.

Many linear accelerators for hybrid magnetic resonance imaging have been developed as a result of the need to profit from directed images of tissues and various body sections during radiation therapy (linear accelerators). There are now a number of linear accelerators for magnetic resonance imaging that cover both low and high magnetic field strengths as well as two directions of the beam field; these systems have the potential to be beneficial. This technology has only recently been used in clinical trials. However, its continued usage as a routine radiation therapy procedure is certain. The majority of the key elements and difficulties encountered in the creation of such technology as well as its present state are outlined in this review article.

Keywords: Linac1; Medical Applications; Construction; Clinical Linear

1. Introduction

In 1952, two innately talented physicists, Namely Henry Kaplan and Ed Ginzton began working on the concept of a linear accelerator. In 1997, A further step was taken to advance the use of linear accelerators by combining with intensity modulation radiation therapy [1]. The result was that many thin beams of radiation could be achieved from any desired angle. Linear accelerator is also named as a linear particle accelerator, it works to speed up that accelerates charged particles, such as electrons, protons, or ions, to high speeds in a straight line using a series of electric fields. Unlike circular accelerators, which use magnetic fields to curve the particles' paths, a linac keeps the particles moving in a straight path [2]. In radiation therapy, this linear particle acceleration is used for medicinal purposes because it produces the X-rays and electrons that have high energy. Hence the linear particle accelerator is used for many therapeutic applications. Also, they are useful in particle physics because they can produce the highest kinetic energy that can be achieved directly by the linear accelerator [3]. Furthermore, a linear accelerator is suitable for electrons and protons in particle physics to get high kinetic energy. The linear accelerator sometimes called linac is a kind of particle accelerator that has the capability to increase the charged subatomic particles or we can say ions where charged particles are subjected to a series of electric potentials that oscillate along with the linear beamline. Well, such a method of charged particle acceleration was first experimented by Leo Szilard[4, 5]. State-of-the-art radiotherapy has the ability

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to deliver highly conformal doses of radiation that can target tumours and avoid normal tissues with high precision; however, the limitations of conventional on-line imaging hinder this technology from achieving its true potential. Current imaging is often limited to a pre-treatment planning scan (usually computed tomography [CT]) or set-up verification at the time of treatment with on-board X-ray [6, 7]. As a consequence, there is little or no adaption of the radiation dose to known changes in anatomy or physiological variations, including that of the tumour target itself, that occur during the course of treatment. The inherent advantages of MRI have inevitably led to the pursuit of hybrid radiotherapy systems that incorporate this imaging capability in the treatment room to realise the benefits of real time guidance and adaption [8, 9]. This article reviews the challenges associated with a linear accelerator in a single processing device, summarizes the main design differences and current state of existing systems, and reviews the most important components of the device that may be developed in the future.

2. Types of Linear Accelerator

2.1. Linear accelerator 1 (Linac1)

Was designed in the early 1950s to serve as an injector for the Proton Synchrotron (PS). It accelerated its first beam in 1958 and was fully commissioned in 1959 when one turn of 50 MeV protons went round the PS. Linac1 was the only supplier of protons to the CERN synchrotrons until Linac2 took over in 1978. Linac1 accelerated light ions – such as deuterons and alpha particles, as well as oxygen and sulphur ions – for 33 years until its retirement in 1992. Linac3 took over ion production in 1994 [10].

2.2. Linear accelerator 2 (Linac2)

Was the starting point for the protons used in experiments at CERN for 40 years. Linear accelerators use radiofrequency cavities to charge cylindrical conductors. The protons pass through the conductors, which are alternately charged positive or negative. The conductors behind them push the particles and the conductors ahead of them pull, causing the particles to accelerate. Small quadrupole magnets ensure that the protons remain in a tight beam. The proton source was a bottle of hydrogen gas at one end of Linac2 [11, 12]. The hydrogen was passed through an electric field to strip off its electrons, leaving only protons to enter the accelerator. By the time they reached the other end, the protons had reached the energy of 50 MeV and gained 5% in mass. They then entered the Proton Synchrotron Booster, the next step in CERN's accelerator chain, which took them to a higher energy. The proton beams were pulsed from the hydrogen bottle for up to 100 microseconds per pulse[13]. The pulses were repeated again and again until enough protons were produced. Linac2 started up in 1978, when it replaced Linac1. It was originally built to allow higher intensity beams for the accelerators that follow it in CERN's accelerator complex. Linac2 was switched off for the last time on 12 November 2018. It was replaced by Linac4, which was inaugurated in 2017 and connected to the PS Booster in 2020 during CERN's Long Shutdown 2 [11].

2.3. Linear accelerator 3 (Linac3)

Is the starting point for the ions used in experiments at CERN. It provides lead ions for the Large Hadron Collider (LHC) and for fixed-target experiments. Researchers have also requested the delivery of other ions, such as argon and xenon in the past and oxygen in the future [14, 15]. The linear accelerators at CERN have swapped and changed roles over the years. After Linac2 was built, Linac1 was used to deliver ions for experiments at the Super Proton Synchrotron (SPS). There was soon pressure to provide heavier ions to study quark–gluon plasma, so the dedicated Linac3 was built. It started up in 1994, providing ions to the Proton Synchrotron Booster. It now injects lead ions into the Low Energy Ion Ring, which prepares them for injection into the LHC. The ions are produced in Linac3's source, where electrons are removed from the atoms inside a plasma. The source uses about 500 milligrams of lead per two weeks of operation. Linear accelerators use the electric fields that are present in radio waves to accelerate the charged particles. When the waves are confined into conducting cavities, they can build up to high field strengths. The cavities can also contain magnets that ensure the particles remain focused over the tens of metres needed for acceleration [16]. Eventually, before entering the SPS, all of the electrons are removed and the lead ions are transformed into bare nuclei, which is more efficient to accelerate than partially ionised ions.

2.4. Linear accelerator 4 (Linac4)

Is designed to boost negative hydrogen ions to high energies. It became the source of proton beams for the Large Hadron Collider (LHC) in 2020. Linac4 accelerates negative hydrogen ions (H^-, consisting of a hydrogen atom with an additional electron) to 160 MeV to prepare them to enter the Proton Synchrotron Booster, which is part of the LHC injection chain. Negative hydrogen ions are pulsed through the accelerator for 400 microseconds at a time. Linear accelerators use radiofrequency cavities to charge cylindrical conductors. The ions pass through the conductors, which are alternately charged positive or negative [17]. The conductors behind them push particles and the conductors ahead of them pull, causing the particles to accelerate. Quadrupole magnets ensure the hydrogen ions remain in a tight beam. The machine comprises a H- ion source and four types of accelerating structure: the particles are accelerated in several stages, first to 3 MeV by a radio-frequency quadrupole (RFQ), then to 50 MeV by drift tube linacs (DTLs), then to 100 MeV by coupled-cavity drift tube linacs (CCDTLs), and finally to 160 MeV by Pi-mode structures (PIMS) [12, 18]. Linac4's hardware also includes an equipment called a chopper line. Its role is to cut up the beam at the same frequency as that of the PS Booster. The ions are stripped of their two electrons during injection from Linac4 into the Proton Synchrotron Booster to leave only protons. This allows more particles to accumulate in the synchrotron, simplifies injection, reduces beam loss at injection and gives a more brilliant beam. Linac4 is 86 metres long and located 12 metres below ground. Beams began to be produced in 2013 and the milestone energy of 160 MeV was reached in 2016, after the commissioning of all the accelerating structures. During the long shutdown 2019–20, it replaced Linac2, which had previously accelerated protons to 50 MeV. The Linac4 is a key element in the project to increase the luminosity of the LHC during the next decade [19].

3. Medical Applications of Linear Accelerators

3.1. Clinical Linear Accelerators (Linacs)

Clinical linear accelerators are at the forefront of medical applications, particularly in the treatment of cancer. They are used to deliver precise and controlled doses of radiation to target cancerous cells while minimizing damage to surrounding healthy tissue. The medical linear accelerator (linac) is the primary workhorse for radiation oncology [20]. While the underlying principle of a linac is remarkably simple, implementation of that principle to produce a consistent stable beam requires a precise and sophisticated design. Understanding the basics of that design is essential to ensure patient safety and machine up-time. In the basic accelerator design, a heated filament boils off a cloud of electrons. These electrons are then accelerated by an electric field applied between the filament (cathode) and a thin metal window (anode) [21]. Clinical linacs operating in the MeV region require an accelerating waveguide to achieve the required acceleration over a reasonable distance. The electrons then hit a target (where they produce Bremsstrahlung X-rays) or a scattering foil (to spatially distribute the electron beam). Finally, the beam may be further shaped in the treatment head see Figure (1) and Figure (2).

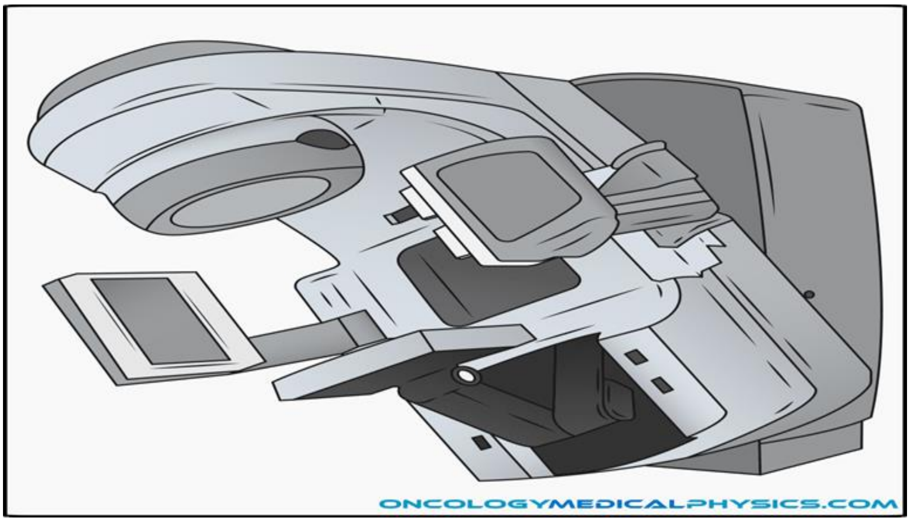

Figure 1 The linear generator [22]

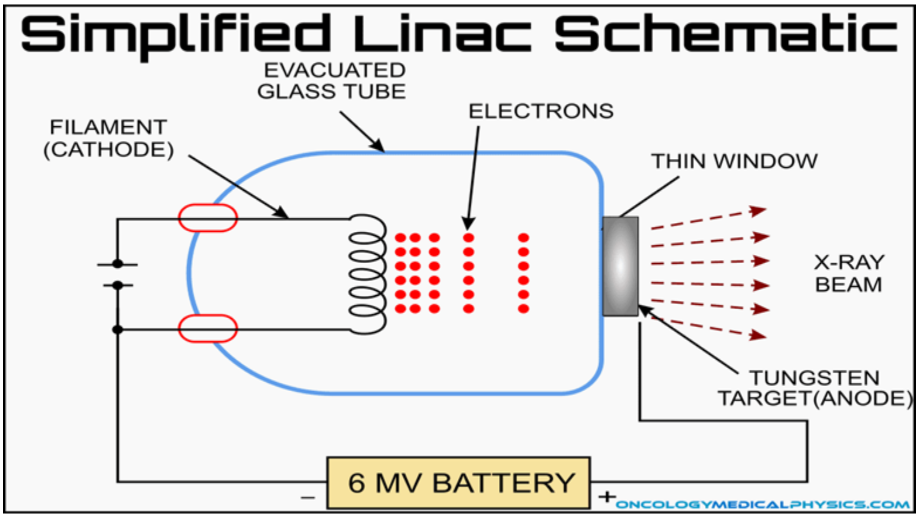

Figure 2 The linear generator circuit [22]

3.1.1. Components of a Clinical Linear Accelerator

External Components

- **Couch (Patient Positioning System):** The couch supports and positions the patient during treatment. Modern couches facilitate precise patient positioning by moving along the x, y, and z axis. Advanced couches may also include the ability to adjust patient roll, pitch, and yaw.
- **Electronic Portal Imaging Device (EPID):** The electronic portal imaging device forms an image using the MV treatment beam. EPIDs are valuable tools for monitoring patient setup and quality assurance.
- **Gantry:** The linac is mounted on a rotating gantry which treatment from multiple angles.
- **kV Imaging System:** The kilovoltage imaging system consists of a kV X-ray generator and an electronic imaging device. The lower energy of this imaging system improves contrast, especially when used to generate a cone-eam CT.
- **Stand**: The stand connects the gantry to the treatment room floor and contains electronics and other systems required for linac operation [23], As shown in the Figure (3).

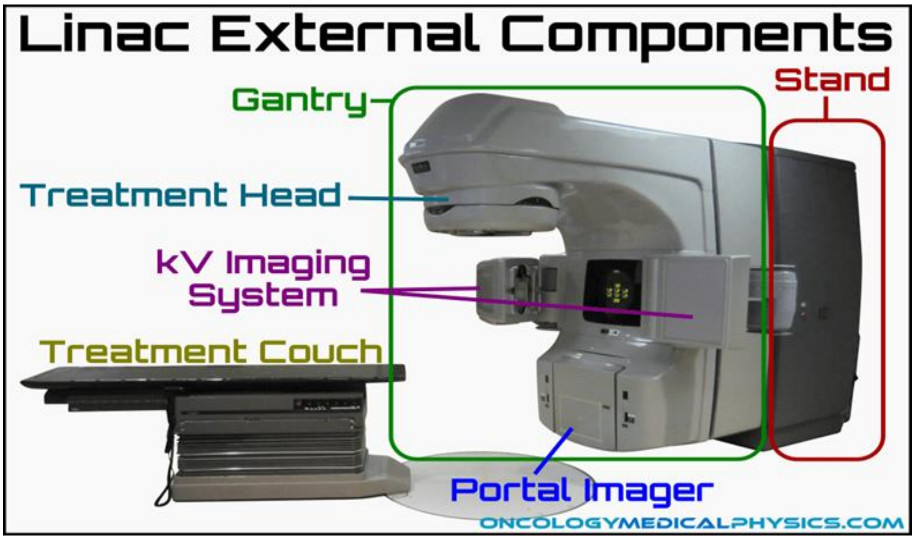

Figure 3 External components of linear generator [22]

Internal Components

- **Accelerating Waveguide**: A series of microwave resonance cavities used to accelerate the electron beam to high energies.

- **Bending Magnet**: The bending magnet is a magnetic lens used to focus and position the beam to intercept the target (for photon treatments) or scattering foil (for electron treatments). The angle of bending varies by manufacturer but may be either 90°, 112.5°, or 270°. Magnetic focus attempts to be achromatic (does not separate by energy at point of focus).
- **Circulator**: A device in the waveguide that is used to prevent microwave energy from reflecting backwards to the Klystron/Magnetron.
- **Cooling System**: Production of a clinical treatment beam is an energy inefficient process due to losses in microwave generation and acceleration. A water or air cooling system is required to maintain a stable operation temperature necessary for consistent beam energy production.
- **Electron Gun**: An electron gun produces the electrons which are accelerated in the accelerating waveguide. Electron guns consist of a heated filament (~800°C – 1100°C) which "boils off" a cloud of electrons. These electrons are immediately accelerated by a low E field (~40kV).2 Electron guns may be either of the diode or triode types. Diode electron guns consist simply of the heated cathode and an anode which set the accelerating voltage. Triode electron guns add a control grid between the cathode and anode which serves to recollect a portion of the liberated electrons. Thus, the triode design allows for variable beam current by preventing a variable fraction of electrons from reaching the accelerator.
- **Energy Selector**: An energy selector may be placed within the bending magnet array to narrow the allowed electron energy range incident on the target/scattering foil. Typical energy band pass range in of the order of 6% (97%- 103% of desired energy) [23], see Figure (4).

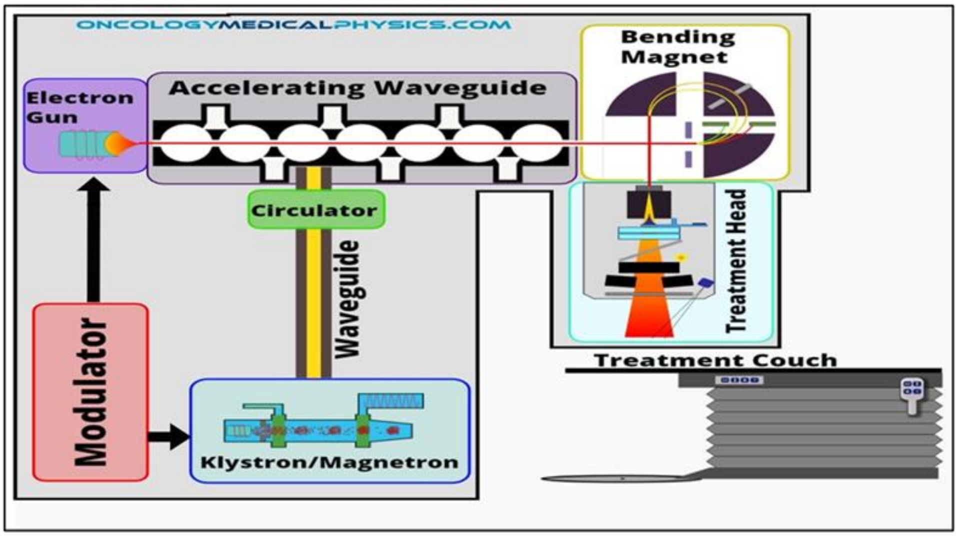

Figure 4 Internal components of linear generator[22]

- **Klystron/Magnetron:** Klystrons and Magnetrons produce the microwave used to power the accelerating waveguide.
- **Treatment Head:** The treatment head contains components required for beam production and shaping including targets, scattering foils, beam shaping collimators and the optical distance indicator.
- **Waveguide:** The waveguide is a channel directing the microwave power from the Klystron/Magnetron to the Accelerating Waveguide. The waveguide is filled with an insulating gas (typically Sulfur Hexaflouride, SF6) to prevent electrical arcing. Microwave transparent ceramic barriers prevent the SF6 from leaking into the vacuum spaces filling the Klystron/Magnetron and the Accelerating Waveguide [23].

4. Linear Accelerator Construction

A linear accelerator is a machine that can accelerate electrons close to the speed of light with an electromagnetic field. Electrons or protons with more than 18 MeV are bombarding to the target, and higher kinetic energy is produced. In a tungsten target, the particles produce the bremsstrahlung radiation like in the conventional tube of X-ray. Well, the design of the LINAC machine is different from the x-ray tube because of higher energy. Linear accelerator works using microwave technology to initiate the electron response. The electrons collide with metal iodes to cause a chain reaction that results in the formation of high energy X-rays. Further, the source of ion provides an electron bunch that accelerates to either drift tube of positive and negative potential. The RF source shifts the polarity when electrons enter the tube [4]. Moreover, the first tube negatively charges while the second drift tube gets a positive charge. After that, the electron comes outside due to inertia. At this instance, the electrons move with the first drift tube and attract by another in the same direction. The accelerated electrons have high velocity and travel at long distances. Hence, the drift tube should be long when the electron comes close to the target due to high velocity. Further, the main reason for the development of the linear accelerator is to deliver high energy rays at a target-specific location. Thus, the high velocity electron emerging from the drift tube an be easily directed towards the specific source or tumour using the gantry of the drift tube, see Figure (5) [24].

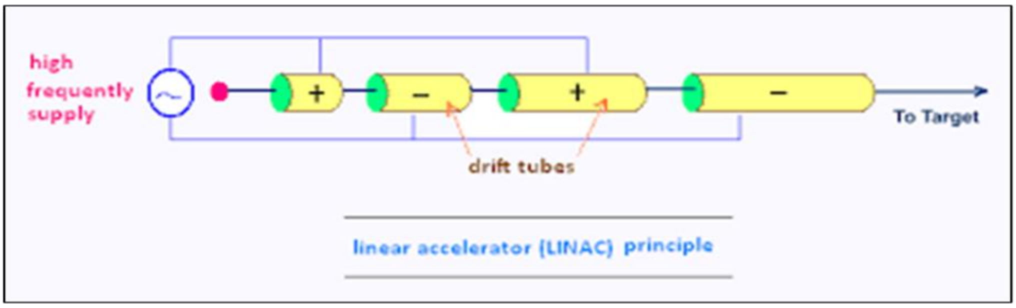

Figure 5 The linear accelerator construction process [4].

5. Linear Accelerator Working Principle

In a linear particle accelerator, the drift tube has positive potential while electrons have a negative potential. A bunch of electrons are accelerated to the drift tube because of this potential difference. RF source changes its polarity as soon as the particles enter the first drift tube. Hence, the first drift tube becomes negatively charged, but the second drift tube is positively charged. The inertia of electrons makes them come out from the drift tube. So, electrons are pushed into the first tube, and at the same time, they are attracted to the second tube in the same direction. Electrons' velocity turns bigger because of their acceleration. So, this is the reason why drift tubes are longer. Speed of electrons increases as soon as electrons come closer to the target. LINAC is long because of longer drift tubes, and the number of tubes is also higher [25].

6. Linear Accelerator Used for

LINAC or a linear particle accelerator device is used in cancer treatment to provide radiation of an external beam to cancer patients. In radiation therapy, radiation oncologists team up with medical physicists and dosimetrist to prepare the personalized radiation treatment for different cancer patients for effective results. Radiation therapist also includes the delivery method of radiation, time of the medication and dosage. Well, cancer in the organ of the body can be treated with a linear accelerator. Different ways are used for the different body parts depending on the cancer type and organ of cancer tumor [26].

7. Conclusions

Through this study, it is possible to conclude that this device and similar devices are still developing and there are many advantages to their development and study, which helps in solving many medical problems and contributes to early diagnosis, in addition to the possibility of integrating many devices, but it certainly requires a period of time and a comprehensive and branched study.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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