

# LINAC-3

## ADVANCES IN MEDICAL LINEAR ACCELERATOR TECHNOLOGY

### Background:-

Radiation Oncology is the branch of medicine that uses various types of radiation to treat and control cancer. The foundation of radiation oncology is based on the interaction between matter and energy. Beginning with the discovery of x-rays by Wilhelm Roentgen in 1895. In 1896 Henri Becquerel discovered radioactivity and in 1898 separation of radium by Marie and Pierre Curie, it known that certain materials also emit radiation.

When radiation does interact with medium, it produces ionization. When cell get enough ionization, it dies, thus interaction between radiation and matter be well understood and this translates the science of radiation physics into clinical treatment of cancer.

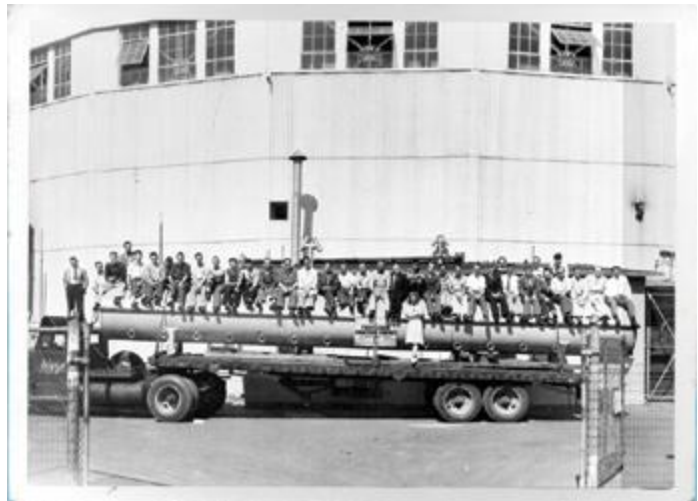
The transmission of radiation in the clinical environment depends on very sophisticated technology, one of such device called Linac. These create the x –rays treatment beam, these beam consist of much higher energy than a standard x –ray machine and must be meticulously maintained in order to guarantee patients safety.

In 1900's treatment for cancer patients started with the KV X-rays machines which are operated at 150 – 350 KV, having low depth penetration and excessive dose to the skin. During 1930 – 40's several types of equipments were introduced including 1 & 2 MeV Van De Graff accelerator and 18 – 45 MeV Betatrons.

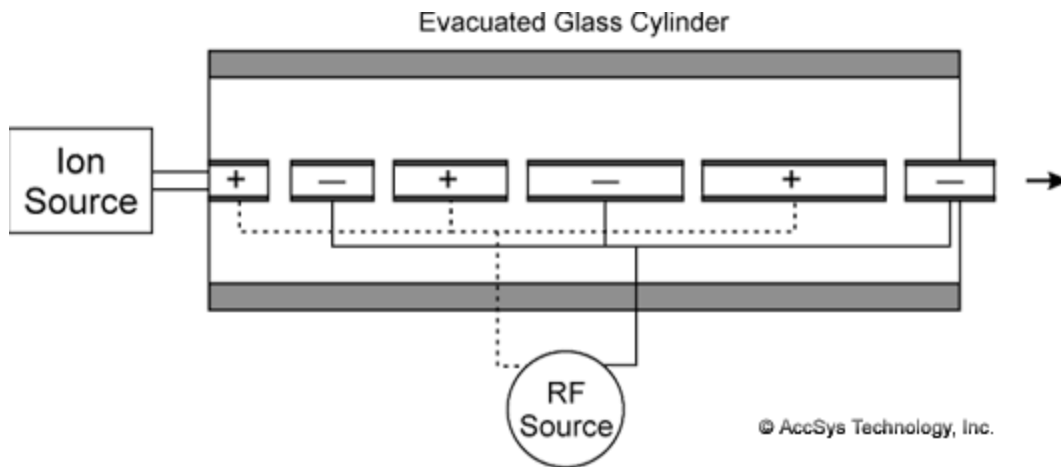
The history of particle accelerators for ion beams is often described in association with the development of cyclotrons, primarily due to their wide-spread use in the medical field. However, what is often not acknowledged is that ion linear accelerators ("linacs") were developed in parallel with the cyclotron and other circular accelerators. While Lawrence and Livingston designed the first small cyclotron in 1930, R. Wideröe had already published a paper in 1928 on his results from an rf powered linear accelerator for ions



Karl Brown at the klystron controls for the Mark II accelerator at Stanford University



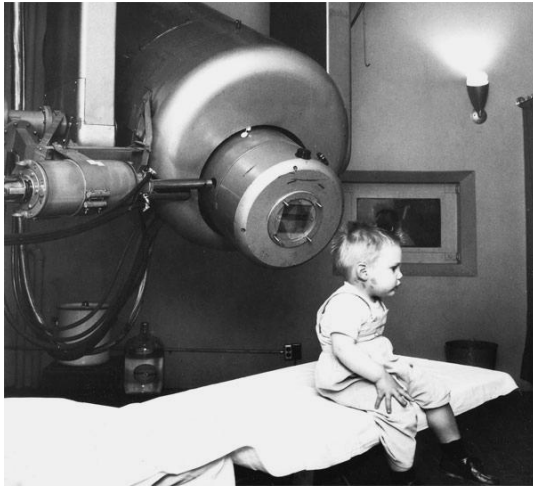
**Berkeley accelerator:** Berkeley Laboratory group seated top of the vacuum tank of their 40-foot 32-MeV proton linear accelerator on the back of a flatbed truck, probably in 1947



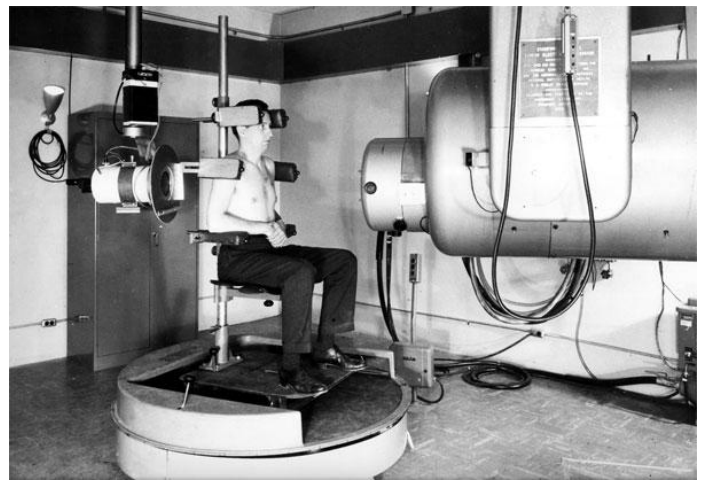
In mid 1950's Linear Accelerators now popularly known as LINAC's are evolved with the earlier advent of microwave power tube such as Klystron developed during the Second World War. These klystrons are a vital source of microwave power for radars during the war. These linacs are in the range of 4 – 8 MeV.

In 1952 , microwave electron based linear accelerators which have made possible modern radiotherapy treatment of tumors with mega voltage x rays. The first one was at HAMMERSMITH HOSPITAL, operational with 8MV built by metropolitan Vickers, the first medical linear accelerator (Linac) treated its first patient, in London, in 1953, so the use of these machines in clinical practice has been almost co-existent with the lifetime of Physics in Medicine and Biology (1)

In 1956 Henry Kaplan utilized the linear accelerator used by the physicists of Stanford, a fighting tool against cancer. 2 year old boy with a retinoblastoma is (the first patient treated with his linear accelerator at Stanford, in western hemisphere) and he survived with the vision intact for the rest of the life, since then the medical Linac have been in vogue. Destroying the tumour while sparing the eye would have been impossible with the earlier less focused radiation sources. This linacs has other medical uses too, its radiation can quell the rejection of an organ transplant, suppress the immune system of patients undergoing blood and marrow transplantation and correct certain neurological and cardiovascular disorders.



A 2-year-old boy the first patient to receive radiation therapy from the medical linear accelerator at Stanford



Original linear accelerator in operation



Henry Kaplan (left) and head of radiological physics Mitchell Weissbluth, at the Stanford accelerator



Early linear accelerator: Vickers

The primary advantage of Linac over Co 60 has been their higher dose rate and more uniform dose. Thus patient shorter treatment and length of time it takes.

The earlier Linacs are limited by their inability to rotate totally around the patient. In 1960 the first 360 degree isocentric Linac was developed at Varian and transported to UCLA.

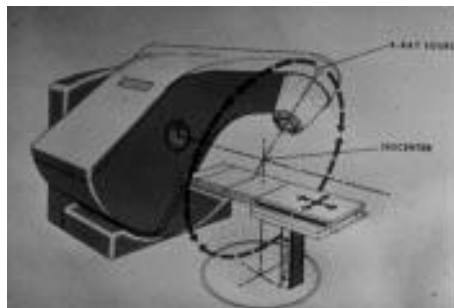
In 1968 the adoption of standing wave accelerator technology became possible to reduce the complexity of accelerator by positioning the accelerator guide collinear with the direction of treatment to eliminate the bending magnet and all the sensitive adjustments associated with it. This reduces the cost of the linear accelerators.

In 1972, Fessender explored how to create linear accelerator that delivered their punch to tumour cells through two types of radiation. Working with the Varian Medical Systems Inc of Palo Alto, his group helped the first machine that combined both x-rays and electron treatment. Varian went on to develop precursor of all modern linear accelerators having 2 or 3 energies of x-rays and up to seven energies of electron giving physicians versatility for crafting the most effective attack.

Additional enabling technologies have occurred to broaden the sophisticated and capability of linacs. These include the energy switch which has made possible high dose rate of photon energies, achromatic bending magnet, which has simplified and stabilized high energy accelerators to the point that they could also be utilized readily. The multileaf collimator which has allowed precise shaping of the photon beams to match the irregular shape of most of the tumors. Dynamic motion of MLC during the treatment will allow shaping of the photon beam in 3D to match the shape and density of the tumors. This leads to the ability of deliver a high dose to the tumour and lower doses and less complication to the healthy tissues



Standing wave accelerator



Concept of 360° isocentric rotation



First commercial 360° isocentric accelerator : the Varian Clinac 6 (ca 1960)

One of the biggest challenges clinicians has aligning the radiation beam and the tumour, The heart beating, the lungs inflating and deflating with by breathing , the blood flow through the vein, subtle movement of skeleton and muscles all this motion adds up to a moving target for a beam of radiation. A Linac was developed at Stanford that can continuously tracking the position of tumour in real time during the treatment. Tracking allows radiation oncologist to deliver a large doses of radiation precisely to the tumour cells, the unit called cyber knife, first used for a patient in 1994.

An added advantage of linear accelerator is that it gives electron beams of various energies. These electron beams offer the advantage of rapid and sharp fall of depth dose, variable depth penetration, less bone absorption than x-ray beams and decreased radiation build up., and the superficial tumors are best treated with the electron beams.

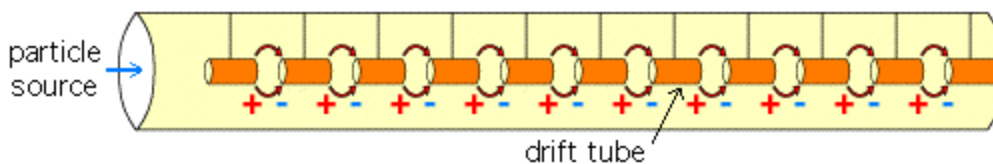
Since the advent of linear accelerator for cancer treatment, the five year survival rate have been improved from 39% to 54%, much of this improvement can be directly attributed to the capabilities provided by linear accelerators.

Basic of linear accelerator:-

Linear Accelerators are the linear devices used to accelerate atomic and subatomic particles to high velocities. Accelerating employ electric and magnetic forces to accurate focus and steer the particles. The electric and magnetic field exerts forces only in charged particles such as ions , protons or electrons. They do not exert forces on neutral particles. The unit of energy for these particle is electron volt, which is the energy imparted to an electron or proton when it is accelerated through a potential difference of one volt. For most applications involving particle energies of one MeV or higher, radiofrequency (RF linacs) linear accelerator is employed. In these electric or magnetic fields oscillate at high frequency, commonly known as radio frequency in the range of million to billion of cycles per second In RF Linac very high electric or magnetic fields are produced by injecting RF energy from a powerful RF system in to a confined cavity bounded by conducting material ( copper) to keep the energy from radiating away. The particles to be accelerated are injected to the Linac structure. In older linacs drift tubes distributed along the axis of the structure. The particles are exposed to longitudinal electrical field, when they are in acceleration and are hidden from the electric field by drift tube when the electric fields are in opposite direction.

## Linac Basics

A Linear Accelerator or LINAC, is a particle accelerator which accelerates charged particles - electrons, protons or heavy ions - in a straight line. Charged particles enter on the left and are accelerated towards the first drift tube by an electric field. Once inside the drift tube, they are shielded from the field and drift through at a constant velocity. When they arrive at the next gap, the field accelerates them again until they reach the next drift tube. This continues, with the particles picking up more and more energy in each gap, until they shoot out of the accelerator on the right.



The drift tubes are necessary because an alternating field is used and without them, the field would alternately accelerate and decelerate the particles. The drift tubes shield the particles for the length of time that the field would be decelerating

The major parts of a linear accelerator are:

- The electron gun
- The buncher
- The linac itself

Each part is responsible for a stage in the acceleration of the electrons.

### A. The Electron Gun

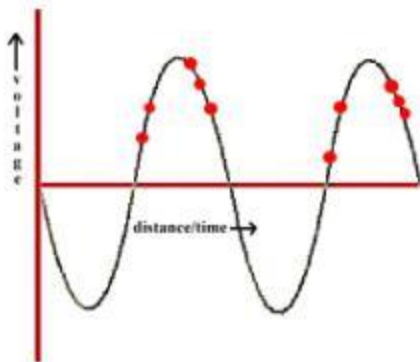
The **electron gun**, is where electron acceleration begins. The electrons start out attached to the molecules in a plate of barium aluminate or other thermionic materials such as thorium. This is the **cathode** of the electron gun. A cathode is a surface that has a negative electrical charge. In linac electron guns this charge/ electrons are emitted on heating the cathode. Barium aluminate is a "thermionic" material; this means that it's electrons tend to break free of their atoms when heated. These electrons "boil" near the surface of the cathode.

The **gate** is like a switch. It consists of a copper screen, or "grid," and is an anode. An anode is a surface with a positive electrical charge. Every 500 millionth of a second the gate is given a strong positive charge that causes electrons to fly toward it from the cathode in tremendous numbers. As these electrons reach the gate, they become attracted even more strongly by the main **anode**, and pass through the gate.

Because the gate is pulsing at a rate of 500 million times per second (500 MHz), the electrons arrive at the anode in loose bunches, a 500 millionth of a second apart. The anode is a torus (a doughnut) shaped to create an electromagnetic field that guides most of the electrons through the hole into the next part of the accelerator, called the **buncher**.

## B. The Buncher

The purpose of the buncher is to accelerate the pulsing electrons as they come out of the electron gun and pack them into bunches. To do this the buncher receives powerful microwave radiation from the klystron. The microwaves accelerate the electrons in somewhat the same way that ocean waves accelerate surfers on surfboards. Look at the following graph:



The yellow-orange disks are electrons in the buncher. The curve is the microwave radiation in the buncher. The electrons receive more energy from the wave--more acceleration--depending on how near they are to the crest of the wave, so the electrons riding higher on the wave catch up with the slower ones riding lower. The right-hand wave shows the same group of electrons a split second later. On the front of the wave, the two faster electrons have almost caught up with the slower electron. They won't pass it though, because they are now lower on the wave and therefore receive less acceleration.

The higher electron on the back of the wave gets just enough acceleration to match the speed of the wave, and is in the same position as it was on the left-hand wave. This represents the last electron in the bunch. The lower electron on the back of the wave gets too little energy to keep up with the bunch and ends up even lower on the right-hand wave. Eventually it will fall back to the electron bunch forming one wave behind.

### **C. The Linac**

The linac itself is just an extension of the buncher. It receives additional RF power to continue accelerating the electrons and compacting them into tighter bunches. Electrons enter the linac from the buncher at a velocity of  $0.6c$ --that's 60% of the speed of light. By the time the electrons leave the linac, they are traveling very close to the speed of light.

### **WORKING AND DESCRIPTION MEDICAL LINEAR ACCELERATOR :-**

With the advances in linear accelerator models and working condition, the disadvantages of earlier cobalt machine based gamma radiation are overcome. The main advantage of linac over Co 60 is skin sparing, means the radiation affects the skin surface. Most of x-ray energy goes to tumour; secondly there is minimal scatter of x-ray energy outside the beam. Sharply defined x-ray beam minimizes the side effects of treatment, so only a small amount of radiation travel to other parts of the body. Linac allows sharpness of the beam edge, allows a very precise treatment and adjacent tissues spared. And this linac may be programmed to treat with electron rather than x – rays for special situations.

Most linear Accelerators make use of isocentric mount, modern linacs use 100 cm isocentre, i.e the source of x-ray is 100 cm from the axis of rotation, so the patient is positioned with the center of tumour on the axis of rotation. Treatment delivered using several angular positioned, without realigning the patient simply by rotating the unit.

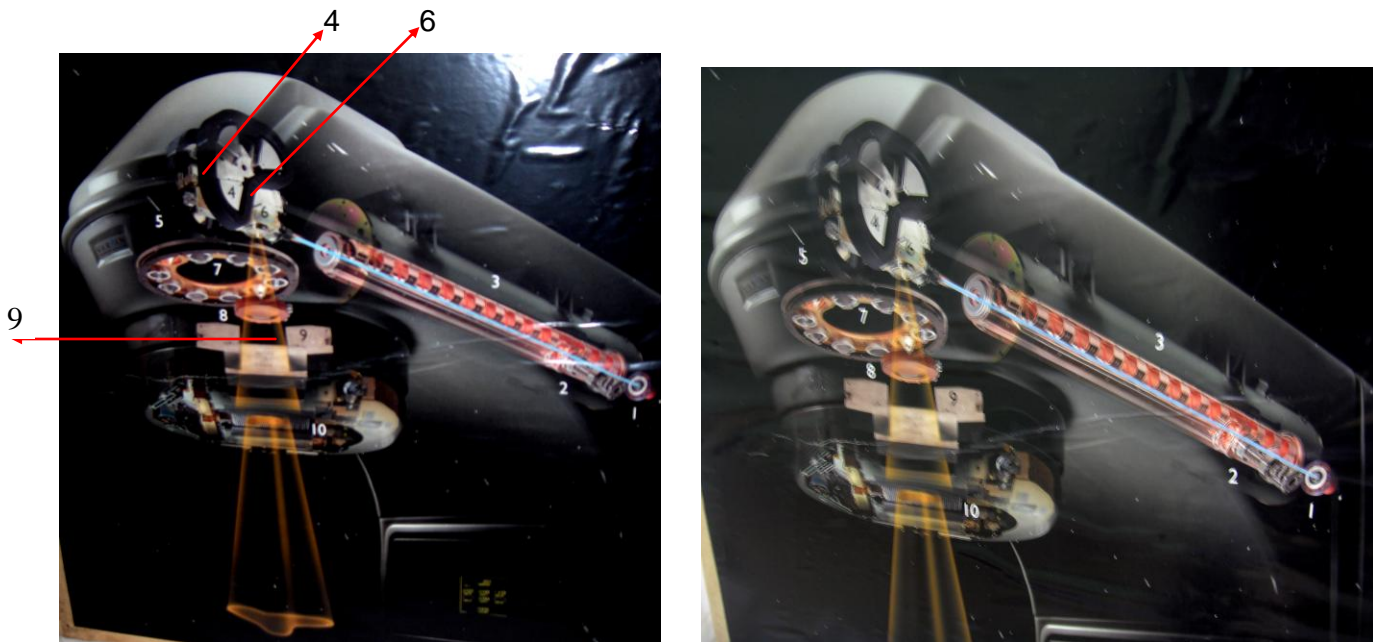
For low energy medical linacs, having energy range of 4 – 6 MeV, the accelerating tube can be made short enough to allow the arrangement. The electrons travel down the tube and strike the target, produce x ray beam symmetrical about the line of source to center of the machine. If electron beam required the target is moved to the side to allow the electron beam emerge thro a thin window.



For high energy machines, the accelerating tube must be made longer. RF power from klystron is brought to the wave guide through the axis of machine using a rotating vacuum seal. The electron beam is bent through an angle of 60 degrees, passes through quadruplet focusing magnets and then bent 90 degrees in the head to hit a target or emerge through a window for electron beam.

In high energy medical linacs there are some important components required to control and shape the beam from a Linac used in both electron and photon modes. High energy electron from wave guide is focused at the target which is thick enough to stop the electron. When we use electron mode of operation in the linac, the tungsten target on the sliding mount moved towards right side and allowing the electron to pass through an open window. Just below the target one more sliding mount is located, which contains a variety of electron scattering foil for different electron energy and a port for photon mode.

These beams pass through a conical hole in the primary collimator made of heavy metal. Below this primary collimator a secondary slide containing the flattening filter of tungsten and a one section for an electron beam. Ion chamber is positioned near the secondary slide to monitor the dose and a quadrant is connected to a servo mechanism to control the beam optics. A light localizer is placed below the ion chamber which is retracted from the beam after patient position under the beam. A pair of collimator at right angles can be rotated about the axis to give square or rectangle field and all these are mounted in the head to about 50 cm, in general from the source.



1. Gridded Electron Gun:-

Controls dose rate rapidly and accurately. Permits precise beam control for dynamic treatments, since gun can be gated. Removable for cost - effective replacement.

2. Energy Switch

Patented switch provides energies within the full therapeutic range at consistently high stable dose rates, even with low energy x ray beams. Ensures optimum performance and spectral purity at both energies.

3. Wave Guide

High efficiency, side coupled standing wave accelerator guide with demountable electron gun and energy switch

4. Achromatic 3 field bending magnet

Unique design with fixed +/- 3 % energy slits ensures exact replication of the input beam for every treatment. The 270 degree bending system, coupled with varians 3 -dimensional servo system, provides for a 2mm circular focal spot size for optimal portal imaging.

5. Real time beam control steering system

Radial and transverse steering coils and a real time feed back system ensures that beam symmetry is within +/- 2%at all gantry angles.

6. Focal spot size

Even at maximum dose rate – and gantry angle – the circular focal spot remains less than 2mm, held constant by a focus solenoid. Assures optimum image quality for portal imaging

7. 10 port carousel

New electron scattering foils provide homogenous electron beams at therapeutic depths. Extra ports allow for future development of specialized beams.

8. Ion chamber

Dual sealed ion chambers with 8 sectors for rigorous beam control provide two independent channels, impervious to changes in temperature and pressure.

Beam Dosimetry is monitored to be within +/- 2% for long term consistency and stability.

9. Asymmetric Jaws

Four independent collimators provide flexible beam definition of symmetric and asymmetric fields.

10. Multi-Leaf Collimator

Dynamic full field resolution 120 leaf MLC with dual redundant safety read out for most accurate conformal beam shaping for IMRT treatments.



Linear accelerator with MLC and Portal vision

## **Techniques used with Medical Linacs:-**

With the current trend using linear accelerator a variety of treatment techniques are possible. Some of the techniques as follow,

1. 3D conformal radiotherapy
2. Intensity Modulated Radiotherapy
3. Stereotactic Radiotherapy(SRT)
4. Stereotactic Radiosurgery(SRS)
5. Dynamic Adaptive Radiotherapy (DART)
6. Image guided Radiotherapy (IGRT)

There are some accessories like MLC, mMLC, cone beam CT, EPID are useful in precision delivery of treatment. Software programme like treatment verification, reduces the general errors and work load of a busy department

### **Types of External Beam Radiation Therapy**

**Conventional external beam radiation therapy** - The science of radiation oncology and medical physics has developed standard approaches to dose delivery. In many cancer cases the treatment approach may be very similar and allows for conventional treatment. For example, many tumors can be treated with a single field from the front and a single field from the back or with two fields from the opposite sides. These are examples of parallel opposed fields. The combination of fields helps to uniformly deliver dose across the tumor. Sometimes 3 or 4 fields will be used. Occasionally, the gantry of the linear accelerator will rotate during treatment using what is called arc therapy.

**3-D Conformal Radiation Therapy** - Through the advancement of imaging technology enhanced images of the body allow for programming of treatment beams to conform better to the shape of a tumor. Hence treatment is more effective and side effects are reduced. By treating with large numbers of beams each shaped with a multileaf collimator (MLC) or cerrobend block, radiation dose is delivered uniformly and conformally to the tumor

**Intensity Modulated Radiation Therapy (IMRT)** - IMRT is one of the latest advancements in radiation therapy. This new approach to treatment allows for dose sculpting and even distribution of delivery to avoid critical structures while delivering precise uniform treatment. In this technique, the multileaf collimator (MLC) moves and modulates the radiation as the linac treats the patient.

## **Future prospective:-**

With the improvement in computer field, diagnostic methods and other breakthroughs in the modern electronics systems, made possible a variety of treatment technique and methods to treat the patient with more accurate and less side effects or nil side effects, sparing the critical organs in and around the tumour region. The electronic Portal Imaging device (EPID) made possible to verify the treatment portal without delivering a high dose and make correction where ever it is mandatory.

Computer assisted treatment delivery and record verify systems reduces the errors and assures the accurate treatment delivery with reduced time frame, and with the less man power. Newer treatment modalities like IGRT, DART and other high resolution treatment modalities made possible the treatment of organs involved with motion due to breath and circulations. Robotic arm based radiosurgery made the skull based radiosurgery programme a grand success with high accuracy.

## **Technology-driven delivery methods**

Technological developments in computers and accelerator designs, particularly inverse treatment planning and dynamic multi-leaf collimation systems (dMLCs), have given the radiotherapy community the ability to deliver conformal and intensity-modulated radiation therapy (IMRT) treatments. With the implementation of image-guided radiation therapy (IGRT), there is a potential to deliver inhomogeneous dose distributions that increase the dose inside the target by 20-30% over the minimal peripheral dose, while decreasing possible normal tissue complications by collapsing the planning target volume (PTV) onto the clinical target volume (CTV), as is often done in Stereotactic radiosurgery.

## **Image-guided intensity-modulated and adaptive helical TomoTherapy**

Image-guided IMRT is redefining the practice of radiation oncology. Traditional methods of implementing beam intensity modulation have included individually designed compensators, static multi-leaf collimators (MLC), dynamic MLC and sequential (serial) tomotherapy. Helical Tomotherapy provides added functionality to enhance the application of IMRT. It facilitates adaptive radiotherapy and conformal avoidance. These advances improve normal tissue sparing and permit dose reconstruction and verification, thereby allowing significant biologically effective dose escalation and reduced radiation toxicity. Recent radiobiological findings can be translated into altered fractionation schemes that aim to improve the local control and long-term survival. The intrinsic capability of helical Tomotherapy for

megavoltage CT (MVCT) imaging for IMRT image-guidance is an added feature aiding in further adaptation of treatments.

### **Stereotactic Radiosurgery :**

The most important component of whether there is radiation injury to the brain is dependent upon the amount of healthy tissue that is targeted. Additional factors will be the radiation dose that the healthy tissue receives and how it receives it. The type of instrument that is available to an individual for treatment will be the deciding factor in radiation damage. Today patients are fortunate in that there are choices for treatment that limit radiation to healthy brain tissue to small amounts or none with one-session radiosurgery. The most common machine for this type of treatment is the neurosurgical instrument the Gamma Knife®. The Gamma Knife severely restricts the radiation of healthy tissue by targeting exactly where the neurosurgeon directs the radiation to the tumor bed with negligible overlap to healthy tissue.

Linear accelerator technology based dedicated linear accelerator like 600 SR models has the capabilities equal to gamma knife and made it possible for a one session treatment or for fractionated radiotherapy.

### **Fractionated Stereotactic Radiotherapy :**

With fractionated radiotherapy, a larger path of healthy tissue is targeted than with one-session treatments due to limitation with the type of linear accelerator machines utilized. In the past , it has been felt that some of the healthy cells that are radiated within the brain will have time to heal if the treatments are given over time (fractionated). Since the brain does not regenerate like other body cells, there is much debate over that value of fractionation within the brain. Machines that do fractionated treatments are linear accelerator based. It should be noted that with daily treatments over time there is less accuracy that with one session radiosurgery as the skull can not be targeted in exactly the same place (repositioned) and manner with each subsequent treatment as it was in the first treatment. IGRT (Image guided radiation therapy) allows for each session to be reimaged before the treatment that can provide more accuracy than without the imaging. All high level linac machines are considered high-level and provide IGRT imaging including the X-Knife®, Trilogy®, SynergyS®, Novalis®, and CyberKnife®. These machines would be considered comparable in effectiveness of treatment and outcomes.

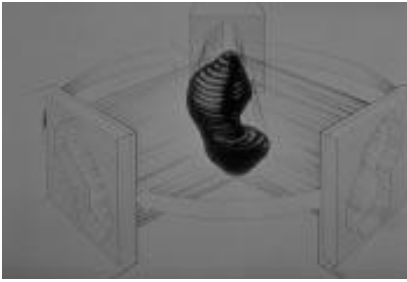
However, the most precise and accurate treatment is still with one session radiosurgery.

## **Helical Tomotherapy**

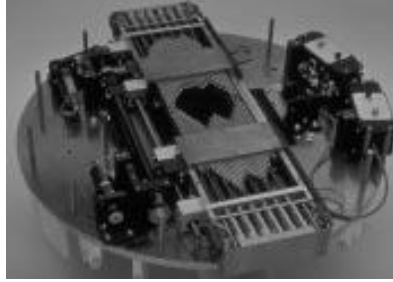
In contrast to standard radiotherapy, helical Tomotherapy delivers treatment with a rotating intensity-modulated fan beam. The patient is continuously translated through a ring gantry, resulting in a helical source trajectory about the patient. The beam delivery is similar to that of helical ('spiral') computed tomography (CT) and requires slip rings to transmit power and data. The ring gantry provides a stable and accurate platform to perform tomographic verification of both the patient setup and delivered dose. The design of the helical TomoTherapy unit allows for continuous delivery over 360 degree beam angles. The helical delivery minimizes the risk of significant high or low dose deposition in areas of overlap or junctioning. Assessments of sequential units presently in use reveal that positioning errors as little as 1 mm can cause dose errors of the order of 10-20% in the abutment regions. In addition to full integration of IMRT delivery, an important advance with helical TomoTherapy over the other current systems is the ability to provide accurate verification of radiation delivery via onboard tomographic imaging. Examples of conformal avoidance planning and delivery using a Linac and Tomotherapy unit are given.

## **Adaptive radiotherapy**

One of the significant features of the helical TomoTherapy unit is the presence of an integrated online MVCT unit. This permits verification of patient positioning, target tumor/organ registration to assess internal motion (including geometric shift and shape/volume changes) and reconstruction of delivered dose. These capabilities offer the radiation oncology team the ability to verify and adjust the therapeutic plan as needed during the course of treatment. This concept is referred to as adaptive radiotherapy. These capabilities can be viewed as a closed-circuit loop. The integration of the MVCT and the treatment unit allows for options not possible with contemporary systems. For example, if a patient setup is found to differ from the planned position, the current approach requires moving the patient to compensate for this positioning error. With the integrated helical unit, another option is having the patient remain in the 'incorrect' position and modifying the treatment delivery. The success of the modification is independent of the extent and direction of the offsets, within certain limits. MVCT images can be obtained at radiation doses of around 2 cGy and are comparable to that of diagnostic CT imaging and lower than reported doses from low-dose megavoltage cone beam CT. Other methods of onboard imaging have been developed recently and are available clinically.



Dynamic multi-leaf collimator  
Three-dimensional tumor treatment



multi-leaf collimator



Stereotactic procedure



Stereotactic Radiosurgery with MMLC



Clinac 600CD with brain labs MMLC



Linac with imaging facility

## Conclusion:-

The history of linac in medical technology represents a significant chapter in the humanitarian contributions of together energy and microwave physics. A revolutionary process in the treatment of radiation oncology patients with improved quality of life. The availability of new imaging modalities before and during radiotherapy planning and delivery has allowed us to launch new tools at every major step of the treatment process.

Radiation therapy is unique among the cancer treatment modalities because it can be modulated in the four dimensions of time and space. Modulation in the time domain gives rise to the time-dose-fractionation problem, and this continues to be one of the most fruitful avenues for further improvement of the therapeutic ratio in radiation oncology.



Linear Accelerators with advanced specifications like, Dynamic MLC, Cone beam CT, Motion synchronization facilities, made enable the future of cancer treatment to a New Era. Hence the 5 year survival rate and quality of life for the rest after the treatment delivery made possible.



Clinac 21Ex with Portal vision facility (Amorphous Silicon)

## History of the medical linear accelerator:

**1952:** Henry Kaplan and Edward Ginzton begin building a medical linear accelerator.

**1956:** The first medical linear accelerator in the Western Hemisphere is installed at Stanford Hospital in San Francisco.

**1959:** Stanford medical school and hospital move to the Palo Alto campus, bringing the medical linear accelerator.

**1962:** Kaplan and Saul Rosenberg begin trials using the linear accelerator with chemotherapy to treat Hodgkin's disease, an approach that dramatically improves patient survival.

**1994:** First use of the CyberKnife, invented at Stanford, which uses sophisticated computerized imaging to aim a narrow X-ray beam precisely.

**1997:** Stanford pioneers the use of intensity-modulated radiation therapy, which combines precise imaging with linear accelerators that deliver hundreds of thin beams of radiation from any angle.

**2004:** Implementation of four-dimensional radiotherapy, which accounts for the motion of breathing during imaging and radiation delivery.

Suggested readings:-

1. Back to the future: the history and development of the clinical linear accelerator  
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6. [Stanford's medical accelerator, first to treat cancer patients, is on display at Smithsonian,](#)  
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7. The Physics of radiology, 4<sup>th</sup> edition, Johns, and John