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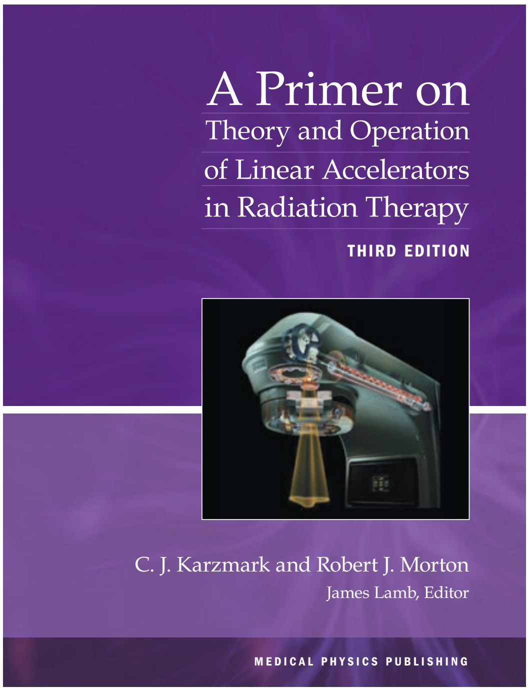
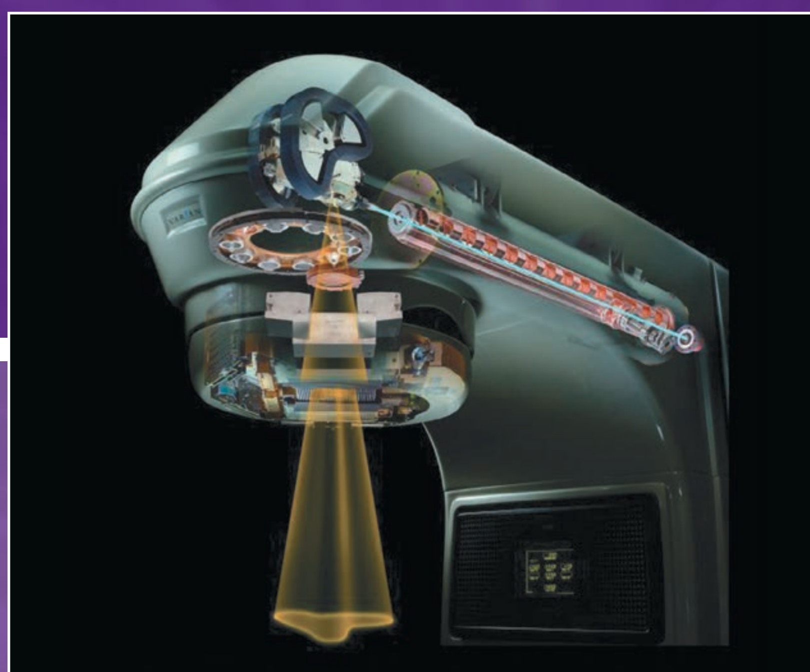


Here is a sample chapter from *A Primer on Theory and Operation of Linear Accelerators in Radiation Therapy*©.

A Primer on Theory and Operation of Linear Accelerators in Radiation Therapy

THIRD EDITION



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A Primer on
Theory and Operation of Linear Accelerators in Radiation Therapy

THIRD EDITION

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Preface

Welcome to the third edition of the classic book *A Primer on Theory and Operation of Linear Accelerators in Radiation Therapy*. Sadly, Dr. Clarence J. Karzmark is no longer with us, but Robert Morton has enlisted James Lamb to help him update this time-tested book for a new generation studying radiation therapy, radiological physics, radiation oncology, and radiation control.

Electron linear accelerators evolved from the microwave radar developments of World War II. The klystron tube, invented at Stanford University, provided a vital source of microwave power for radar then, as it does now. In the late 1940s, the high-power klystron and the microwave principles incorporated into its design were used to construct and power an electron linear accelerator, or linac, for use in physics research and later for industrial radiography. By the mid-1950s, a linac suitable for treating deep-seated tumors was built in the Stanford Microwave Laboratory and installed at Stanford Hospital, which was located in San Francisco at that time. It served as a prototype for commercial units that were built later.

Since that time, medical linear accelerators have gained in popularity as major radiation therapy devices, but few basic training materials on their operation had been produced for use by medical professionals. Dr. Karzmark, a radiological physicist at Stanford University, was involved with medical linacs since their development, and he agreed to collaborate with Robert Morton of the Center for Devices and Radiological Health (formerly the Bureau of Radiological Health) at the U.S. Food and Drug Administration to write the first edition of this primer. The first primer was originally published by the U.S. Department of Health and Human Services in December 1981 as FDA 82-8181. It provided an overview of a linear accelerator's components and how they function and interrelate. The auxiliary systems necessary to maintain the operation of the linear accelerator were also described. The primer promoted an understanding of the safe and effective use of these devices. It was produced in cooperation with the Division of Resources, Centers, and Community Activities of the National Cancer Institute, and it was intended for students of radiation therapy, radiological physics, radiation oncology, and radiation control.

For ease in understanding, much of this text describes the components as they appear in just one electron linear accelerator treatment unit: the Varian Clinac 18. This choice in no way constitutes an endorsement of this manufacturer's models. Variations in design do occur with other manufacturers and models.

This third edition takes into account the significant advances occurring in radiotherapy linacs since the second edition was published in 1998. Again, the level of treating these advances is simplified so that the audience of radiation therapists—as well as physicians, engineers, and physicists—can benefit. New sections 12 and 13 have been added to describe the essential components of image-guided radiotherapy and physiologic beam gating, respectively, both of which have become standard radiotherapy techniques since the publication of the second edition. The previous section 12 describing beam stoppers has been removed, as these are no longer widely used.

Throughout the text, changes have been made to reflect a modern radiotherapy work flow that is integrated with image guidance and record and verify systems.

Acknowledgments

The need to simplify complex microwave and physics phenomena while retaining rigor in the treatment of these phenomena presented a significant dilemma in writing this primer. We are deeply indebted to our many colleagues who gave generously of their time in critically reviewing the manuscript, suggesting changes, simplifying analogies, and identifying areas that were unclear. Their incisive comments enabled us to have a better perception of how the primer should be written.

We also wish to acknowledge the assistance, critical review, and encouragement of Bureau of Radiological Health staff members Frank Kearly and Marcia Shane. We thank Craig Nunan for important contributions, in particular, Section 9. For editorial contributions, we acknowledge John R. Cameron, Ph.D.

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1 INTRODUCTION

Cancer patients are treated by radiation, surgery, or systemic therapies such as chemotherapy. A treatment method proving increasingly effective is radiation, used by itself or in combination with other modalities. The principal radiation modality for the treatment of deep-seated tumors is x-rays of very high energy and penetrating power. Such x-rays are created when high-energy electrons are stopped in a target material such as tungsten. Alternatively, the electrons themselves may be used directly to treat more superficial cancers. The electron linear accelerator (linac) accelerates charged particles in a straight line, in contrast to the circular or racetrack orbits that characterize the cyclotron and synchrotron. The purpose of this primer is to explain the principles of operation and use of the electron linear accelerator and to acquaint the reader with pertinent features and terminology.

The medical linear accelerator will be introduced by first examining the treatment room. Figure 1 shows a patient being readied for treatment with a linac. The thick concrete walls of the treatment room shield the radiation therapist and other staff from the penetrating radiation during treatment. The linac is mounted in a gantry that rotates on a stand containing electronic and other

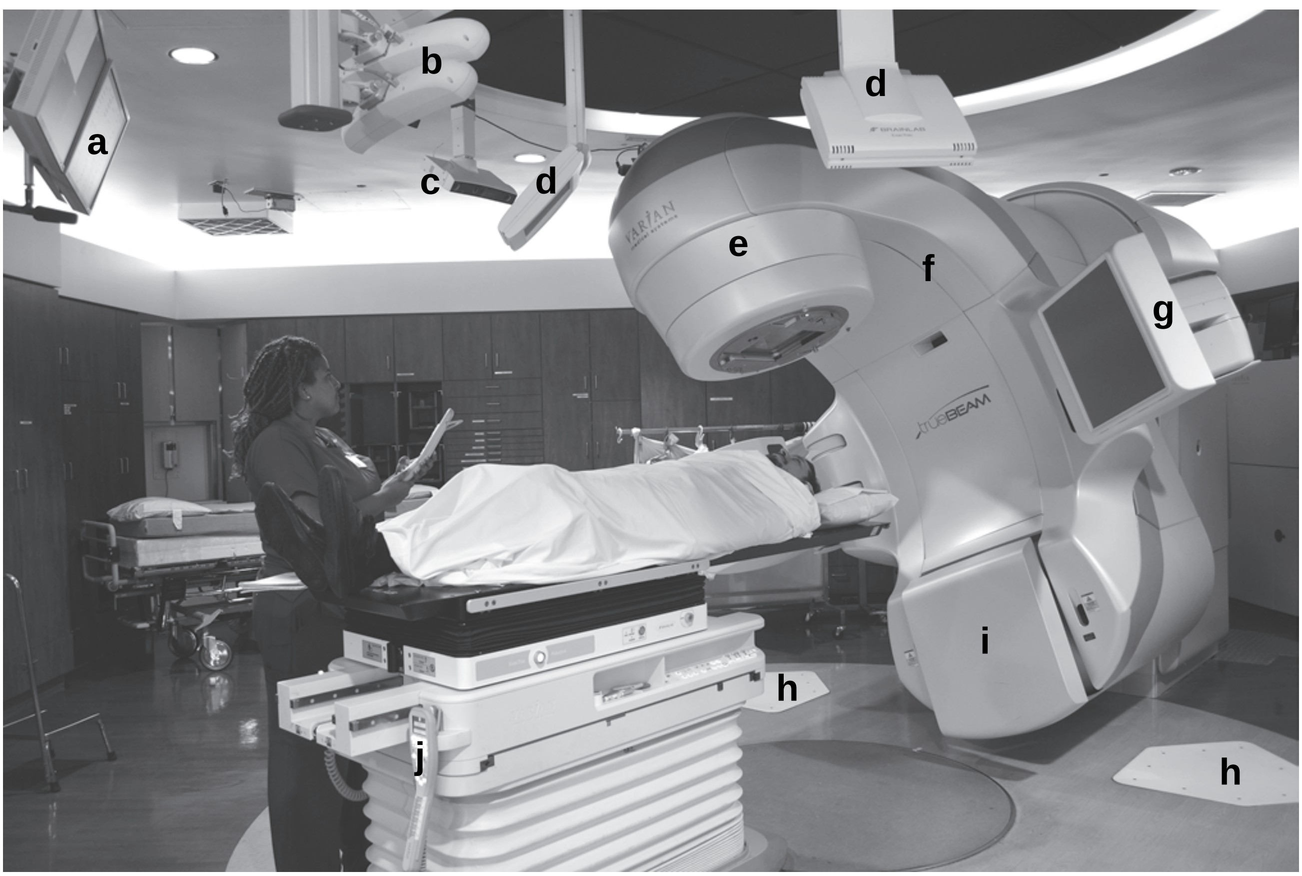


Figure 1. A typical radiation therapy treatment room composed of a Varian TrueBeam linear accelerator and various third-party devices to suit the facilities' needs. a) Position-monitoring flat panel display; b) infrared camera for image guidance (Brain Lab ExacTrac); c) infrared camera (Vision RT); d) flat panel kV detectors (Brain Lab ExacTrac); e) treatment head; f) gantry; g) on-board flat panel kV detector (partially retracted); h) kV x-ray tubes (ExacTrac) under floor panel; i) on-board flat panel MV detector (fully retracted); j) motion control pendant. (Photo courtesy of James Lamb, UCLA.)

systems (Figure 2). The linac can be rotated into position about the horizontal gantry axis for use in treatment. The radiation beam emerging from the collimator is always directed through and centered on the gantry axis. The beam central axis intersects the gantry axis at a point in space called the isocenter. In the majority of cases, the couch is positioned so that the patient's tumor is centered at the isocenter. Usually, the patient lies supine or prone on the treatment couch (sometimes called patient support assembly). The couch incorporates three linear motions and rotation about one or more axes through the isocenter to facilitate positioning the patient for treatment. Side and ceiling lasers project small dots or lines that intersect at the isocenter. These facilitate positioning the patient in conjunction with reference marks, often tattoos, placed on the patient's skin. In a process called image-guided radiotherapy (IGRT), patient positioning is verified and refined using x-ray, optical, ultrasound, or magnetic resonance based in-room imaging systems. Digital position indicators display the treatment field size together with collimator and gantry rotation angles. The isocentric system facilitates comfortable, precise reproducible treatment when using multiple fields directed at the tumor from different gantry angles (Figure 3). In this unit, a constant radiation source-gantry axis-distance (SAD), usually 100 centimeters (cm), is employed. Alternatively,

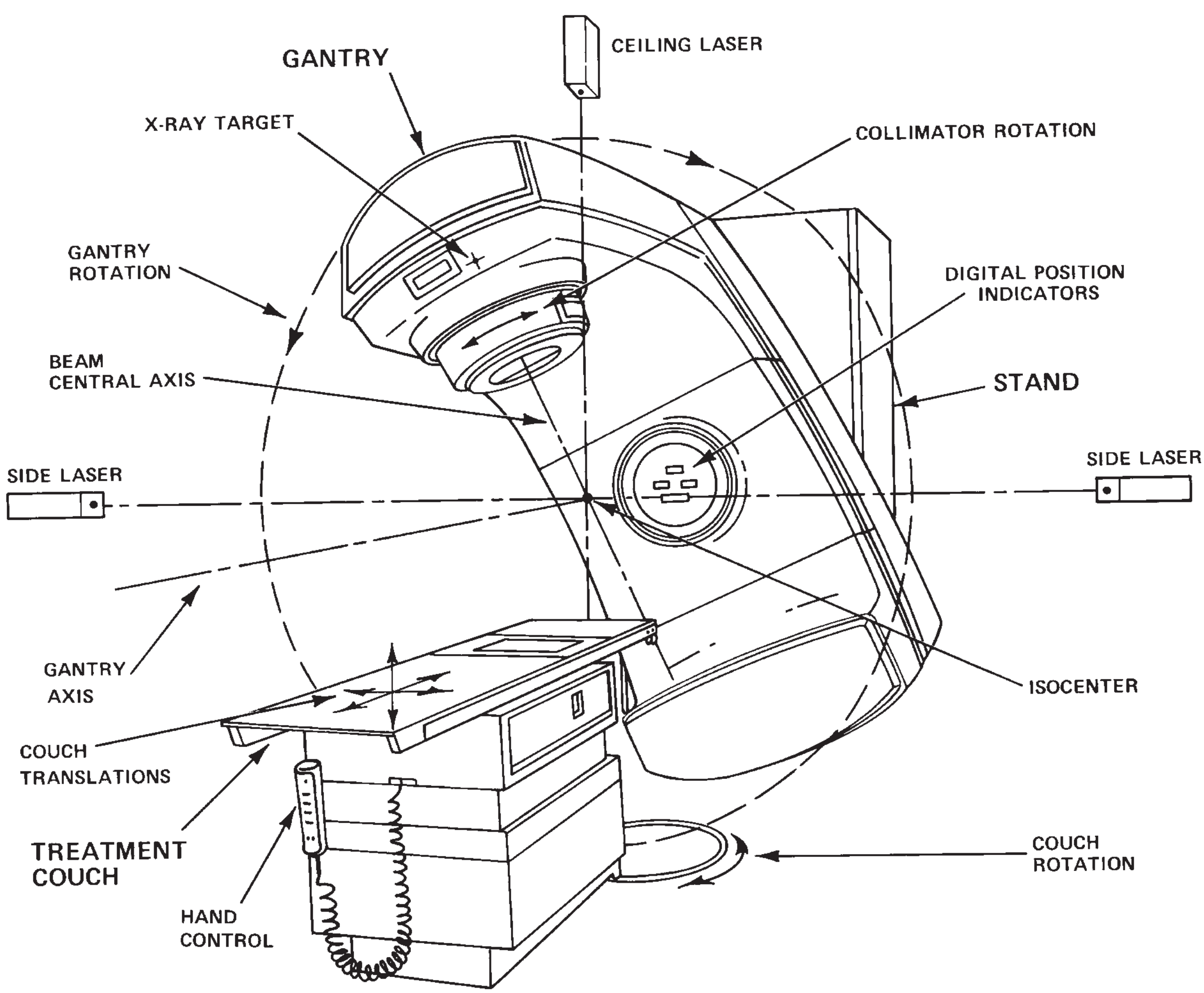


Figure 2. Schematic view of a Varian Clinac 18 linear accelerator system, emphasizing the geometric relationship of the linear accelerator system, positioning lasers, treatment couch, and related motions.

some treatment techniques use a constant radiation source-skin (of patient) distance (SSD), usually for electron treatments or for large fields at distances of 100 cm or greater.

After positioning the patient for treatment in the treatment room, the radiation therapist confirms the treatment parameters from the record and verify system and loads the patient's radiation plan using the control console keyboard (Figure 4). The treatment plan contains collimator positions and monitor units for all the beams of the patient's treatment. From this position at the control console outside the treatment room, the radiation therapist can view the patient on the video monitors and the real-time image of the treatment field on the console monitor display

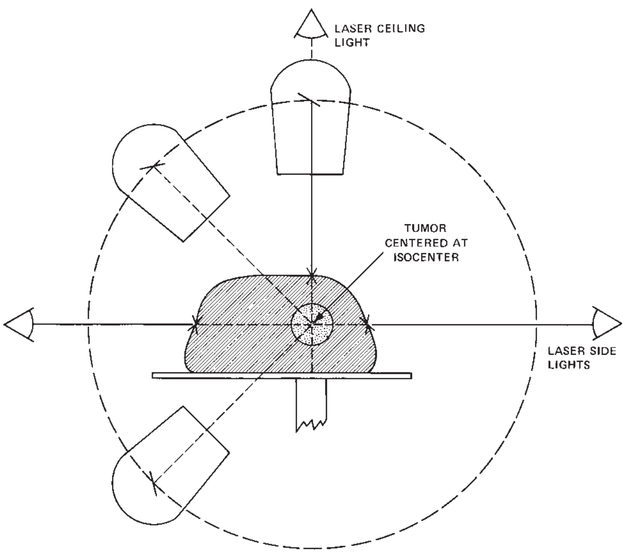
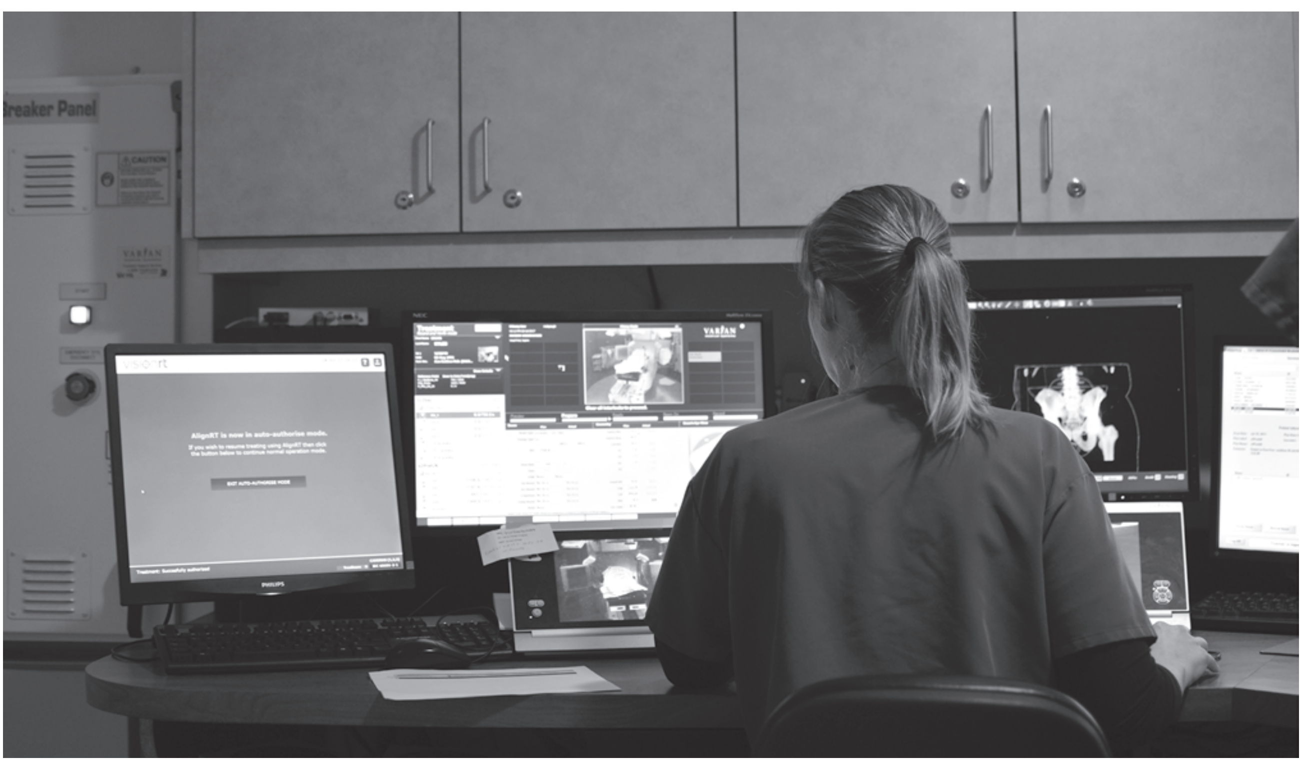


Figure 3. The "isocentric" treatment technique. The tumor center, shown within a patient's cross section, is positioned at the isocenter with the aid of skin marks and the lasers shown. The tumor is now positioned for easy and accurate irradiation from any desired gantry angle. The dashed circle depicts all possible x-ray source locations at 100 cm radius (source-axis distance [SAD] = 100 cm).

Figure 4. Therapists initiate, monitor, and control the treatment at the control console. Video monitors display two views of the patient and the linac. The record and verify system stores, verifies, and displays the patient treatment parameters. The electronic portal imaging terminal displays a real-time image of the photon treatment field. (Photo courtesy of James Lamb, UCLA.)



and can take emergency action, should it be necessary.

The discussion and illustrations, which follow a brief description of the linac, explain the basic concepts of operation and extend them to the design of an elementary electron linear accelerator. Later, the major modules of a medical linac are identified. Their principles of operation and how they function collectively to produce x-ray and electron treatment beams are described. First, however, we must explain how the energy of a radiotherapy beam is designated.

2 ENERGY DESIGNATION IN ACCELERATORS

Figure 5 shows a simple device that will accelerate electrons. It consists of a 1-volt (V) battery connected to two conducting plates spaced 1 cm apart in an evacuated glass tube. The glass tube is an electrical insulator. The negative plate is termed the **cathode** and the positive plate the **anode**. In order to set up the associated electrical charges, the battery causes electrons to flow from the anode to the cathode via the external circuit. This results in a deficiency of electrons at the anode (positive charge) and an excess of electrons at the cathode (negative charge) as shown. This charge distribution creates an **electric "E" field** (denoted by an arrow) in the region between the plates in the direction shown. The size of the electric field is the force that a unit positive charge would feel if placed between the two plates and, in this example, is 1 volt per cm (V/cm). That is, the difference in the electrical potential between the plates, divided by the distance between them, is 1 V/cm. By definition, the arrow identifies the direction a positively charged particle would move; an electron with its negative charge would move in the opposite direction. It is not possible to see "E" fields, but they are known to exist because of the force they exert on charged particles such as electrons. If the electrons in Figure 6 are released from the negative plate (the cathode), they will be accelerated by the force of the "E" field to the positive plate (the anode). An **electron volt** (eV) is the energy gained by an electron accelerated across a potential difference of 1 V.

Exerting a force through a distance is a basic measure of work and energy. On the atomic scale,

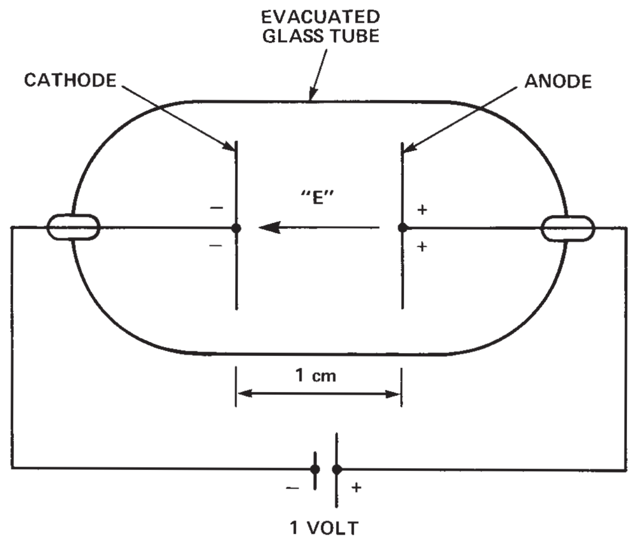


Figure 5. Illustration of an electric "E" field used to accelerate charged particles such as electrons. The "E" field is directed to the left, i.e., from the positive to the negative terminal.

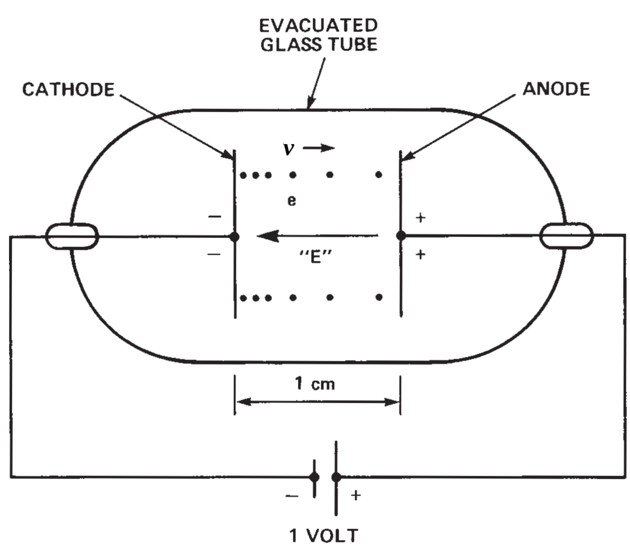


Figure 6. A simple electron linear accelerator of energy one electron volt (1 eV). Electrons, "e," are depicted by dots moving with a velocity (v) to the right. The "E" field is one volt per cm (1 V/cm) in the opposite direction. Note that the density of electrons is highest near the cathode, where their velocity is lowest.