Introduction to radiation physics. Neill Serman
White and Pharoah. Principles of Dental Imaging. Ch. 1. Sept. 00

Wilhelm Conrad Roentgen discovered X-rays in November 1896 while experimenting with cathode rays (electrons) in a high energy cathode ray tube. Fortuitously, there was a plate of barium platinocyanide nearby, which glowed in the dark and this fluorescence set the stage for a new era of science that was to change the world and medicine for ever. While experimenting he placed his hand in the path of the beam and he was able to see the bones of his own hand. He later recorded the hand of his wife for posterity.

There is some basic radiation physics that the dental student is expected to master in order to understand the workings of the dental X-ray machine.

COMPOSITION OF MATTER.

All physical things are composed of matter that is inert but occupies space and can occur as a gas, a solid or a liquid. All matter consists of substance composed of **e*lements*** or ***compounds***. Elements consist of only one material / species; where as compounds consist of at least two different elements.

Atoms are the fundamental units of any element and are composed of the nucleus and orbiting electrons. The nucleus is composed of many sub atomic particles but we are only concerned with protons (positively charged nucleons) and neutrons (no charge); collectively called **nucleons**. The **charge** of the proton is equal to but opposite to that of the electron immaterial of the substance. The proton and the neutron have *approximately* the same **mass** which is about 1840 times greater than the mass of the electron. The number of protons only in a nucleus is called the **atomic number (** the **Z** number)**.** The **atomic mass (A)** is the total number of protons and neutrons in the nucleus of an atom. When the number of protons equals the number of electrons that atom is known to be in a stable or neutral state.

No matter what material, all electrons and all protons are identical. According to the Bohr concept, electrons circuit the nucleus in definite orbits known as the K, L, M, N, O and P orbits known as the **principal quantum numbers.** $\mathbf{2n^2}$ is the formula to determine the maximum number of shells in an orbit. n = principle quantum number. All atoms of an element have the same Z [atomic] number, but an element may have **isotopes** where the number of protons are the same but there is a different number of neutrons.

The electrons in the orbit are maintained by the **electrostatic** force between the positively charged nucleus and the negatively charged electrons on the one hand, balanced by the **centrifugal** force of the revolving electrons. The amount of energy required to remove an electron from a given shell is known as the **binding energy** and is specific for each shell of each atom. Electrons in the K shell have the greatest amount of binding energy because they are closest to the nucleus. (Inverse Square Law - inversely proportional to the square of distance between the nucleus and the electron). The further away the electron is situated from the nucleus the greater the **potential** energy. When an electron moves from the K to the L shell it will give off an amount of energy equal to the difference between the binding and the potential energy. **Tungsten** has a K-shell energy of 69.5keV; L shell of 12 and M shell of 2keV.

Ionization.

When an electrically neutral atom loses an electron it becomes a **positively** charged **ion** and the free electron a **negative ion.** The process of losing or gaining an electron is known as ionization. For this to occur the energy must be greater than the binding energy; the electrostatic force binding the electron to the nucleus. Electrons in the inner shells have a greater binding energy and can only be removed by high energy particles.

Nature of Radiation.

Radiation is the transmission of energy through space [or matter] and consists of **electromagnetic** (non particulate) and **particulate** energy.

Particulate energy consists of Alpha rays, Beta rays, cathode rays and fast moving electrons.

Alpha rays result from the decay of many radioactive materials and are high speed doubly ionized helium **nuclei** (2 protons and 2 neutrons) that quickly give up their energy and have very little penetrating power. Beta rays and cathode rays are both swiftly moving **electrons**; beta rays from radioactive nuclei and cathode rays from some manufactured device e.g. inside the tube of an X-ray machine.

Linear Energy Transfer. LET.

The rate of loss of energy from a **particle** (particulate energy) as it moves along a track through tissue is known as the linear energy transfer. The greater its physical size and charge and the lower its velocity, the greater the LET. Alpha particles transfer more energy in a given path than beta particles and are more damaging per unit dose. Both penetrate relatively little into tissue.

Electromagnetic (non particulate) radiation is the movement of energy through space or matter as a combination of electric and magnetic fields that travel at right angles to each other. [e.g. heat; radar; radio waves, TV waves; microwaves; visible light infra red; ultra violet; cosmic rays, x-rays, gamma rays]. It is generated when the velocity of an electrically charged particle is altered. [as at the focal spot in the X-ray machine]

In addition the energy may be ionizing or non ionizing. If the energy is sufficient to knock out an orbital electron the energy is **ionizing radiation.**

Dual nature of energy.

To explain the reactions of energy, radiation is considered as either a **wave** (wave theory) or a **packet** or **photon** of energy (quantum theory).

The **wave theory** of electromagnetic radiation suggests that the energy moves forward similar to a wave of water and travels at the speed / velocity of light in a vacuum.
The **quantum theory** of electromagnetic radiation assumes that energy moves as finite bundles / photons of energy. Each photon travels at the speed of light and contains a specific amount of energy. The photon unit of energy is the **electron volt** [eV]

The X-ray machine.

An X-ray is an invisible beam of light. Please distinguish between an X-ray, an X-ray film and a radiograph. An X-ray machine consists of a **control panel** and the head of the X-ray machine that contains an **X-ray tube** and generators and which receive **alternating** current from the control panel. The control panel is used to select exposure factors and to make the exposure.

The X-ray tube is surrounded by **oil** to dissipate heat and to prevent sparking from one electrical component to another. Inside the tube a **vacuum** is created to facilitate movement of electrons from the negative to the positive side.

The X-ray tube consists of a cathode (negative side) and an anode (positive side).

A. Cathode.

Consists of a **nickel** or **molybdenum focusing cup** and a **filament** that is the source of the electrons. The **filament** is a coil of **tungsten** wire about 0.2cm in diameter and about 1cm long. It is attached to the wires that carry the current. The mounting wires lead through the glass envelope and is attached to the high and the low voltage electrical circuits. The current first goes through the step down transformer (about 4 to 15 mA [milliamperage]) The mA button controls the current. mA [strictly mAs] is the **quantity** of electrons flowing per unit time and affects the **density** of the film. Electrons are boiled off from the outer orbits of atoms by a process known as **thermionic emission** producing an electron cloud. Thus, the filament temperature controls the **number** of x-ray photons produced due to the **degree** of **incandescence**.

Focusing Cup.

The filament lies in the focusing cup which electronically directs the electrons produced toward the focal spot on the anode. Like charges repel each other and only a few of the electrons generated would otherwise strike the focusing cup.

B. The Anode.

Consists of a tungsten **target** / focus / **focal spot** imbedded in **copper**. The function of the target is to convert the kinetic energy (electrons) into photon energy.

Tungsten was chosen for the target of the anode because of

1. **high atomic number** (74) which makes it more efficient in the production of photons.
2. **high melting point** (3370^0C) to withstand the high temperatures produced during the generation of photons.
3. When photons are generated the greater majority of kinetic energy is converted into heat. However, it is **not a good conductor** of heat and that is the reason it is embedded in copper to assist to dissipate the heat generated. Copper is a good thermal conductor.
4. Ideally the metal utilized for the focal spot **should not vaporize**. Unfortunately there is some vaporization with tungsten.

Dental machines have **stationery** anodes but some medical X-ray machines have **rotating** anodes in the form of a beveled disc to further assist in dissipating heat.

The smaller the size of the focal spot the **better the detail** / sharpness of the image produced on the radiograph - common Board question.

Line Focus Principle.

Heat is uniformly distributed over the focal spot, and a large focal spot allows the accumulation of large amounts of heat before damage to the target occurs. The conflicting need for the large focal spot for the distribution of heat and the small focal spot for detail of the image outline are overcome by the Line Focus Principle. The actual focal spot may by 1mm x 3 mm but the effective focal spot may be 1mm x 1mm.
This is achieved by placing the target and an angle of 20 degrees to the central ray of the X-ray beam.

Heat dissipation

1. Oil surrounding the X-ray tube. The main function of the oil is electrical insulation.
2. Tungsten target imbedded copper, a good conductor of heat.
3. Rotating anodes - larger medical X-ray machines.

Power Supply

The primary function of the power supply of an X-ray machine are

1. provide low voltage current to heat the filament by use of a step down transformer.
2. generate high potential difference between the cathode and the anode by utilizing a high voltage [autotransformer] transformer.

Transformers consist of 2 wire coils wrapped around a closed, rectangular core. The circuit through which the energy initially passes is the primary circuit / coil. When current flows through the primary coil, it creates a magnetic field within the core and this magnetic field induces a current in the secondary coil. The voltage in the two circuits is proportional to the number of turns in the two coils. If the if the initial potential difference is 100V and primary coil has 100 turns and the secondary coil 30,000 turns, the potential difference across the secondary coil will be

$$\frac{100}{30{,}000} \times \frac{100}{V} \qquad V = 30{,}000V$$

The step down transformer reduces the voltage of the incoming alternating current from 110 volts to about 10 volts [and to about 4 - 15 milliamps from 15 amps] and is controlled by the mA switch [on the control panel] which in turn regulates the temperature of the filament. The electrons emitted at the cathode are directed toward the anode and constitute the tube current.

The output of the autotransformer [step-up] is regulated by the kVp dial [on the control panel] and controls the voltage between the cathode and the anode. The greater the potential difference between the cathode and the anode, the faster the electrons will travel toward the anode, the

greater will be the change in velocity and the greater will be the kVp. [penetrating power] produced. The energy travels in a wave. The longer the wave length (kVp) , inversely proportional the lower the intensity of the beam. Or the shorter the wavelength, the greater the penetrating power - and this is what you want.

Hertz.

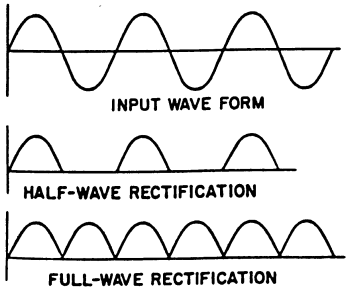
The line current from the plug in the wall is alternation current [AC] and has 60 cycles per minute. This is known as the Hertz. This means that in one second there are 60 pulse alternating in each direction making a total of 120 pulses. The current is permitted to travel in one direction only so that the current can only flow

Rectification

Rectification is the process of changing alternating current into direct current.

Half wave rectification.

The **rectifier** blocks current flow in the inverse half of the electrical cycle resulting in the flow of the current in one direction only and this is known as **half wave rectification** and also as **self rectification**. This is the current found in most dental X-ray machines. Larger X-ray machine use **full wave rectification**



Recently some X-ray manufacturers have used **amplifiers** to increase the number of cycles and are claiming that they are obtaining a **continuous direct current r**esulting in a current that has higher energy at the same voltage.

Timer.

The timer must be of the dead **man type** of switch so that the radiation to the patient can be stopped for any reason [such as patient movement]. When the timer switch is pressed the current initially passes through the step down transformer and heats up the filament to the temperature determined by the mA setting. The second current then is switched on and the electrons are directed to the anode.