The Discovery

- Roentgen discovered x-rays on November 8th, 1895
- Using a cathode ray tube and a piece of cardboard painted with platinocyanide, he was able to see a fluorescent glow in his darkened laboratory

The first radiograph – Mrs. Roentgen’s hand

Source: http://compepid.tuskegee.edu/syllabi/clinical/small/radiology/chapter2.html
Enter Dentistry

This radiograph was made on February 1st, 1896 by Dr. Walter Konig of Germany.

The Dangers

Although many had noted difficulties associated with "X-ray burns," it was not until the death of Clarence Dally (1865-1904), Edison’s longtime assistant in X-ray manufacture and testing, that observers finally agreed that the magic rays could kill as well as cure.

Roentgen’s Apparatus

HITTORF-CROOKES’ TUBES

Forces

- Electrostatic forces maintain electrons in the shells (e- and protons)
- Centrifugal forces of revolving (orbiting) electrons balance electrostatic forces
- Electron binding energy (ionization energy) – amount of energy required to remove an e- from its shell, specific for each shell

Radiation Physics
Forces

- Energy required to remove e\(^-\) from a given shell must exceed the electrostatic force of attraction between e\(^-\) and the nucleus
- Electrons in the K shell have the greatest binding energy due to the proximity to the nucleus
- Binding energy of e\(^-\) in successive shells decreases

Ionization

- An electrically neutral atom loses an electron
- Atom becomes positively charged ion
- Electron becomes a free, negatively charged ion
- Occurs by heating, collisions with high energy x-rays or particles
- Usually, outer shell electrons are lost

Radiation

- Transmission of energy through space and matter
- Occurs in two forms
  - Particulate radiation
  - Electromagnetic (EM) radiation

Particulate Radiation

- Atomic nuclei or subatomic particles
  - Move at high speed
  - Include
    - α particles
    - β particles
    - Cathode rays

Cathode Rays

- High speed electrons
- Man-made
  - X-ray tubes
  - Television sets (CRTs, not flat panel)
  - Computer screens (CRTs, not flat panel)
  - Cathode ray tubes

Linear Energy Transfer (LET)

- Capacity of particulate radiation to ionize atoms depends on mass, velocity, and charge of the particle
- Rate of loss energy from particle as it moves along its track through matter is the Linear Energy Transfer
Linear Energy Transfer (LET)
- Greater physical size and charge and lower velocity, the greater the LET
  - α particles transfer more energy in a given path than β particles and are therefore more damaging per unit dose
  - Both penetrate a relatively small distance into tissue

Electromagnetic Energy
- Movement of energy through space or matter as a combination of electric and magnetic fields
- Includes radio waves, radiant heat, visible light, and γ radiation
- Generated when the velocity (speed) of an electrically charged particle is altered
- Ionizing or non-ionizing
- Enough energy will knock an orbital electron out of its shell – ionizing radiation

Dual Nature of Energy
- Wave Theory – energy moves forward similar to a wave in water and travels at the speed of light in a vacuum
- Quantum Theory – energy moves as finite bundles or packets of energy (quanta of photons), with each photon moving at the speed of light and containing a specific amount of energy – an electron volt (eV)

Wave Theory
- Waves consist of electric and magnetic fields oriented in planes at 90º to each other
- Electric and magnetic waves oscillate perpendicular to the direction of the motion

Figure 1
**X-ray Machine**

- Distinguish between
  - X-ray - an invisible beam of energy
  - X-ray receptor
  - Radiograph

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**Definitions**

- An **x-ray** is an invisible beam or photon of energy.

![Image of Photon Emission](Image courtesy of University of Pennsylvania)

**Definitions**

- **Image receptor** is the material on which the latent image is created. This may be a film, fluoroscope, or digital receptor. The receptor is processed, and a radiograph is made.

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**Intraoral Image Receptors**

- A 2 intraoral film
- Size 2 PSP plate
- Gendex #2 CCD sensor
- Schick #2 CMOS sensor

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**A radiograph** is the resultant image.
• X-ray tube is positioned within the tube head with some components of the power supply.
• Tube may be recessed within the tube head to improve the radiographic image quality.
Coolidge Tubes

• Basic design introduced in 1913
• Composed of
  – Anode
  – Cathode – source of electrons
  – Evacuated glass tube
• Electrons from cathode strike anode, producing x-ray photons

Coolidge Tubes

• Requires power supply to:
  – Heat the filament to generate electrons
  – Establish a high-voltage potential between the anode and the cathode to accelerate the electrons

X-ray Tube

Cathode

• Filament (source of electrons)
  – Coil of Tungsten wire 1 cm long and 0.2 cm in diameter
  – Mounted on 2 stiff wires for support and carrying electric current
  – Wires connect to high and low voltage electric sources
  – Incandescence of the wire causes the release of electrons (boiling off of electrons)
Cathode Features

- Focusing cup – negatively charged concave reflector (charge repels electrons)

Cathode

- Nickel or molybdenum focusing cup – directs the electrons produced by the filament toward the focal spot on the anode
- Electrons travel from cathode to anode by repellent forces on the negatively charged cathode and attractive forces on the positively charged anode

Anode

- Tungsten target embedded in copper stem
- Converts the kinetic energy of electrons from the filament into photon energy (x-rays)
- Inefficient process – 99% of energy is lost as heat

Rotating Anode

- Embedded in a large block of copper (a good thermal conductor)
  - Dissipates heat from the tungsten – reduces risk of target melting
- Insulating oil surrounds the x-ray tube
- Stationary anode

Modern Dental X-ray Tube

- Tungsten target
Coolidge X-ray Tube circa 1930

Focal Spot
- Area on target where focusing cup directs electrons from the filament
- Sharpness of radiographic image increases as the size of the focal spot decreases

Focal Spot
- Heat generated increases as the size of the focal spot decreases
- Target is angled to decrease effective focal spot size while maximizing distribution of electrons over a large target
- Projection of focal spot is 90º to the electron beam (effective focal spot is smaller than the actual focal spot)

Focal Spot
- Smaller focal spot = sharper images
Production of X-rays

- Current heats the filament of the cathode, releasing electrons – Thermionic Emission
- Higher temperatures produce more free electrons (electron cloud)
- Electrons accelerate from the cathode to the tungsten target on the anode
- X-rays are produced as the electrons decelerate or stop

Electric Circuits

- Electric current is the movement of electrons through a conductor
- Rate of flow (electrons/second past a set point) is measured in amperes
- Depends on voltage and resistance of the conductor to flow, measured in ohms
- Ohm’s law: \( V = IR \), \( V=\text{potential} \), \( I=\text{current} \), \( R=\text{resistance} \)

Power Supply

- Heats the filament using low-voltage current to generate electrons
- Establishes a high-voltage potential between the anode and the cathode to accelerate the electrons

Power Supply (Electric Circuits)

- Tube current (mA)
- Tube voltage (kVp)
- Together, mA and kVp determine the intensity of the x-ray beam, along with the target material and the filtration used

Tube Current (mA)

- Determines the number of electrons produced
- The higher mA, the greater the number of electrons generated, and consequently, the more x-rays produced
- Tube current is the flow of electrons from the filament to the anode, then back to the filament through wiring of the power supply
**Tube Current (mA)**

- Filament step-down transformer reduces voltage of the alternating current to ~ 10V
- Controlled by the mA switch, adjusting resistance and current through the low-voltage circuit
- Regulates temperature of the filament and number of electrons emitted

**Tube Voltage (kVp)**

- Requires high voltage between the anode and the cathode to generate x-rays
- Autotransformer converts the primary voltage from the input source to the secondary voltage
- High voltage transformer provides the high voltage required by the x-ray tube to accelerate electrons from the cathode to the anode

**Tube Voltage (kVp)**

- Peak voltage of the incoming line current is boosted to 60 - 100 kV
- Boosts peak energy of the electrons to 60 - 100 keV
- Line voltage is variable (alternating current), so intensity is greatest at peak of each positive portion of the cycle
- No x-rays are generated during the negative portion

**Half-Wave Rectification**

- AKA self-rectification
- Limits x-ray production to half of the AC cycle
- Almost all dental x-ray units are self-rectified

**Rectification**

- kVp determines the energy of the electrons that generate the photons from the target
- kVp determines the maximum energy (quality) of the x-rays produced
- For tungsten targets, at least 70 kVp must be used to produce the K-characteristic radiation
Filtration

- Removes low energy photons (long wavelength)
- Accomplished with an aluminum filter placed in the path of beam
- Preferentially removes low energy photons

Inherent Filtration

- Consists of materials in path of the photon beam from the focal spot to the point of exiting the x-ray head
- These include
  - Glass wall of the tube
  - Insulating oil
  - Barrier surrounding oil
- Ranges from 0.5 to 2.0 mm aluminum equivalent

Total Filtration

- Sum of inherent filtration and added external filtration
- External filtration consists of aluminum discs placed over the exit port of the tube head
- Federal regulations require 1.5 mm aluminum equivalent for beams up to 70 kVp and 2.5 mm for beams over 70 kVp

Half-Value Layer

- The thickness of any given material where 50% of the incident energy has been attenuated is known as the half-value layer (HVL). The HVL is expressed in units of distance (mm or cm). Like the attenuation coefficient, it is photon energy dependant. Increasing the penetrating energy of a stream of photons will result in an increase in a material’s HVL.

[Diagram from White & Pharoah 3rd Edition]

[Diagram from White & Pharoah 3rd Edition]

[Diagram from White & Pharoah 3rd Edition]
Collimation

Control Panel

- Controls power supply to the tube head
- Controls number of impulses generated (the exposure time)
- Controls the kVp
- Controls the mA

Control Panel

- Voltage Meter (kVp)
- Time Adjustment (Impulses)
- Exposure Switch
- Milliamperage Selector
- Power Indicator
- Exposure Indicator

Control Panel

- kVp Indicator
- mA Indicator
- Tooth Indicator
- Receptor Indicator
- Exposure Indicator
- Exposure Switch
Wave Theory

- Waves travel at the speed of light in a vacuum
- May be reflected, refracted, diffracted and polarized
- Waves have the properties of wavelength ($\lambda$) and frequency ($\nu$)
  \[ \lambda \times \nu = c = 3.0 \times 10^8 \text{m/sec} \]
  \( (186,000 \text{ miles/sec}) \)

Quantum Theory

- The actual energy is calculated using Planck’s constant ($6.62 \times 10^{-34}$ joules seconds [J.s]):
  \[ E = h \nu \]
- NB: photon energies are measured in kilo-electron volts (keV)
- Photons with 15 eV or higher of energy are capable of ionizing atoms or molecules.

Bremsstrahlung

- Braking radiation
- Process by which most x-rays are generated in a dental x-ray machine
- Kinetic energy is converted into heat (99%) and x-ray photons (1%)

Not Bremsstrahlung

Bremsstrahlung
Bremsstrahlung

• Primary source of x-ray photons from an x-ray tube
• Produced by the sudden stopping (braking) or slowing of high-speed electrons
• Electrons strike tungsten target, creating x-ray photons if the electron strikes a target atomic nucleus directly or passes close to the nucleus

Bremsstrahlung Radiation

• The closer the electron passes to the nucleus, the greater the change in direction of the electron, the greater the intensity of the energy given off
• Electrons participate in many Bremsstrahlung reactions, losing energy with each reaction, until they pass from the field or lose all their energy

Bremsstrahlung Radiation

• Most electrons past near or widely miss the nuclei
• Negatively charged electron is attracted toward the positively charged nucleus and loses some of its velocity
• Deceleration causes the electron to lose some kinetic energy, given off as a photon

Bremsstrahlung Radiation

• Produces photons with a continuous spectrum of energy (low energy to high energy)
• The energy of an x-ray beam may be described by identifying the peak operating voltage (kVp)
• 70 kVp refers to the fluctuating voltage across the tube (tube voltage), producing photons with energies ranging to a maximum 70,000eV (70keV)

Polychromatic Radiation

• Beam has varying energies and wavelengths
• Beam must be filtered to remove long wavelength, low energy photons
• Beam must be collimated to limit the size of the diameter
Primary Radiation

- Main beam from the tungsten target
- Used to record an image on the x-ray film
- Central portion of main beam is known as the central ray or the central beam

Secondary Radiation

- AKA scatter radiation
- Primary radiation that reflects from the patient and other objects (walls, ceiling, floor, dental unit, etc.)
- Detracts from image quality

Ionizing Radiation

- Ion – an atom that has gained or lost an electron (a charged particle)
- Ionizing radiation causes the loss (or gain) of an electron in a molecule in a cell that may result in cell damage or death
- Higher radiation doses cause damage or death to greater numbers of cells

Characteristic Radiation

- Occurs when an electron from the filament displaces an electron from an inner shell, causing ionization of the tungsten atom
- An outer shell electron drops in to fill the void in the inner shell, emitting a photon with energy equivalent to the difference in the orbital binding energies

Characteristic Radiation

- Atomic number of the target material determines the energy of the characteristic x-rays produced
  - Tungsten (74) – 57 to 69 keV
  - Tin (50) – 25 to 29 keV
  - Lead (81) – 72 to 88 keV
**Milliamperes (mA)**

- Size of the electron cloud
- Number of electrons and, subsequently, photons formed
- Quantity
- Density of the film
- mAs (milliAmperes/second) – exposure time

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**Peak Kilovoltage (kVp)**

- Tube Voltage
- Wavelength-short wavelength, better penetration
- Penetrating power
- Quality of the beam – number of photons generated
- Gray scale of the film

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**Power Supply**

Primary functions

- Provide low voltage current to heat the filament, using a step-down transformer
- Generate a high potential difference between the cathode and the anode, using a high voltage transformer (autotransformer)

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**Transformers**

- Two wire coils wrapped around a closed core
  - First coil is the primary circuit
  - Second coil is the secondary circuit
- Current flowing through the primary coil creates a magnetic field within the core
- The magnetic field induces a current in the secondary coil

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**Coherent (Thompson) Scatter**

Coherent scatter occurs when a photon with less energy than the binding energy of the electron it strikes is absorbed exciting the electron. The atom responds by ejecting a photon of equal wavelength and frequency to the incident photon, but in a random direction.
**Photoelectric Effect**
- Important to imaging
- Incoming photon ceases to exist
- Energy is used to eject an electron from its orbit

**Compton Scatter**

**Radiobiology**

**Absorbed Dose**
Radiation exposure is measured in an international (SI) unit called the gray (Gy). The radiation exposure is equivalent to the energy “deposited” in a kilogram of a substance by the radiation. Exposure is also referred to as absorbed dose. The important concept is that exposure is measured by what radiation does to substances, not anything particular about the radiation itself. This allows us to unify the measurement of different types of radiation (i.e., particles and wave) by measuring what they do to materials. The gray is a large unit and for normal radiation protection levels a series of prefixes are used:
- nanogray (nGy) is one thousand millionth of a gray (1/1,000,000,000)
- microgray (µGy) is one millionth of a gray (1/1,000,000)
- milligray (mGy) is one thousandth of a gray (1/1,000)

**Equivalent Dose**
Often we are interested in the effect of radiation exposure on human tissue. Enter a quantity called equivalent dose. This relates the absorbed dose in human tissue to the effective biological damage of the radiation. Not all radiation has the same biological effect, even for the same amount of absorbed dose. Equivalent dose is measured in an international (SI) unit called the Sievert (Sv). Like the gray, the sievert is a large unit and for normal radiation protection levels a series of prefixes are used:
- nanosievert (nSv) is one thousand millionth of a Sievert (1/1,000,000,000)
- microsievert (µSv) is one millionth of a Sievert (1/1,000,000)
- millisievert (mSv) is one thousandth of a Sievert (1/1,000)

**Effective Dose**

The probability of a harmful effect from radiation exposure depends on what part or parts of the body are exposed. Some organs are more sensitive to radiation than others. A tissue weighting factor is used to take this into account. When an equivalent dose to an organ is multiplied by the tissue weighting factor for that organ the result is the effective dose to that organ. The unit of effective dose is the sievert (Sv).

If more than one organ is exposed then the effective dose, $E$, is the sum of the effective doses to all exposed organs.


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**Limit of X-ray exposure for Radiation Workers**

- **Staff**
  
  5 REM = 5000mREM = 5 Sv per yr

- **Pregnant Staff**
  (after official declaration)
  0.5Sv per pregnancy

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**Image Receptors – Film**

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**Film**

![Diagram of film structure](image)
Dose Reduction: Improvements In Film

Emulsion

- Covers both sides of base
- Flexible to allow film to bend
- Thin homogenous mixture of pure gelatin containing silver halide grains sensitive to light and photons

Film types

- All X-ray film is sensitive to both X-ray photons and visible light
- Intraoral film is called direct exposure film and is intended to be exposed by X-ray photons only
- Direct exposure film produces high resolution images, but requires a relatively high dose of radiation

The Film Packet

Image from White & Pharoah 5th Edition
Screen film

- USED FOR EXTRAORAL IMAGING
- ALWAYS USED WITH INTENSIFYING SCREENS
- DECREASED RESOLUTION WHEN COMPARED TO DIRECT FILM
- USES A LOWER DOSE OF IONIZING RADIATION TO CREATE THE LATENT IMAGE

Common Oral & Maxillofacial Projections Where Screen Film is Used:
- PANORAMIC
- LATERAL AND POSTERO-ANTERO CEPHALOMETRIC
- SKULL FILMS
  - PA
  - TOWNES
  - WATERS
  - LATERAL OBLIQUE

Screen film

- SCREEN FILM IS DESIGNED TO BE SENSITIVE TO BOTH X-RADIATION AND VISIBLE LIGHT RADIATION. SPECIAL DYES ARE INCLUDED IN THE EMULSION SO THAT IT IS SENSITIVE TO CERTAIN WAVELENGTHS OF LIGHT. THESE WAVELENGTHS ARE EMITTED BY THE INTENSIFYING SCREENS.

Fluorescence

Image from White & Pharoah 5th Edition

Cassettes

Image from White & Pharoah 5th Edition
Radiographic Density

- The overall degree of darkening of the radiographic image. Three factors which determine radiographic density are:
  - Exposure
  - Subject thickness
  - Object density

Radiographic Density

Exposure
- Determines the # of photons that are absorbed by the emulsion
- Four exposure factors
  - kVp
  - ma
  - Impulses (time)
  - Source to film distance

Radiographic Density

Subject thickness

Radiographic Density

Object Density. The denser the object and higher the atomic #, the better the absorption of photons.

Radiographic Density

- In decreasing order of density:
  - Metallic restorations
  - Enamel
  - Dentin
  - Bone
  - Fat/fluid
  - Air
Radiographic Contrast

- The difference in densities between adjacent areas of the image
- Influenced by:
  - Subject contrast
  - Film contrast
  - Beam energy and intensity
  - Fog and scatter radiation

Radiographic Contrast

- By adjusting kVp, contrast can be varied
  - **High contrast films** can enhance detection of lesions where subject contrast between the lesion and healthy tissue is low
  - Examples include:
    - Caries
    - Apical lucencies

Radiographic Contrast

- By adjusting kVp, contrast can be varied
  - **Low contrast films** can enhance detection of subtle findings.
  - Examples include:
    - Calculus
    - Soft tissue outlines
    - Small changes in crestal bone
Resolution
- Generally expressed as line pairs per millimeter (lp/mm)

Thank you!