Physics for Mammography

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Bushberg,Seibert, Leidholdt & Boone, The Essential Physics of Medical Imaging, 3rd edition, 2011

Physics

- Influences our decision-making in selection of imaging equipment & appropriate technical factors for individual patients

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Physics

- Study of energy & matter, & the relationship between the two
- In diagnostic imaging, we use varied sources of energy to image many different types of tissue (matter)

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Physics

- Tube construction
- X-ray generation
- X-ray spectrum produced
  - Resulting affect on image contrast

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Atom

- In Greek, the word atom means "indivisible"
- The smallest particle of an element that still retains the characteristic properties of the element

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Niels Bohr 1885-1962

- Bohr described the true structure of an atom in 1913
- He discovered the basic atomic structure—a positively charged nucleus surrounded by orbiting electrons , which laid the groundwork for how we understand atoms today

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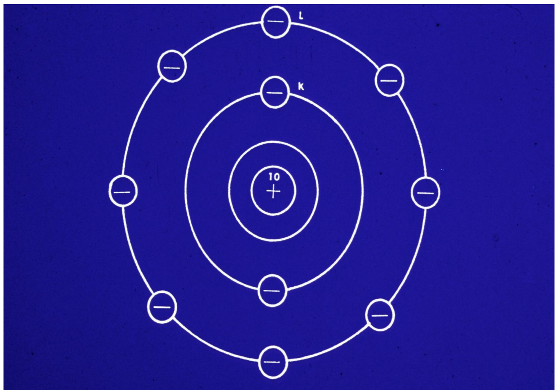
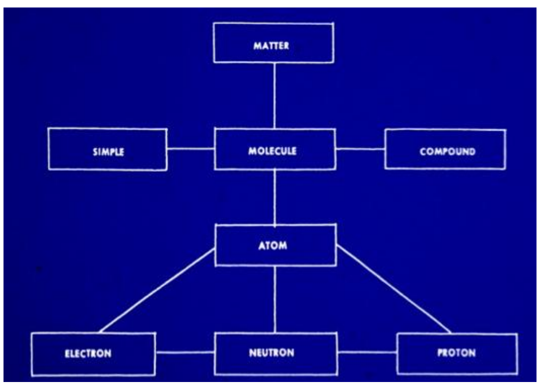


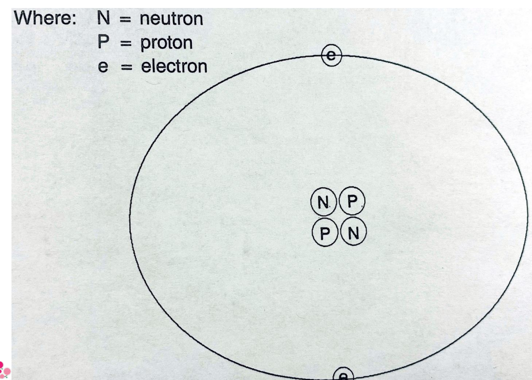
FIGURE 1. — THE ATOM

Source: Campeau, Fleitz. Limited Radiography, 2017.

Nucleus

- Center of the atom
- Contains almost the entire mass of the atom
- Contains 2 main types of particles (collectively called nucleons)





Source: Campeau, Fleitz. Limited Radiography, 2017.

Electrons

- Each carries a single negative charge
- Each moves in its own path, or orbital

Orbitals or Shells

- These shells are identified by letters of the alphabet
- The innermost is the K shell; the next L, and so on until Q

Orbitals

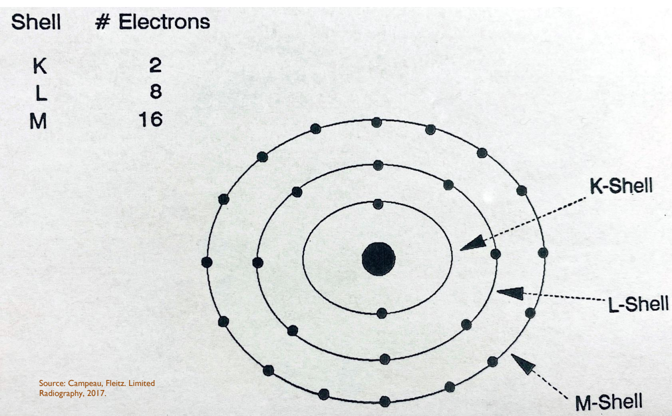
- There is a specific maximum number of electrons that can occupy a particular shell
- This can be determined by the formula:
  - $2(n)^2$

Orbitals or Shells

K shell	2 electrons
L shell	8 electrons
M shell	18 electrons
N shell	32 electrons

A shell <u>may</u> contain fewer electrons than the maximum allowable, but may not contain more

Sulfur atom



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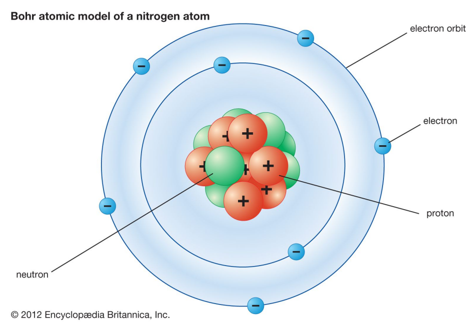

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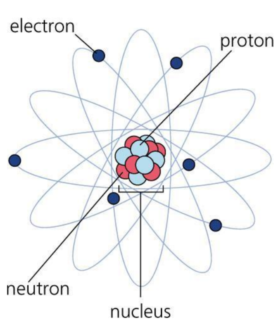


Bushberg,Seibert, Leidholdt & Boone, The Essential Physics of Medical Imaging, 3rd edition, 2011.

Nucleons

Protons

- Positively charged

Neutrons

- Electrostatically neutral
  - Carries no charge

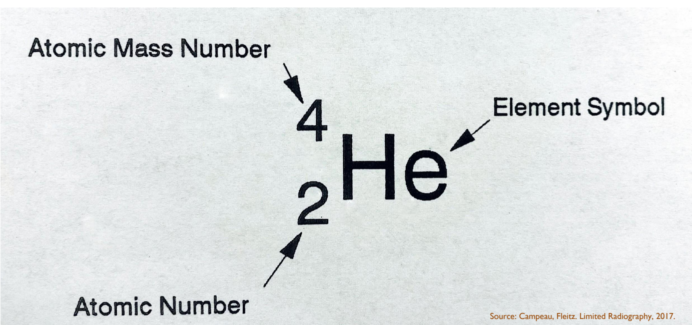
Atomic Number

- What determines the identity of an element?
- The number of nuclear protons, or arrangement of orbital electrons

Atomic Number (z)

- The number of protons (+) in the nucleus of an atom denotes its atomic number
- Total number of protons + neutrons denotes Atomic Mass Number (nucleons)

Periodic table nomenclature



Isotopes

- Atoms with the same number of protons, but a *different* number of neutrons are called isotopes.

(Same Z, but different AMN)

Hydrogen isotopes

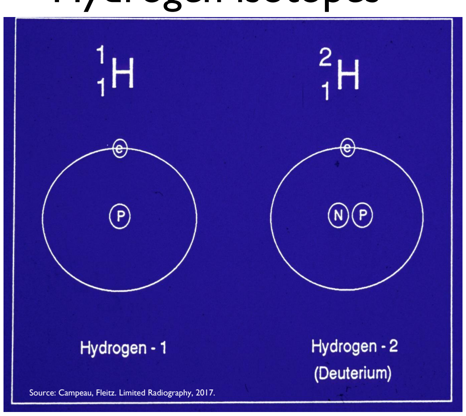


TABLE 5–3 ELEMENTS IMPORTANT TO RADIOLOGY

CHEMICAL SYMBOL	ELEMENT	ATOMIC NUMBER (Z)	ATOMIC MASS NUMBER (A)
C	Carbon	6	12
O	Oxygen	8	16
Al	Aluminum	13	27
Ca	Calcium	20	40
Fe	Iron	26	56
Cu	Copper	29	63
Mo	Molybdenum	42	98
Ru	Ruthenium	44	102
Ag	Silver	47	107
Sn	Tin	50	120
I	Iodine	53	127
Ba	Barium	56	138
W	Tungsten	74	184
Pb	Lead	82	208

Source: Campeau, Fleitz. Limited Radiography, 2017.

Law of Electrostatics

- Like charges *repel* each other, and
- Unlike or opposite charges *attract*

Law of Conservation of Energy

- Energy cannot be created or destroyed; it can only change form

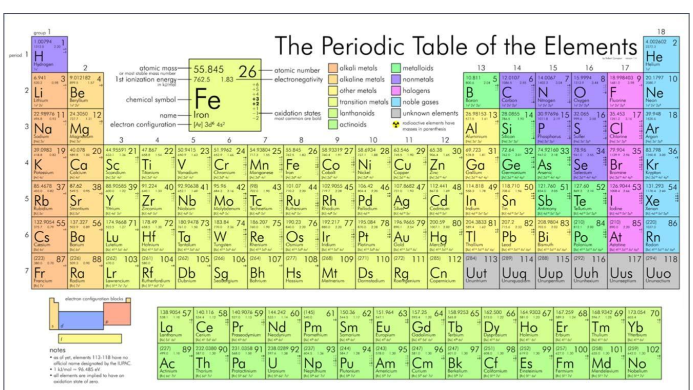
4 conditions required for production of X-rays:

- Source & Separation of electrons
- Production of high speed electrons
- Focusing of the electrons
- Stopping of electrons- in the target

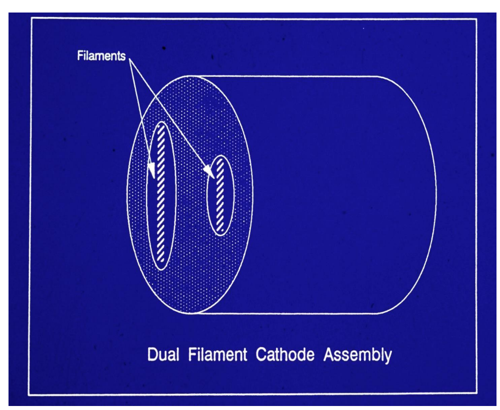
Separation of electrons

- Certain substances, when heated, readily give off electrons in a process called *Thermionic Emission*
- These substances are in the family of metals and have a relatively high atomic number (z)

Periodic table



https://www.relypsa.com/file.cfm/130/docs/periodic-table-of-elements4.jpg



Source: Campeau, Fleitz. Limited Radiography, 2017.

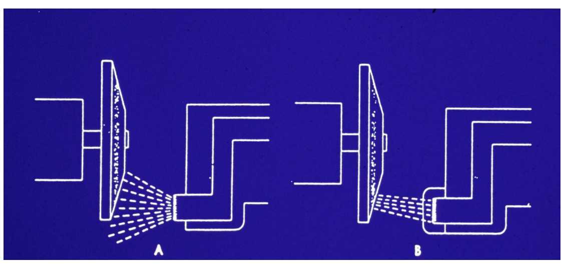
Production of high-speed electrons

- High potential difference (kVp)
- Electrostatics also drive electrons from cathode (-) to anode (+)

Focusing of electrons

- Mo focusing cup
- "Focuses" electron beam
- Results in smaller target area and more efficient production of x-rays

Focusing of electrons



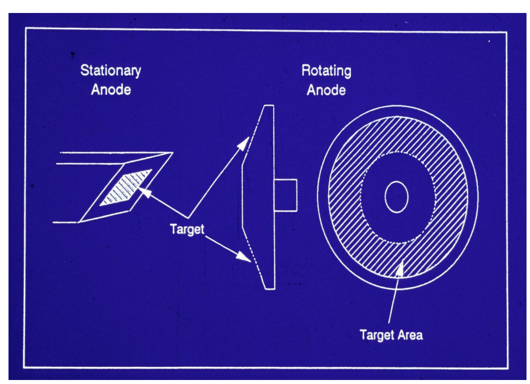
Source: Campeau, Fleitz. Limited Radiography, 2017.

Stopping of high speed electrons

- More than 99% of the kinetic energy imparted to the electrons is converted to heat on the anode
- Remaining 1% is emitted as useful xrays
- This Total Energy transfer= 99% heat (thermal) and 1% X-ray

Total Energy Transfer

- The heat must be transferred or the target would melt
- To help dissipate this heat, the anode is rotating

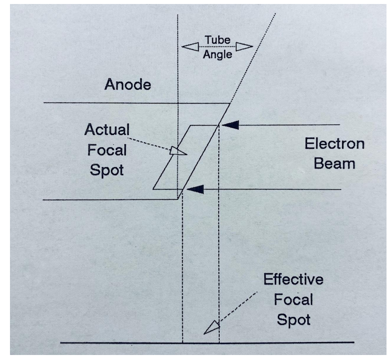


Source: Campeau, Fleitz. Limited Radiography, 2017.

Anode

- The target face is cut diagonally
- The target is cut on a diagonal so that the emitted x-rays fly off the surface at an angle different from the incident electrons
- A 45° cut makes the x-rays exit perpendicular to the axis of the tube
- Is usually coated with some other metal

Anode



Source: Campeau, Fleitz. Limited Radiography, 2017.

Xray Production

- X-rays are produced by *energy conversion* when fast-moving electrons from the filament of the x-ray tube interact with the anode (target)

X-ray production

Two concurrent processes:

- Characteristic radiation &
- Bremsstrahlung radiation

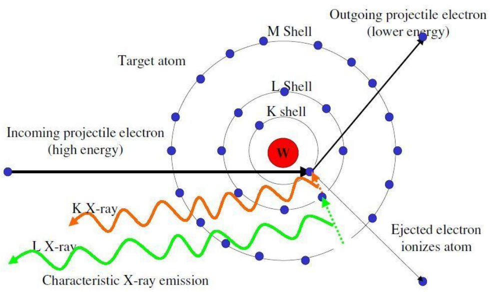
Characteristic Radiation

- One mechanism by which xrays are produced is through transition of electrons between atomic orbits
- Interaction with electrons in the shells or orbitals
- These transitions involve the movement of electrons from outer orbits to vacancies within inner orbits

Characteristic Radiation

- In making such transitions, electrons emit photons of x-radiation with discrete energies
- Because such x-rays are distinctive for the particular element and transition, they are called ***characteristic x-rays***

Characteristic X-Ray Production



Bushberg,Seibert, Leidholdt & Boone, The Essential Physics of Medical Imaging, 3rd edition, 2011.

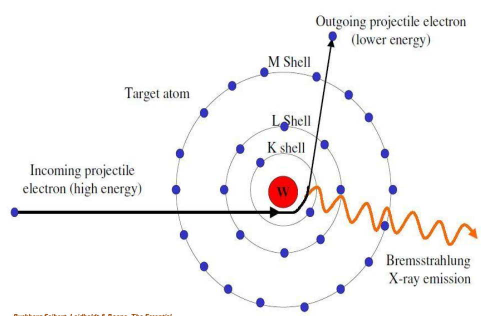
Characteristic Radiation

- Monoenergetic
- Homogeneous beam produced
- “clones” – all alike

Bremsstrahlung Radiation

- This mechanism involves the rapid deceleration of a high speed electron as it enters the electrical field of a nucleus
- During this process the electron is deflected and emits a photon of x-radiation
- This type of x-ray is often referred to as bremsstrahlung or "braking radiation”
- Output is a spectrum of X-ray energies

Continuous (Bremsstrahlung) X-Ray Production



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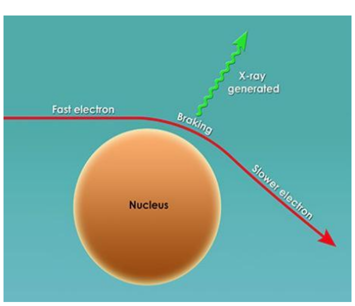
Bremsstrahlung Radiation

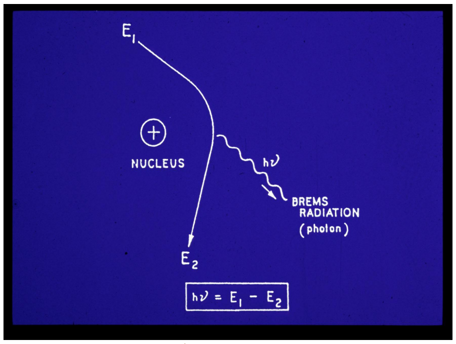


Bushong, Radiologic Science for Technologists : Physics, Biology & Protection,11th edition, 2016

Bremsstrahlung Radiation “braking”

- Interaction with the nucleus of the target (anode) atom
- Lost kinetic energy of slowing down is radiated as an x-ray of equivalent energy

Incoming energy wavelength minus the loss of speed equals outgoing energy wavelength



Curry, Dowdey & Murry, Christensen's Physics of Diagnostic Radiology,4th edition,1990.

Brems Radiation

- Polyenergetic; many energy levels
- Heterogeneous beam
- The wavelength of x-rays in the "continuous" spectrum varies
- "Cousins" – from the same family, but vary

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Brems-Continuous Spectrum

- This variation is produced by the different energies with which the electrons reach the target
- Most electrons give up their energy in stages, rather than all at once

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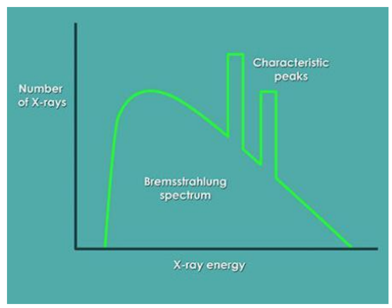
The X-ray spectrum



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X-ray Tube Construction

Two parts:

- Cathode
- Anode

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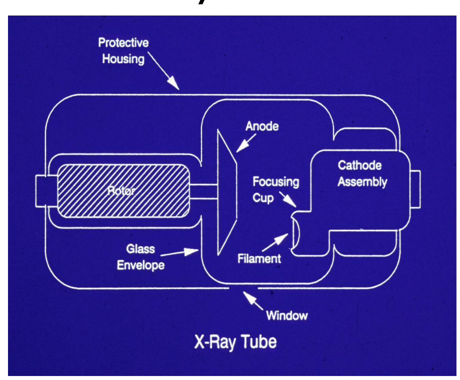
X-ray tube



Source: Campeau, Fleitz. Limited Radiography, 2017.

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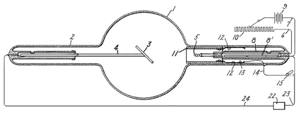
Xray tubes



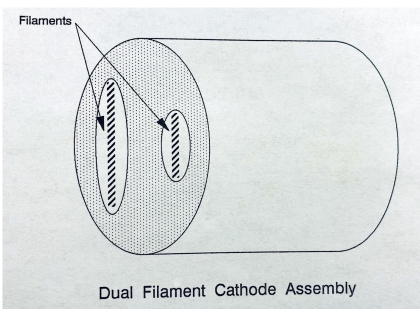
- Most x-ray tubes in use today are "filled" with a vacuum
- This "entirely new variety" of x-ray tube was invented in 1913 by the American electrical engineer William Coolidge (1873–1975)
- Nearly every incandescent light bulb made after 1913 contains a tungsten filament made using Coolidge's process

Bushberg,Seibert, Leidholdt & Boone, The Essential Physics of Medical Imaging, 3rd edition, 2011.

Cathode

- Electron source (emitter)
- The cathode is a coiled filament of wire heated to around 2000 °C
- In a sense, the electrons "boil" off the metal surface
- The ones that leave are always replaced by new ones
- Electrons produced in 2 filaments, which correspond to the large, small focal spots

Cathode



Source: Campeau, Fleitz. Limited Radiography, 2017.

Cathode (electron emitter)

Composed of 2 parts:

- Tungsten wire, formed into a helix
- Focusing cup (Mo)

Anode

- Electron receptor or "target"
- Kinetic energy of electrons is transformed to the radiant energy of x-rays

Anode (electron receiver)

- May be composed of a single material or more commonly, a composite

Example: Tungsten/Rhenium
Molybdenum/Vanadium

Interaction between X-rays & tissues

- Before understanding the final production of an X-ray image, it is essential to understand the interaction of X-rays with individuals exposed to X-rays
- There are 3 important types of interactions that occur between xrays & the tissues of the body

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Interaction between Xrays & tissues

1. "Classical" or "coherent" interactions occurs when an xray strikes an orbital electron, bounces off & changes direction

a. These are low energy & do not cause ionization

b. They add only a small dose to a patient

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Interaction between Xrays & tissues

2. In "Compton" scattering, xrays of higher energy strike an outer shell electron & are strong enough to remove it from the shell, causing ionization of an atom

a. This contributes to dose & also contributes to scatter

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Compton Scattering

- Some scattered photons expose the image receptor and decrease contrast
- With higher photo energies (>20 keV), Compton's is much more likely to occur that *Photoelectric Absorption*
- Compton's is the predominant interaction in diagnostic radiology

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Photoelectric Effect

3. "Photoelectric interactions occur when an incoming xray strikes an inner shell electron, removing it from the shell, & causing a cascade of outer shell electrons filling inner orbit vacancies

a. Contributes to image contrast

- *Photoelectric Effect*
  - With low x-ray photo energies (>20 keV), photoelectric absorption dominates

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X-ray/Tissue Interactions

- With *Photoelectric effect*, the incident electron transfers all of its energy to a electron, ejecting the electron from its atom
- This increases subject contrast because there is no scatter to degrade the image
- However, increases dose to the patient

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Dedicated Mammography Units

- Dedicated mammography units are designed to maximize the probability of *Photoelectric Absorption* and decrease the probability of *Compton scattering*

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Dedicated Mammography Units

- The selective combination of anode materials, electron energies and filtration produces an x-ray spectra rich in photo-energies of 15-20 keV

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Dedicated Mammography Units

- The variation of kVp combined with Mo or Rh filtration allows spectral shaping over a wide range of photo energies

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Dedicated Mammography Units

- An increase in the energy spectrum can be achieved by:
- Increasing kVp
- Using anode materials with higher characteristic energy emissions
- Using k-edge filtration, or combinations or both

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Summary: X-ray Production

- In the generation of X-ray production, a cathode filament is activated causing intense heating of the cathode filament
- Heating of the filament leads to release of electrons in a process called thermionic emission
-

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Summary: X-ray Production

- The released electrons form an electron cloud at the filament surface, and repulsion forces prevent ejection of electrons from this negatively charged cloud
- Upon application of a high voltage by an X-ray generator to the cathode as well as the anode, there is an acceleration of electrons ejected to an electrically positive anode

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Summary : X-ray Production

- Thermal energy allows electrons to form a space cloud in the vacuum
- Application of an electric field allows the electrons to be collected on an anode

Summary: X-ray Production

- A tungsten wire is used in most x-ray tubes to take advantage of the high temperature for melting
- Once the high kinetic energy electrons finally reach the anode target, this initiates the process of X-ray production

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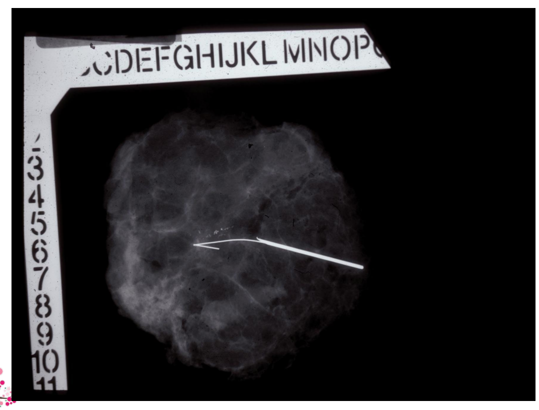

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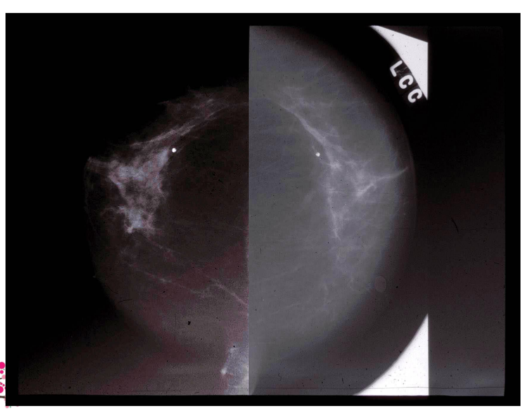

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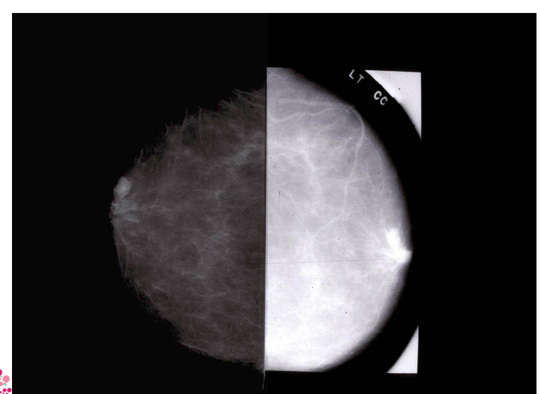

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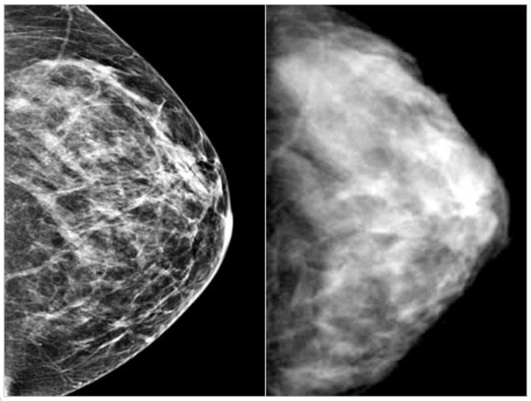

Evolution of Breast Imaging

- Utilizing principles of Physics, the practice of breast imaging has transitioned through a wide variety of technological advances from the early days of mammography

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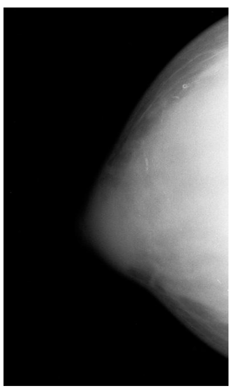
Evolution of Breast Imaging

Direct exposure without compression



Sickels E. 2014

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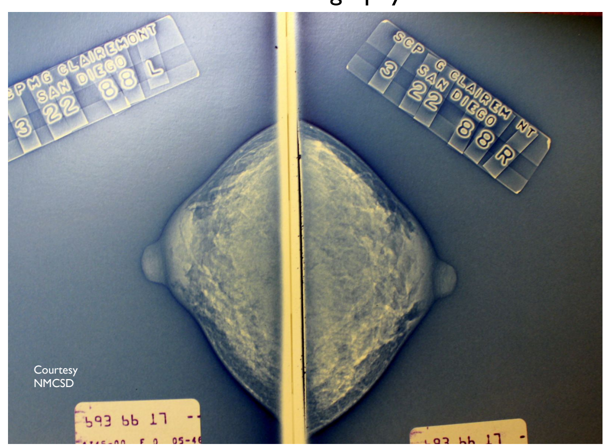
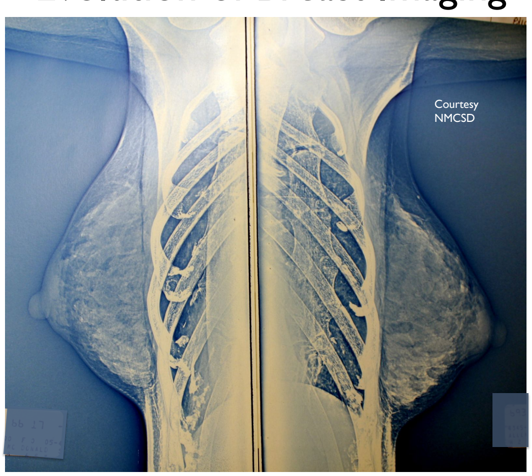
Evolution of Breast Imaging

Xeromammography

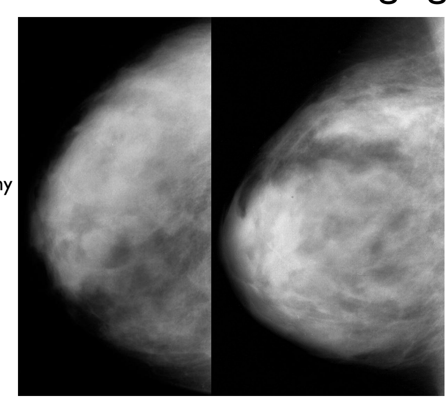


Evolution of Breast Imaging



Evolution of Breast Imaging

Film/Screen Mammography



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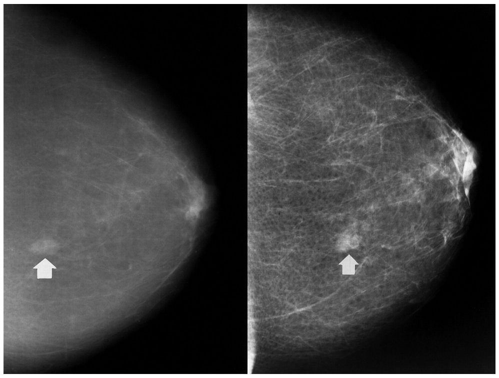
LCC views with fibroadenoma



Sickels E. 2014

Evolution of Breast Imaging

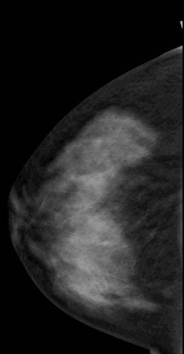
FFDM
Mammography

Courtesy NMCSD

Evolution of Breast Imaging

- In 2011, Hologic introduced DBT or Digital Breast Tomosynthesis (with FDA approval)
- Requires longer imaging time (more images) & slightly more dose
- To solve these challenges, machine uses a Tungsten (W) anode with various filtration options (Rh, Ag & Al)
- Overcomes the problems of superimposition or summation of tissues

3D- Tomo



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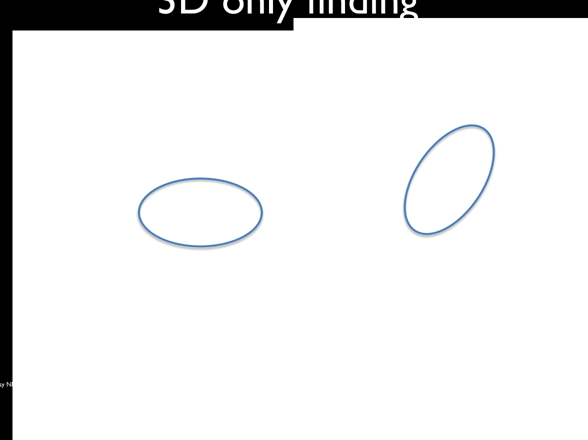
3D only finding



Courtesy N

Evolution of Breast Imaging

- Numerous major advances in breast imaging over the past 30+ years
- This permits more accurate diagnosis of benign breast disease
- Also, more importantly, enables the earlier diagnosis & more effective preoperative staging of breast cancer

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Evolution of Breast Imaging

- Like all other radiologic subspecialties, Breast imaging is a “Work in Progress”
- Expectation for future advances to be at least as important & valuable as those that have taken place in the last few decades
- ALL are based on utilization of the principles of Physics

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Physics

- Rather than viewing Physics as a “*dreaded foreign language”,* we need to view it as a necessary “bag of tricks” at our disposal to use every day

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