UNIVERSITY OF MICHIGAN
Michigan Engineering

NERS/BIOE 481

Lecture 01
Introduction

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Henry Ford Health System
RADIOLOGY RESEARCH

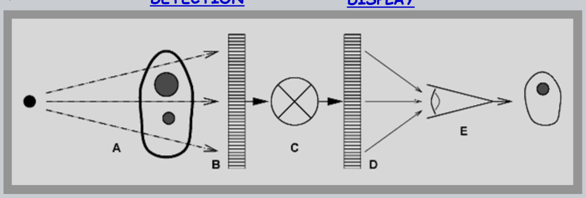
I.A – Imaging Systems (6 charts)

A) Imaging Systems
1) General Model
2) Medical diagnosis
3) Industrial inspection

I.A.1 - General Model – xray imaging

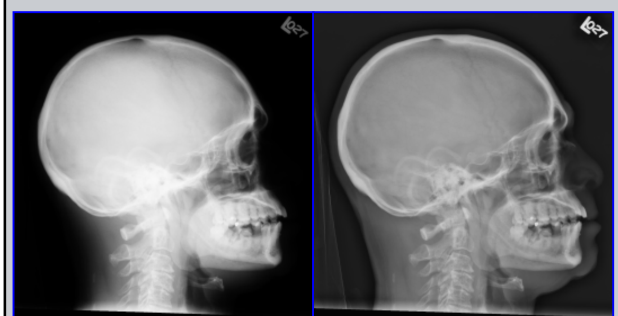
Xrays are used to examine the interior content of objects by recording and displaying transmitted radiation from a point source.

DETECTION DISPLAY



(A) Subject contrast from radiation transmission is
(B) recorded by the detector and
(C) transformed to display values that are
(D) sent to a display device for
(E) presentation to the human visual system.

I.A.2 - Medical Radiographs



Traditional Film-screen Radiograph | Modern Digital Radiograph

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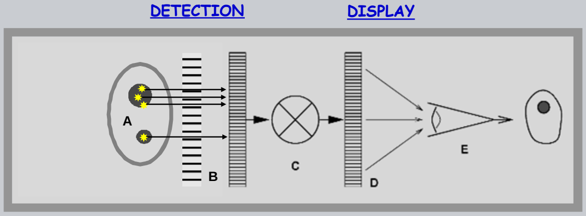
I.A.1 - General Model – radioisotope imaging

Radioisotope imaging differs from xray imaging only with repect to the source of radiation and the manner in which radiation reaches the detector

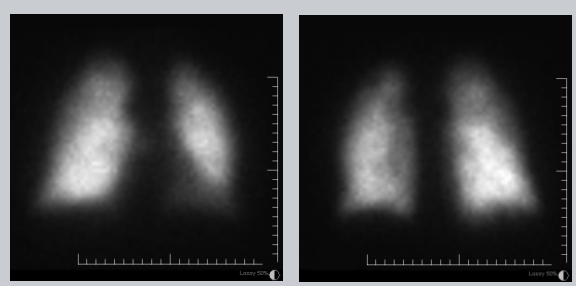
DETECTION DISPLAY



Pharmaceuticals tagged with radioisotopes accumulate in target regions. The detector records the radioactivity distribution by using a multi-hole collimator.

I.A.2 - Medical Radisotope image

Radioisotope image depicting the perfusion of blood into the lungs. Images are obtained after an intra-venous injection of albumen microspheres labeled with technetium 99m.

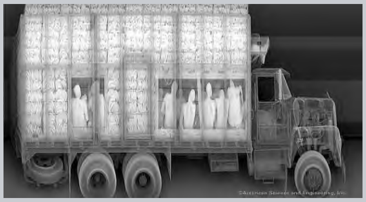


Anterior | Posterior

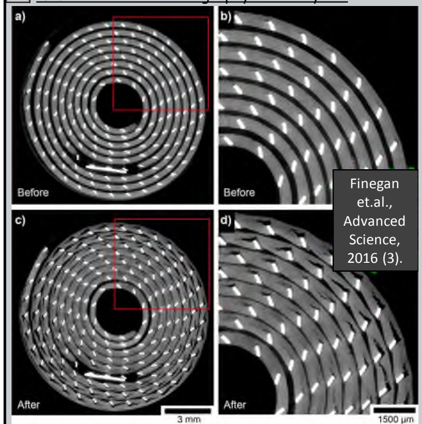
I.A.3 - Industrial Radiography – homeland security

Aracor Eagle

High energy x-rays and a linear detector are used to scan large vehicles for border inspection



I.A.3 - Industrial radiography – battery CT



Finegan et.al., Advanced Science, 2016 (3).

CT image of a lithium battery (Duracell CR2)

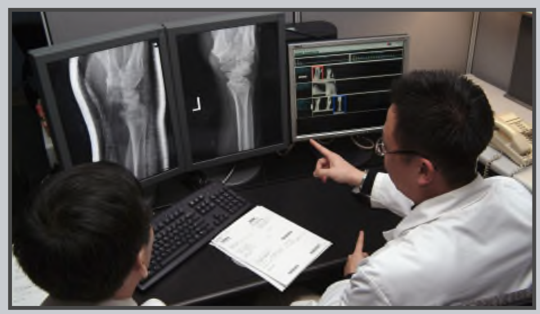
"Tracking the dynamic morphology of active materials during operation of lithium batteries is essential for identifying causes of performance loss". CT images (left) show changes before and after battery discharge.

I.B– Modern Radiation Imaging (15 charts)

B) Modern Radiation Imaging
1. Electronic Imaging
2. Digital Radiography
3. X-ray computed tomography
4. Radioisotope imaging
5 Emission tomography
   a. SPECT
   b. PET

I.B.1 – Electronic imaging

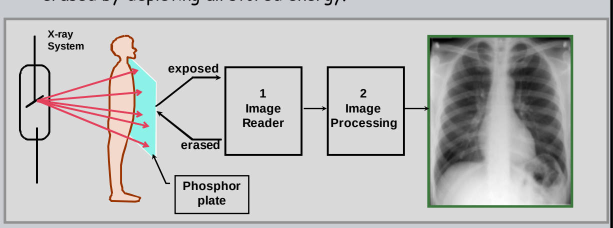
- Radiology is now practiced at most centers using computer workstations to retrieve images from storage servers.
- High fidelity, monochrome LCD monitors with 3 to 5 megapixels are used with zoom & pan inspection of specific areas in high detail.



I.B.2.a – CR systems, 1985

- Storage Phosphor Radiography (CR, Computed Radiography)
- Phosphor plate in a standard cassette are exposed using conventional Buckey devices.
- Energy deposited in the plate forms a latent image that is read by a scanned laser.
- After a digital image is read, the plate is erased by depleting all stored energy.

CR Plate Reader

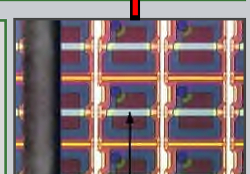


I.B.2.b – Digital Radiography, DR, 2000

Amorphous Silicon Flat Panel Detectors

Flat panel digital radiography detectors integrate the absorbtion of radiation and the electronic readout in a single panel

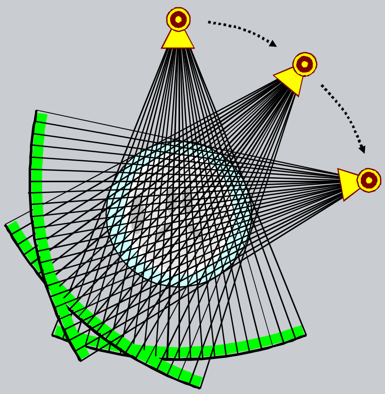
Electronic circuits made of amorphous silicon form thin film transisters (AM-TFT) that read charge created by x-rays. The AM-TFT technology is similar to that used in common LCD displays



Human hair for size reference

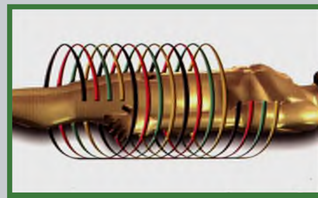
I.B.3.a – X-ray CT

X-ray Computed Tomography (CT)



- By recording radiation transmission views of the object from a large number of directions, the interior attenuating properties can be deduced from mathematical inverse solutions.
- Medical CT images reflect interior tissue density.

I.B.3.c – X-ray CT, Helical



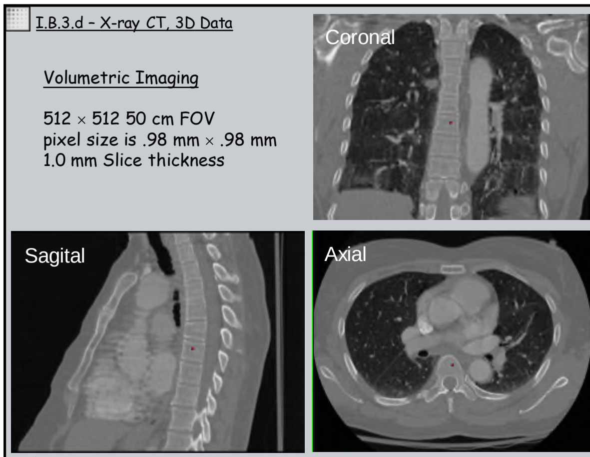
A helical scan of the x-ray source and detector is accomplished by scanning continuously while moving the patient table.

GE Lightspeed pro16
MUSC, 2003

I.B.3.d – X-ray CT, 3D Data

Volumetric Imaging

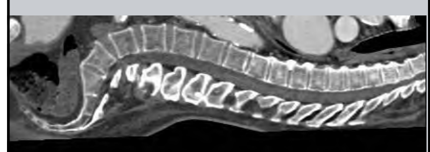
512 × 512 50 cm FOV
pixel size is .98 mm × .98 mm
1.0 mm Slice thickness

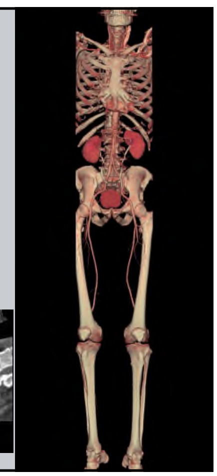


I.B.3.e – Multi-Slice Applications

Multi-slice technology has led to:

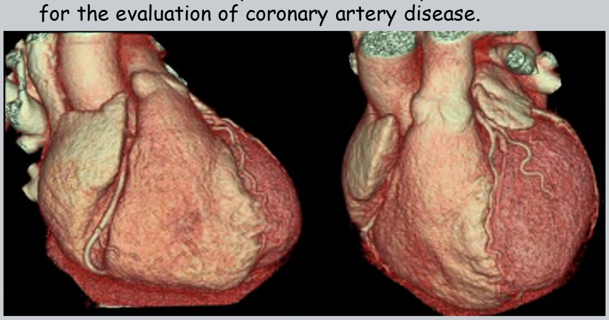
- Increased use of CT angiography.
- Thin slice lung scans with single breath hold.
- Whole body scans and increased utilization for trauma evaluation.
- Increased use of 3D image analysis.
- Emerging cardiac utilization.





I.B.3.f – Cardiac CT

Most recently, CT scanner that can acquire data in 64 to 256 slices simultaneously in ½ second or less have led to the ability to examine the dynamic heart for the evaluation of coronary artery disease.

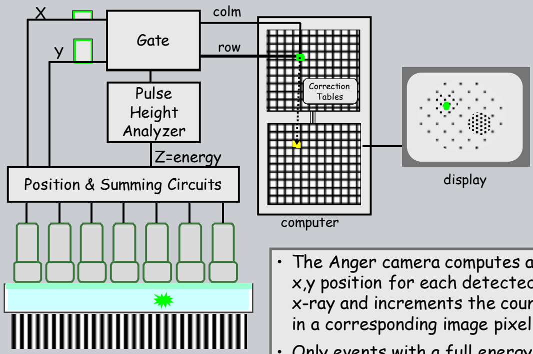


Univ Penn Medical Center

I.B.4.a – Gamma camera detector assembly

- Photomultiplier tubes (PMT) are distributed in a regular array on the back side of a scintillation crystal.
- The crystal and PMT assembly is surrounded by 'mu' metal to minimize the influence of magnetic fields.
- The assembly is then mounted in a lead shielded cabinet assembly mounted on a gantry.

I.B.4.b – Radioisotope Imaging – the Anger Camera



- The Anger camera computes an x,y position for each detected x-ray and increments the count in a corresponding image pixel
- Only events with a full energy sum (Z) in the photo-peak are processed.

I.B.4.c – Gamma camera detector assembly

- The detector assembly is often mounted in a gantry providing circular rotation for SPECT examinations.
- Reduced examination time is achieved by using two detectors.

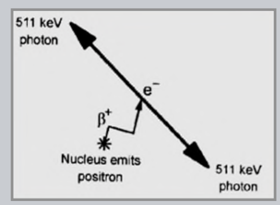
GE Millenium, MUSC

I.B.4.d – Radioisotope Imaging

- Radioisotope image typically have poor spatial detail in relation to x-ray radiography or CT.
- The functional specificity of radioisotope images associated with the biological transport characteristics of the radio pharmaceutical tracer provides unique information.

I.B.5.a – Emission Tomography PET

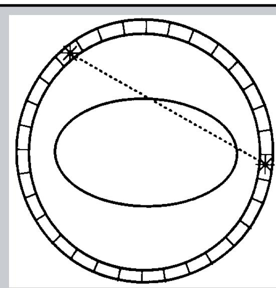
- When some unstable nuclides decay, a positron is emitted
- The positron travels a short distance, losing energy in collisions

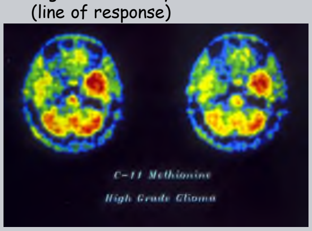


- As the positron slows, it interacts with an orbital electron and both get annihilated
  - releases two 511 keV photons
  - each travels in opposite directions (due to conservation of momentum)

I.B.5.b – Emission Tomography PET

- Detectors arranged in a ring around the patient detect the annihilation photons
- The detection of photons in coincidence by opposing detectors confines the annihilation event to a cylindrical region defined by the detectors (line of response)





Images have poor detail but contain important information on tissue function

I.C – Radiation Imaging Industy (5 charts)

C) Industry
   1) Medical Markets
   2) Imaging Manufacturers and Engr. Employment

Medical Imaging Devices

- Ionizing Radiation Imaging Systems
  - DR - Digital Radiography Systems
    - DX - Radiographic
    - XA - Fluoroscopic, angiographic
  - CT - Computed Tomography scanners
  - NM - Radioisotope Imaging Cameras
    - SPECT - Single Photon Emission Computed Tomography
    - PET - Positron Emission Tomography
- Non-Ionizing Radiation Imaging Systems
  - MR - Magnetic Resonance Imaging
  - US - Ultrasound Imaging Systems
- Image and information management systems
  - PACS - Picture Archive and Communication Systems
  - RIS - Radiology Information Systems

The Medical Imaging Market

Market Value		Global Market Share	
Global	24B USD	Americas	46%
US	8B USD	Western Europe	29%
		Eastern Europe	5%
		Asia	18%
		Mid East, Africa	2%

In comparison, the global automotive market has sales of about 60 million units for ~120B USD.

Medical Imaging Market Growth

- Growth markets
  - Digital Radiography
  - Multislice CT scanners
  - High field MRI
  - Multimodal CT/PET scanners
  - Ultrasound
- Static markets
  - Conventional radiography & fluoroscopy
  - Gamma cameras
- Digital storage and display of images has largely replaced the use of x-ray film leading to significant reductions in film sales and increased sales for computing equipment used for electronic imaging and information management. The global PACS market is now 3B USD and growing at 9%.

Cost for Medical Imaging Exams (US)

- US Population (est. Jan 2017): ~ 324 Million
- Imaging procedures / person / year: ~ 1.2
- Average cost / procedure: ~ $150

Therefore:

Medical Imaging Health Delivery: ~ $58 Billion/year

This cost includes labor and overhead in addition to the cost of imaging equipment.

Thus, about 14% of the revenue from medical imaging exams is spent on purchasing or upgrading equipment used to perform procedures (i.e. $8B / $58B).

Medical Imaging Manufacturers

- United States
  - General Electric Medical Systems (23%)*
  - Carestream (formerly Eastman Kodak)
- Europe
  - Siemens Medical Systems (23%)*
  - Philips Medical Systems (22%)*
  - Agfa Medical Systems
- Japan
  - Canon Medical Systems
  - Shimadzu Medical Systems
  - Fuji Medical Systems

* Approximate global market share

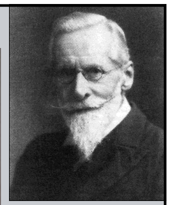
D) Historical foundations.

1) Discovery

(a)	Crookes	-1879, cathode ray tubes
(b)	Roentgen	-1895, x-rays
(c)	Thomson	-1897, electrons
(d)	Becqurel	-1896, radioactivity (uranium)
(e)	Curie’s	-1898, radioactivity (pitchblend)
(f)	Marie Curie	-1902, radium, polonium

I.D.1.a - Sir William Crookes – Crookes tubes

Crooke's tube with phosphorescent minerals manufactured by Müller-Uri, Braunschweig, 1904 and in the collection of the Innsbruck University. Fluorescent minerals like calcium tungstate or fluorite light up when hit by the electrons.


Sir William Crookes,
1832-1919,

paved the way for many discoveries with various experiments using different types of vacuum tubes. The German glassblowers Gundelach and Pressler were the two firms who made many of his tubes in the beginning of the 20'th century.

I.D.1.b – Wilhelm Roentgen – xray discovery

Physics Institute, University of Wurzburg, laboratory room in which Roentgen first observed the effects of x-rays on the evening of 8 Nov. 1895 and subsequently performed experiments documenting their properties. The results were submitted for publication on 28 Dec and printed 4 days later.


Wilhelm Roentgen,
1845-1923,

While experimenting with a Crookes tube discovered that a plate of Barium Platinum Cyanide did glow when he activated the tube. Even when he covered the tube with black material it kept glowing. In the next experiments he used photographic material and made his first x-ray picture.

I.D.1.b – Wilhelm Roentgen – x-ray discovery

Radiograph of the hand of Albert von Kolliker, made at the conclusion of Roentgen's lecture and demonstration at the Wurzburg Physical-Medical Society on 23 January 1896. This was his first and only public lecture on the discovery. It was Kolliker who suggested the new phenomenon be called Roentgen rays. Roentgen refused to patent x-rays and preferred to to put his discovery into the public domain for all to benefit.

I.D.1.c – J.J. Thomson – electron discovery

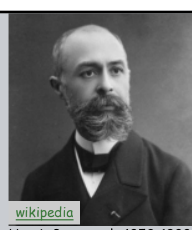
Crookes tube with Maltese Cross showing that cathode rays travel in straight lines.

In the late 19'th century, most scientists thought that the cathode ray responsible for various phenomena observed in Crookes tubes was an 'oscillation of the aether'. In 1897, J.J. Thomson (Physics Prof, Cambridge) reported that they were in fact charged particles that were either very light or very highly charged. In 1899, Thomson showed that the charge was the same as that of hydrogen ions and the mass was much smaller. Thomson resisted calling the particles electrons, a term that was otherwise in use at the time to describe units of charge and not particles.

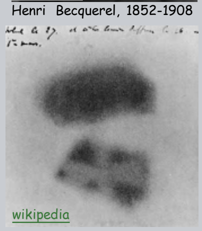
I.D.1.d – Henri Becquerel – radioactivity (uranium)

Radioactivity Discovery - 1896

Becquerel exposed phosphorescent crystals to sunlight and placed them on a photographic plate that had been wrapped in opaque paper. Upon development, the photographic plate revealed silhouettes of metal pieces between the crystal and paper. Becquerel reported this discovery .. on February 24, 1896, noting that certain salts of uranium were particularly active. He thus confirmed that something similar to X rays was emitted by this luminescent substance. Becquerel learned that his uranium salts continued to eject penetrating radiation even when they were not made to phosphoresce by the ultraviolet in sunlight. He postulated a long-lived form of invisible phosphorescence and traced the activity to uranium metal.



Henri Becquerel, 1852-1908



Uranium exposed plate

I.D.1.e – The Curie's - radium

Radium Discovery - 1898

Following Becquerel's discovery (1896) of radioactivity, Maria Curie, decided to find out if the property discovered in uranium was to be found in other matter. Turning to minerals, her attention was drawn to pitchblende, a mineral whose activity could only be explained by the presence in the ore of small quantities of an unknown substance of very high activity. Pierre Curie then joined her in the work. While Pierre Curie devoted himself chiefly to the physical study of the new radiations, Maria Curie struggled to obtain pure radium in the metallic state. By 1898 they deduced that the pitchblende contained traces of some unknown radioactive component which was far more radioactive than uranium. On December 26th Marie Curie announced the existence of this new substance. (abstracted from wikipedia)



1904 Vanity Fair illustration from the UTMB Blocker Collection

I.D.1.f – Marie Curie

Over several years of unceasing labor, the Curie's refined several tons of pitchblende, progressively concentrating the radioactive components, and eventually isolated initially the chloride salts (refining radium chloride on April 20, 1902) and then two new chemical elements. The first they named polonium after Marie's native country, and the other was named radium from its intense radioactivity.

- 1903 – Curie's share the Nobel Prize in Physics.
- 1906 - Pierre Curie died in a carriage accident.
- 1908 - Marie Curie awarded the Nobel Prize in Chemistry

In 1914, Marie was in the process of leading a department at the Radium Institute when the First World War broke out. Throughout the war she was engaged intensively in equipping more than 20 vans that acted as mobile field hospitals and about 200 fixed installations with X-ray apparatus.


Nobelprize.org

Marie driving a Radiology car in 1917

I.D.1.f – Marie Curie

The work of Madame Curie and others at the Radium Institute led to important medical uses of radiation particularly in the treatment of superficial cancers. Unfortunately, a lack of understanding of the effects of radiation by other led to inappropriate devices.

Revigator (ca. 1924-1928)

Advertised by the company as "an original radium ore patented water crock", hundreds of thousands of units were sold for over a decade.

The glazed ceramic jar had a porous lining that incorporated uranium ore. Water inside the jar would absorb the radon released by decay of the radium in the ore. Depending on the type of water, the resulting radon concentrations would range from a few hundred to a few hundred thousand picocuries per liter.

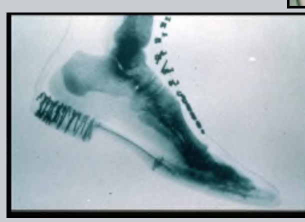
www.orau.org/collection/quackcures/revigat.htm

I.D.2 – Evolution (14 charts)

D) Historical foundations.
  1) Discovery
  2) Evolution
    (a) 1896 - Crookes tube & coil
    (b) 1896 - Fluoroscopy & screens
    (l) 1913 – 1930s, Coolidge tubes
    (d) 1913 – 1925, antiscatter grids
    (e) 1953 - image intensifier
    (f) 1949 – 1958 radioisotope imaging
    (g) 1970s – Computed Tomography (CT)
      i. x-ray CT
      ii. PET
      iii. SPECT

I.D.2.a - Crookes tube and coil

In the year following Roentgens discovery, investigators all over the world obtained Crookes tubes and high voltage coils to explore radiography.



Foot in high-button shoe, radiograph made in Boston by Francis Williams in March 1896. Typical of early images reproduced in the popular press.

The Radiology Centenial, Inc

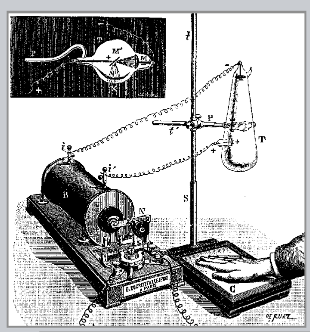
I.D.2.a – Induction coils


Oak Ridge Historical Instr. Collection

Until ~1910, the high voltages required for x-ray tube operation was provided by induction coils powered by DC batteries. An induction coil consists of two separate coils. The inner "primary" coil consists of insulated wire wrapped around a central iron coil. The outer "secondary" coil is wrapped around the primary. When current is applied to the primary coil, a magnetic field is created and voltage generated in the secondary coil. This only happens when there is a change in the magnetic flux created by the primary. To induce a current in the secondary, the current in the primary is rapidly turned on and off. This is accomplished by a device known as an interrupter.

I.D.2.a – Alfred Londe, France

From: etudes photographiques, 17 2005
http://etudesphotographiques.revues.org/index756.html



Albert Londe (1858-1917) was an influential French photographer, medical researcher, … and a pioneer in X-ray photography" http://en.wikipedia.org/wiki/Albert_Londe

I.D.2.a – Victorian Ethics

Literature & Medicine, 16.2 (1997) 166

Because of the skeletal images surrounding Röntgen's discovery, X-rays were quick to capture the public imagination. Journals of the time portrayed a skeptical, even paranoid public, grasping to understand the implications of the penetrative powers of these new rays. A poem from Punch titled "The New Photography" reveals some of these concerns:

Toronto Globe, 1896

O, RÖNTGEN, then the news is true,
And not a trick of idle rumour,
That bids us each beware of you,
And of your grim and graveyard humour.

We do not want, like Dr. SWIFT,
To take our flesh off and to pose in
Our bones, or show each little rift
And joint for you to poke your nose in.

We only crave to contemplate
Each other's usual full-dress photo;
Your worse than "altogether" state
Of portraiture we bar *in toto!*

The fondest swain would scarcely prize
A picture of his lady's framework;
To gaze on this with yearning eyes
Would probably be voted tame work!

I.D.2.b – Fluoroscopy & calcium tungstate screens

Upon learning of Roentgen's discovery, Edison set about to investigate this new phenomenon. Edison's initial research was devoted to improving upon the barium platinocyanide fluorescent screens used to view X ray images. After investigating several thousand materials, Edison concluded that calcium tungstate was far more effective than barium platinocyanide. In 1896, Edison had incorporated this material into a device he called the Vitascope (later called a fluoroscope).

National Park Service

Smithsonian Science Service

One of Edison's most dependable assistants, developed a skin disorder which progressed into a carcinoma. In 1904, he succumbed to his injuries - the first radiation related death in the United States. Immediately, Edison halted all his X-ray research noting "the X rays had affected poisonously my assistant..."

Nuclear Science & Techn.

I.D.2.b – Fluoroscopy & calcium tungstate screens

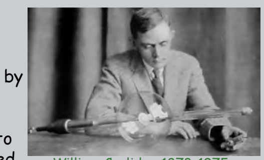
Surgical Fluoroscope.

A physician draws outlines on a patient's skin while looking through a fluoroscope. The fluoroscope is held farther away from the patient than is necessary in practice so the pencil can be shown in the picture. Image is from Roentgen Rays in Medicine and Surgery, 1903.

From "Moments in Radiology History: Part 1 -- X-rays after Roentgen", AuntMinnie.com

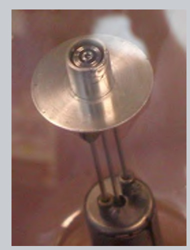
I.D.2.c – Coolidge, hot cathode tubes

In 1913 William Coolidge and Lilienfeld made there first hot Cathode X-ray tube by heating the Cathode. X-ray's could be controlled and were more reliable . However, Anode heat was a problem due to it's small size. A new design was developed with heavy copper Anode bases to conduct the heat away and increase the capacity of the tube to withstand a high current.



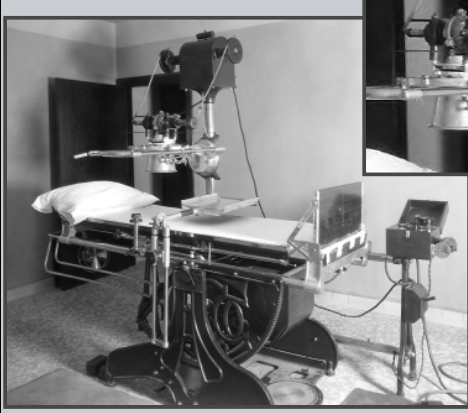
William Coolidge 1873-1975

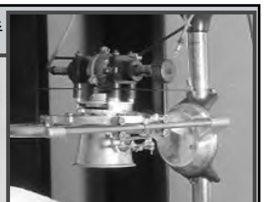
1920s Okco tube
Dr. Hakim's collection



Hot cathode, 1920s Universal tube
Oak Ridge Historical Instr. Collection

I.D.2.c – 1918 xray system with Coolidge tube





1918 Radiology Tilt Table system

Henry Ford Health Sys.

Historical Collection

I.D.2.c – Coolidge, rotating anodes

The first practical application of the rotating anode concept was described by Coolidge in 1915.

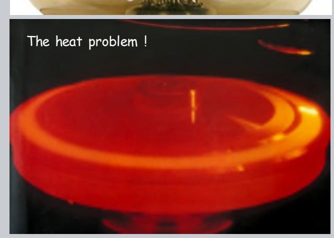
Amer. J. Roentg., Dec 1915

.. the tube had a "target rotation of 750 revolutions per second with the focal spot describing a circle 0.75" (19 mm) in diameter. 2.5 times as much energy for the size of the focal spot is obtained when compared with the stationary target."

Rotating anode tubes came into their own in the 1940s, and by the 1950s or so they had become the standard tube design for diagnostic work.

(adapted from Oak Ridge Hist. Collection)

1960s Machlett tube



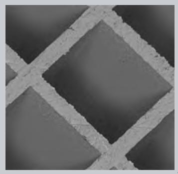
The heat problem !

I.D.2.d – antiscatter grids

The Chicago Radiological Society

- In 1913, Dr. Gustav Bucky published findings describing a cross-hatched or "honey-combed" lead grid which would reduce scatter and improve contrast. To this day, the antiscatter grid assembly in a radiographic room is known as the "Bucky".
- In 1916, Hollis Potter constructed a grid consisting of parallel slits of lead interspersed with strips of wood. The grid was made concave so that the lead strips were parallel to the divergent radiation beam. These changes removed the shadow of the lead strips.
- In 1925, the development of the reciprocating grid was then described by workers at the University of Chicago in 1925. Before the work of Hollis Potter, there were no satisfactory radiographs of the skull, hip, or other thick parts of the body.

Mammography grid made by Creatv MicroTech
- grid Septa – 30 μm
- Periodicity 250 μm
- Parallel Septa
- Material – Copper

I.D.2.e – Fluoroscopy and dark adaptation

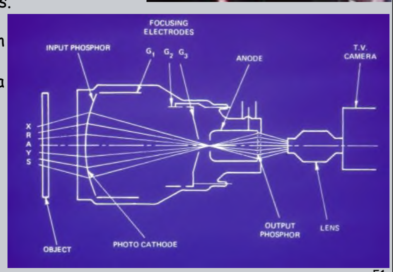
- Four years after Roentgen's discovery of the X-ray, Antoine Beclere published a paper on the theory of dark adaptation, the process of adjusting the user's eyes to a dark room for fluoroscopy.
- In 1916, Wilhelm Trendelenburg introduced red goggles to enhance the procedure. Dark adaptation with red goggles for 15-20 minutes was required before fluoroscopy could begin.


1933 Fluoroscopic System, Mayo Foundation (Schueler BA, Radiographics 2000; 20:1115-1126)

I.D.2.e – Fluoroscopy & the Image Intensifier

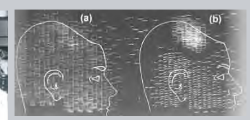
The image intensifier was developed by J.W. Coltman of Westinghouse in 1948. A commercial unit was first marketed by Westinghouse in 1953. With this unit, a brightness gain of 1000 became available. This dramatically changed fluoroscopic examinations.

Electrons produced at an input phosphor are accelerated to produce a bright image at the output phosphor. Cameras record this image for presentation on room monitors. Cineradiography using high speed film cameras was introduced in 1954.



I.D.2.f – Radioisotope imaging – scanners and cameras

- Benedict Cassen, rectilinear scanner, 1949
- Gorden Brownell, Positron scanner, MGH 1953
- Hal Anger, Anger camera, Donner labs 1953
- First commercial anger camera 1958

First positron imaging system at Mass. General Hospital, Gordon Brownell

I.D.2.g – Computed Tomography – CT, SPECT, PET

- 1917, Radon proves it's possible
- 1956-1965, Kuhl* develops emission CT
- 1968-1971, Brownell develops first PET
- 1956-1972, Foundation work on xray CT
  Cormack, Bracewell, Oldendorf, Hounsfield

- 1972 –
  EMI develops commercial CT


G. Hounsfield EMI CT

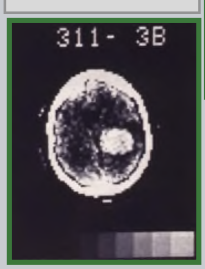

EMI CT Bench Prototype

* David E. Kuhl M.D, Nuclear Med. Chair, Univ. of Mich., 1986-2011.

I.D.2.g- EMI head scanner

1973

First commercially available clinical CT head scanner on market (EMI)



- One of the first EMI head CT scanners in the US was installed at Henry Ford Hospital (Detroit, MI) in 1973.
- The CT image shown to the left was obtained at the Cleveland Clinic in 1974. A large meningioma has been enhanced by iodinated contrast material.

1970s

In the early 70s Phelps and Ter-Pogossian, developed experimental PET scanners with hexagonal ring detectors.

Ortec licensed the rights from Dr. Phelps and sold its first PET scanner in 1976 to the University of California at Los Angeles, where Dr. Phelps had moved. Over the next couple of years, Ortec sold three or four scanners a year, mostly to institutions doing brain research. The business was sold to CTI in 1983 and to Siemens in 2005.