Pattern Recognition Lab

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
FACULTY OF ENGINEERING

Medical Engineering - Imaging Systems

X-Ray

Prof. Dr.-Ing. habil. Andreas Maier
Pattern Recognition Lab (CS 5)
SS 2021

X-Ray

X-Ray History

Generation of X-Rays

X-ray and Matter Interaction

X-ray Imaging

Applications of X-Rays

Further Questions?

X-Ray History

- November 8, 1895: Wilhelm Conrad Röntgen discovers X-rays
- December 28, 1895: Röntgen publishes the paper “Über eine neue Art von Strahlen” (On A New Kind Of Rays)

Wilhelm Conrad Röntgen

X-ray of his wife’s hand.

Sources: Wikimedia Commons

Modern X-Ray Images

Breast X-ray. Note the clearly visible structures in the soft-tissue.

X-ray taken from the thorax (chest) of a patient.

Sources: Siemens Healthcare, Erlangen, Germany

Nature of X-Rays

- X-rays belong to the group of electromagnetic radiation
- Characterized by wavelength λ_p or frequency f_p, where $\lambda_p = c_0/f_p$
- Typical wavelengths for X-rays: 10^{-8} to 10^{-11} m

Nature of X-Rays

- Energy of X-rays is also determined by their wavelength

$$E_p = \frac{hc_0}{\lambda_p} = hf_p$$

- h denotes Planck's constant, with $h \approx 6.626\,069 \cdot 10^{-34}\,\mathrm{J\,s}$
- The energy unit is electron volt [eV]
- 1eV is the kinetic energy that a particle with the charge of an electron achieves when being accelerated in a potential difference of 1V

Nature of X-Rays

Absorption of X-rays

- X-ray photons are partially absorbed while traveling through the patient. This process is also called attenuation.
- Attenuation is higher in dense materials than in non-dense materials
- This difference in attenuation leads to contrast in the image
- E. g. bones appear darker than soft tissue as more photons are absorbed
- The amount of attenuation also depends on the energy of the X-rays

Nature of X-Rays

Propagation of X-rays

- X-rays are propagated along straight lines through homogeneous material

Refraction of X-rays

- Refraction is the change of direction at the transition of two different media
- Refraction of X-rays is very small, thus building X-ray lenses is an open problem

Diffraction of X-rays

- X-rays are slightly bent when passing an edge or slit
- Exploited in *Phase Contrast Imaging*

X-Ray

X-Ray History

Generation of X-Rays

X-ray and Matter Interaction

X-ray Imaging

Applications of X-Rays

Further Questions?

Generation of X-Rays

- X-ray tube current: when high potential difference is applied across the tube, electrons flow from cathode filament to anode

The Cathode

- The cathode is the negative side of the tube. It consists of two principle parts:
  - The filaments: mostly two which provides large and small focal area
  - The focusing cup houses the filaments. Has negative voltage to focus the beam to a small area

The Anode

- The anode is the positive side of the tube
- Can be classified by the type and usage:
  - Stationary: long exposure times, large focal spots. (dental X-ray)
  - Rotating: short exposure times, smaller focal spots with high resolution

Source: Medical Imaging Systems: An introductory guide [1]

Quality Aspects for Medical X-Ray Generators

- High power $\longrightarrow$ short exposure time
- Small focus $\longrightarrow$ sharp images
- Variable photon energy $\longrightarrow$ contrast
- Cost efficient production
- Low service and long durability

Focal Spot Size

The focal spot size is the anode area that is hit by the electron beams

- Penumbra at X-ray Images

Technical Aspects of a X-Ray Tube

- A modern rotating anode X-ray tube encased in a metal or glass protective housing
- It contains two principle parts: the rotating anode and the cathode
- Vacuum tube

Source: Daniel W. Rickey (CC BY-SA 3.0)

Cross-Sectional View of a Turning Anode Tube

- Acceleration Voltage: 20 to 150 kV
- Electron Current: 1 to 5 mA (for continuous operation)
- Electron Current: 0.1 to 1.0 A (for short exposures)

X-ray energy spectrum

Typical Values for X-Rays:

- *soft X-rays*:
  - U_A up to 1 kV
  - 10 to 1 nm wavelength
- *average X-rays*:
  - U_A up to 10 kV
- *hard X-rays*:
  - U_A from 10 up to 120 kV
  - 0.10 to 0.01 nm wavelength

X-ray energy spectrum

The X-ray tube provides an environment for X-ray production via bremsstrahlung and characteristic radiation mechanisms.

Bremsstrahlung

On the event of an electron passing close to an atomic nucleus. . .

- **Probable Event:** acceleration and change of direction
- **Less probable:** deceleration and generation of a photon
  - Conversion of kinetic energy to a photon: *Bremsstrahlung*
  - Bremsstrahlung photons can obtain an arbitrary energy between 0 and the complete kinetic energy of the electron
  - Relative amount of bremsstrahlung emitted increases with increasing electron kinetic energy and with increasing atomic number, Z, of the anode material.

Bremsstrahlung photons are the basis for X-ray diagnostic imaging

Characteristic X-Rays

- When a high speed electron collides with a K-shell electron, the electron in the K-shell is ejected, leaving a ‘hole’ in the K-shell
- This hole is filled by an outer shell electron with an emission of a single X-ray photon
- Unlike the continuous spectrum from Bremsstrahlung, the characteristic radiation creates a line spectrum

Energy Level Diagram for Tungsten

Source: Slides BVM

X-ray energy spectrum

- When the electron reaches the anode, most of its energy is converted to heat energy (about 99%!)
  - For example, 80 kVp tube voltage, 99.4% is heat, 0.6% is X-rays.

Diagnostic X-Ray Tube Spectrum

Energy Efficiency

$$\eta = \frac{J_{total}}{I_A \cdot U_A}$$

J_{total} = total X-ray power
I_A = anode current
U_A = anode voltage

Efficiency as Function of Atomic Number and Anode Voltage

$$\begin{aligned} \eta &= k \cdot U_A \cdot Z \\ \left(k \right. &\approx \left. 1 \cdot 10^{-9} V^{-1}\right) \end{aligned}$$

- Tungsten ($Z = 74$), with $U_A = 100$ kV $\Rightarrow \eta = 0.7$ %
- Emitted X-ray power: $J_{total} = \eta \cdot I_A \cdot U_A$

Pattern Recognition Lab

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
FACULTY OF ENGINEERING

Medical Engineering - Imaging Systems

X-Ray - Part 2

Prof. Dr.-Ing. habil. Andreas Maier
Pattern Recognition Lab (CS 5)
SS 2021

X-Ray - Part 2

X-Ray History

Generation of X-Rays

X-ray and Matter Interaction

X-ray Imaging

Applications of X-Rays

Further Questions?

X-Ray Attenuation

Define I_0 is the incident X-ray intensity.

Lambert-Beer's Law: For a monoenergetic beam that passes through a homogeneous material with linear attenuation coefficient μ

$$I = I_0 \cdot e^{-\mu \cdot x}$$
$$I = I_0 \cdot e^{-\int \mu dx}$$

In practical, emitted X-ray photons have various energies, resulting in polyenergetic energy spectra. The expected total number of photons after passing through the object is:

$$I = \int_0^{E_{\max}} I_0(E) e^{-\int \mu dx} dE$$

Interaction of X-Rays with Matter

$$\mu_{\text{total}} = \mu_{\text{pe}} + \mu_R + \mu_C + \mu_{\text{pair}} + \mu_{\text{ph.n}} \tag{1}$$

μ_{pe} = attenuation coefficient for photoabsorption
μ_R = attenuation coefficient for Rayleigh scattering
μ_C = attenuation coefficient for Compton scattering
μ_{pair} = attenuation coefficient for pair production
$\mu_{\text{ph.n}}$ = attenuation coefficient for photon-nuclear reactions

Photoelectric Absorption

- Incident photon collides with an inner-shell electron in an atom of the absorbing material
- Incident photon ceases to exit
- The electron is ejected from its shell and becomes a recoil electron
  - $\Rightarrow$ **Photoelectron**

Photoelectric Absorption

Compton Scattering

- Incident photon interacts with an outer orbital electron
- Incident photon with lower energy is deflected and scattered from the atom
- Almost all scattered radiation in diagnostic radiology comes from Compton scattering

Compton Scattering

Rayleigh Scattering

- Low energy incident photon interacts with the outer-shell electron
- Electron is set into vibration, which emits radiation
- The direction of the incident Photon is altered
- Contributes very little in diagnostic radiology

Mass Attenuation Coefficient for Iron

Source: Jarekt (CC BY-SA 3.0)

Mass Attenuation Coefficient for Lead

$\frac{\tau}{\rho}$ Attenuation due to photoelectric effect

$\frac{\sigma}{\rho}$ Compton effect

$\frac{\sigma_R}{\rho}$ Rayleigh scattering

$\frac{\kappa}{\rho}$ Pair production

$\frac{\mu}{\rho}$ Total attenuation

Mass Attenuation Coefficient for Water

Source: MIT OpenCourseWare (CC BY-NC-SA 2.0)

Pattern Recognition Lab

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
FACULTY OF ENGINEERING

Medical Engineering - Imaging Systems

X-Ray - Part 3

Prof. Dr.-Ing. habil. Andreas Maier
Pattern Recognition Lab (CS 5)
SS 2021

X-Ray - Part 3

X-Ray History

Generation of X-Rays

X-ray and Matter Interaction

X-ray Imaging

Applications of X-Rays

Further Questions?

Definition

X-ray Generation	$\longrightarrow$	Conversion of electrons to X-rays
X-ray Matter Interacation	$\longrightarrow$	Attenuation of X-rays
X-ray Imaging	$\longrightarrow$	**Conversion of X-rays to images**

We will discuss:

- Image intensifier systems
- Flat panel detectors
- Sources of noise in X-ray imaging

Image Intensifiers

- Image intensifier are vacuum tubes that convert X-rays to visible light
- Light intensity can be adjusted by electron optics
- Image can then be viewed directly at an output screen
- First introduced in the late 1940's for fluroscopy applications

Sources: Siemens Healthcare, Erlangen, Germany

Image Intensifiers - Function

1. X-rays are converted to light by scintillator material (Input Phosphor)
2. Light photons are converted to electrons using a photocathode
3. Electrons are accelerated and focused by an electron optics
4. Fast electrons are converted to light when they hit the output phosphor, which yields the output image.
5. Image is typically captured by a camera and transferred to a monitor

Image Intensifiers – Detailed Function

Scintillator – Input Phosphor

- Only absorbed X-ray photons can be converted to light
  $\rightarrow$ Scintillator material should have high attenuation coefficients for energies of typical X-ray spectra
- Light should exit the scintillator at position of absorption to preserve spatial resolution
  $\rightarrow$ Scattering of light photons inside material should be low
- Produced light photon's wavelength should match the photocathode
- Typical scintillator materials are
  - zinc-cadmium sulfide (ZnCdS)
  - cesium-iodide (CsI)

ZnCdS vs. CsI - Attenuation and Light Photon Wavelength

Mass attenuation coefficient of CsI and ZnCdS and the estimated X-ray spectrum after transmission through the patient.

Sensitivity of an $SbCs_3$ photocathode and characteristic light spectra emitted from a CsI as well as a ZnCdS phospor layer.

ZnCdS vs. CsI - Spatial Resolution

- CsI can be manufactured with tubular structure
- Tubes act as optical-fibre and prevent scattering of light
- Produced light can be better assigned to incoming X-ray location

Image Intensifiers – Known Problems

- Small changes in external magnetic or electric field can change electron trajectories in electron optics $\rightarrow$ Image distortion
- Light scattering in output phosphor is isotropic
- However, no scattering contribution from outside the material to periphery $\rightarrow$ Vignetting effect

Vignetting artifact: Luminescence drops at image periphery.

Distortion due to electric or magnetic field.

Flat Panel Detectors

- Flat Panel Detectors (FPD) digitize image data directly
- There exist direct and indirect FPDs
  - Direct $\rightarrow$ Converts X-rays directly to electrical charges
  - Indirect $\rightarrow$ Converts X-rays to light and then to electrical charge
- Images can be easily viewed, shared, stored, etc.
- First introduced in the mid 1990s
- Suitable for radiography, fluroscopy and cone-beam CT

Sources: Siemens Healthcare, Erlangen, Germany

FPD – Direct Conversion

1. X-ray sensitive photoconducter absorbs X-rays
2. X-ray absorption causes electron-hole pairs
3. Global electric field E_{ph}: Anode at top and Cathode at bottom
4. In each pixel cell the positive charges travel to the bottom and are stored locally in capacitors

FPD – Indirect Conversion

1. Scintillator material (CsI) converts X-rays to light photons
2. Dense matrix of photodiodes (pixels) convert light to electrical charge
3. Electrical charge is stored locally in each pixel's capacitor

FPD – Data Readout (Direct and Indirect)

- After a certain time of radiation exposure each pixel will have charges in its storage capacitor
- Read-out is done row-wise with a certain read-out frequency
- Row is selected by switching on the Thin-Foil Transistors (TFT) of this row's pixels
- Stored charges in pixels are directed to a charge integrating amplifier
- After amplifier the datastream is digitized (analog-to-digital-conversion)
- Data is directly sent to a computer system over a bus
- Pixels can be combined (binning) to increase read-out speed and SNR

Sources of Noise

- Two types of undesired effects in X-ray imaging
  - Image noise
  - Image artifacts
- Both based on physical effects
- Difference: When scan is repeated with identical settings,
  - artifacts (e.g., aliasing) will remain unchanged
  - noise pattern will vary as it is a probabilistic effect
- Prerequisites: Discrete statistical distributions
  - Poisson distribution
  - Binomial distribution

Poisson distribution

- Poisson distribution is discrete distribution with density function:

$$p(\mathcal{N} = n) = \frac{(N_0)^n}{n!} e^{-N_0}$$

- N_0 is the expectation value and only parameter
- Comparable to a normal distribution for large N_0

Poisson distribution - Example

- Local shop writes down number of customers per day for one year
- The average number of customers per day is $N_0 = 15$
- What is probability that tomorrow will be $n = 20$ customers in the shop

$$
\begin{aligned}
p(\mathcal{N} = 20) &= \frac{(N_0)^n}{n!} e^{-N_0} \\
&= \frac{15^{20}}{20!} e^{-15} \\
&\approx 0.0418
\end{aligned}
$$

- Probability that tomorrow will be $n = 20$ customers there is 4.18%

Binomial distribution

- Used for a series of independent random experiments with binary outcome, e.g., “yes or no” or “heads or tails”

$$p(\mathcal{N} = n) = \binom{N}{n} p^n (1-p)^{N-n} = \frac{N!}{n!\,(N-n)!} p^n (1-p)^{N-n}$$

- Probability that exactly n positive outcomes occur for N independent trials
- p is the probability that a single trial has a positive outcome

Binomial distribution - Example

- Probability that coin shows $n = 20$ times heads if tossed $N = 30$ times
- If coin is ideal the chance is "fifty-fifty", i.e., $p = 0.5$

$$
\begin{aligned}
p(\mathcal{N} = 20) &= \binom{N}{n} p^n (1-p)^{N-n} \\
&= \frac{30!}{20!\,(30-20)!} (0.5)^{20} (1-0.5)^{30-20} \\
&\approx 0.028
\end{aligned}
$$

- Probability of 20 times heads for 30 times coin tossing is 2.8%

Sources of Noise

- Different statistical processes occur at the different states of an X-ray imaging system
- Conversion from electrons to X-rays follows Poisson distribution
- Each generated x-ray photon interacts independent of the others, thus, all following steps follow binomial distributions

Statistics of the X-ray Generation Process

- Number of generated X-ray photons at anode is Poisson distributed
- N_e is the number of accelerated fast electrons
- p_{ex} is probability that a fast electron triggers an X-ray photon
- The probability that the source produces n photons is then given by

$$
\begin{aligned}
P(\mathcal{N} = n) &= \frac{N_0}{n!} e^{-N_0} \\
&= \frac{N_e p_{ex}}{n!} e^{-N_e p_{ex}}
\end{aligned}
$$

- Where the expectation value is given with $N_0 = N_e p_{ex}$

Statistics of the X-ray Matter Interaction

- Generated X-ray photons interact with matter
- Photons either absorbed or unaffected $\rightarrow$ Binomial distribution
- Probability p_a for a photon passing unaffected is given by Beer's law

$$p_a = e^{-\int \mu(s) ds}$$

- The probability that n_s photons pass unaffected **and** that N_x photons have been produced is called the **Joint Probability** $P(n_s, N_x)$

SNR and Noise

- The signal-to-noise ratio (SNR) can also be defined by statistics

$$SNR(\mathcal{N}) = \frac{\mu}{\sigma} = \frac{E(\mathcal{N})}{\sqrt{E((\mathcal{N}-\mu)^2)}}$$

- μ is the expectation value of $\mathcal{N}$ $\rightarrow$ Measure for signal strength
- σ is the square root of the variance of $\mathcal{N}$ $\rightarrow$ Measure for noise
- SNR increases if the signal strength increases or if the noise reduces

SNR and Noise

- For Poisson the expectation value equals the variance, thus $\mu = \sigma^2$
- Hence, $\mu = N_0 p_a$ and $\sigma = \sqrt{N_0 p_a}$
- The SNR after the X-rays pass through the patient computes to

$$
\begin{aligned}
SNR(\mathcal{N}) &= \frac{N_0\, p_a}{\sqrt{N_0\, p_a}} \\
&= \sqrt{N_0\, p_a} \\
&= \sqrt{N_0}\; e^{-\frac{1}{2}\int \mu(s) ds}
\end{aligned}
$$

- SNR increases with the square root of the number of input photons
- High mass attenuation $\mu(s)$ or thick materials decrease the SNR

X-Ray - Part 3

X-Ray History

Generation of X-Rays

X-ray and Matter Interaction

X-ray Imaging

Applications of X-Rays

Further Questions?

Radiography

- Two dimensional X-ray projection images
- Object is exposed to X-rays and attenuation of the object is measured
- Main application: Examination of fractures or changes of skeletal system
- Bones attenuate more than surrounding tissue $\rightarrow$ Good contrast

Sources: Wikimedia / Public Domain

Fluroscopy

- Sequence of radiography images with certain framerate
- X-ray source either triggered or constant radiation
- Framerate is typically limited by acquisition speed of detector
  - Image Intensifier: Inertia of final fluorescent screen
  - FPDs: Electronic detector readout step
- Important for minimally invasive interventions $\rightarrow$ catheters, endoscopes or other tools can be tracked over time
- Also key technology for digital subtraction angiography

Fluroscopy

Image of fluoroscopy sequence showing the placement of two electrodes of a pacemaker.

Typical clinical setup of a minimally invasive surgery with a C-arm device. X-ray source at the bottom and the FPD is right above the patient.

Sources: Steven Fruitsmaak, Wikimedia Commons / Siemens Healthcare, Erlangen, Germany

Digital Subtraction Angiography — Contrast Agent

- Angiography = Imaging of arteries to analyze shape, size, lumen, etc.
- ↯ Attenuation of vessels not much different to surrounding tissue ↯
- Contrast agent: Liquid with substantially higher attenuation coefficient than background material
- Contrast agent injected into vascular system to improve vessel contrast
- Typical contrast agent media are iodine and barium
- Iodine: Used for intravascular injections
- Barium: Stomach or colone examinations (Can be swallowed)

Digital Subtraction Angiography — Principle

- Fluroscopic sequence of fixed anatomy over time
- Simultaneous injection of contrast agent into arteries
- X-rays without contrast = Background tissue
- Subtract non-contrasted reference image from contrasted images
- Subtraction will result in image of contrasted arteries only
- Non-contrasted image = “mask image”
- Contrasted images = “fill images”

Digital Subtraction Angiography — Example

(a) Mask image (b) Fill image (c) Angiogram

Process of creating a DSA. In (a) the hand was imaged and no contrast agent has been injected (mask image). In (b) the same hand has been imaged but including injected contrast agent. The difference of (a) and (b) represents the angiogram as shown in Figure (c).

Source: Adam Galant, Siemens Healthcare, Erlangen, Germany.

X-Ray - Part 3

X-Ray History

Generation of X-Rays

X-ray and Matter Interaction

X-ray Imaging

Applications of X-Rays

Further Questions?

Further Readings

- M. Berger, et al., “X-ray imaging”, in *Medical imaging systems: an introductory guide*, edited by A. Maier, et al. (Springer International Publishing, Cham, 2018), pp. 119–145, 10.1007/978-3-319-96520-8_7