Medical Imaging

Roland Kwitt

Department of Artificial Intelligence and Human Interfaces
University of Salzburg

Summer 2022
(Course Nr.: 911.933)

Logistics

Some information about myself

Short Vita

PhD	University of Salzburg (2007–2010)
Post-Doc	University of Salzburg (2010–2011)
R&D Engineer	Kitware Inc. (2011–2013)
Ass.-Prof.	University of Salzburg, (2013–2017)
Assoc.-Prof.	University of Salzburg, (2017–2020)
Univ.-Prof.	University of Salzburg, (2020–now)

Research Interests

- **Machine Learning**
- Computer Vision
- Medical Imaging

Logistics

Grading (Vorlesung)

One *final test* at the end of the semester.

Course Overview

Why "Medical Imaging"?

In this lecture we will learn about medical imaging modalities and the peculiarities that come with this kind of data.

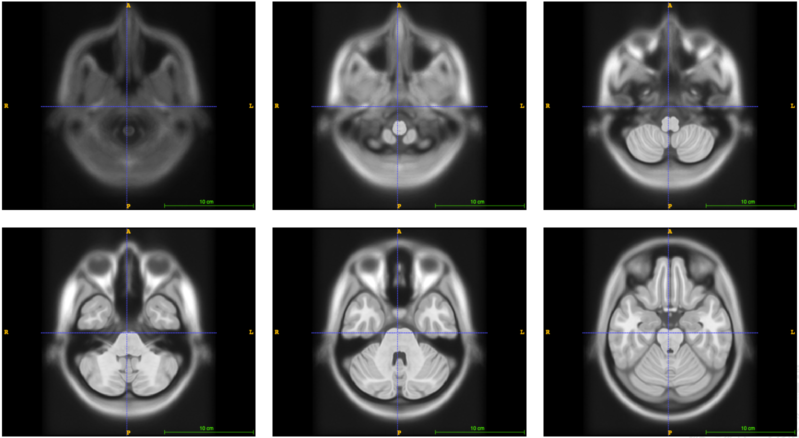
Topics include (but are not limited to) ...

- Radiography (X-Ray & CT)
- Magnetic Resonance Tomography (MRT)
- Ultrasound (US)
- Image Registration
- Point Cloud Registration

We will learn (1) about the image acquisition process as well as (2) algorithms and (3) tools to process the data.

Some examples

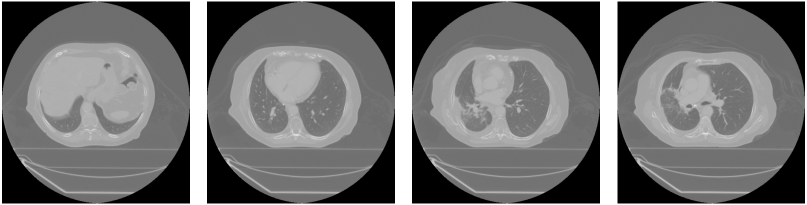
MRT



Brain MRT

Some examples

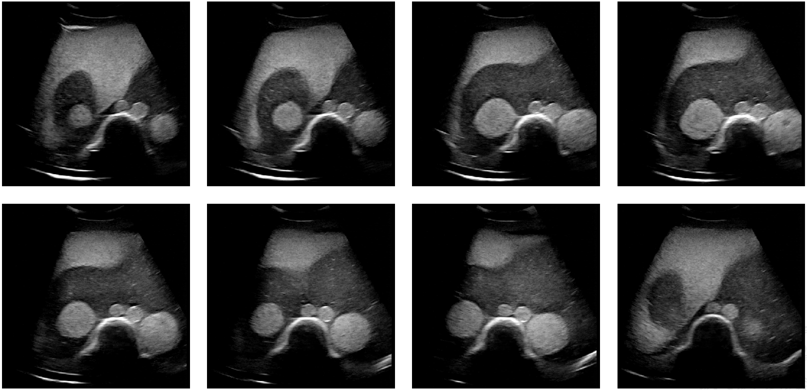
Computed Tomography (CT)



Lung CT

Some examples

Ultrasound (US)



Freehand US of a phantom

Preliminaries

(with slides adapted from H. Delingette)

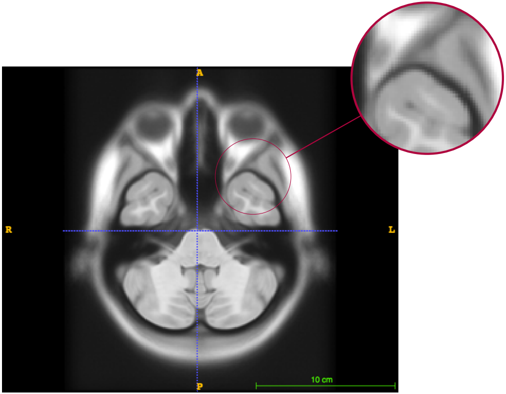
Miscellaneous

First Nobel prize (ever) awarded to Willhelm C. Röntgen (Physics, 1901)

Other Nobel-prize winners:

- Lautebur & Mansfield for MRT (Physics, 2003)
- Cormack & Hounsfield for CT (Physiology or Medicine, 1979)

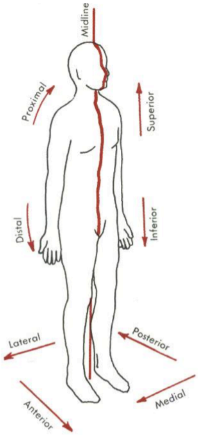
Characteristics of Medical Images



Intensity values are related to physical tissue characteristics which, in turn, may be related to some physiological phenomenon!

Anatomical Orientations

Definitions



- Superior vs. Inferior
- Right vs. Left
- Anterior vs. Posterior

Note that "Left/Right" is seen from the view of the patient.

Anatomical Orientations

Conventions

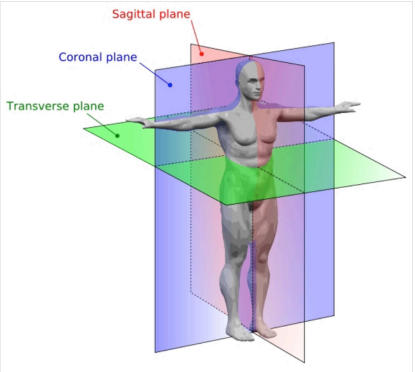
Orientation information is typically encoded in a 3 letter code, which describes the *positive direction* of each axis.

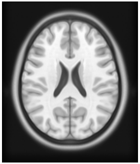
Example: RAS

- R: x-axis from left to right
- A: y-axis from posterior to anterior
- S: z-axis from inferior to superior

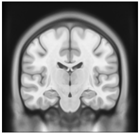
Imaging Planes

Exemplified on slices of brain MRT

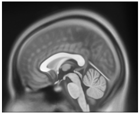




Transverse/Axial

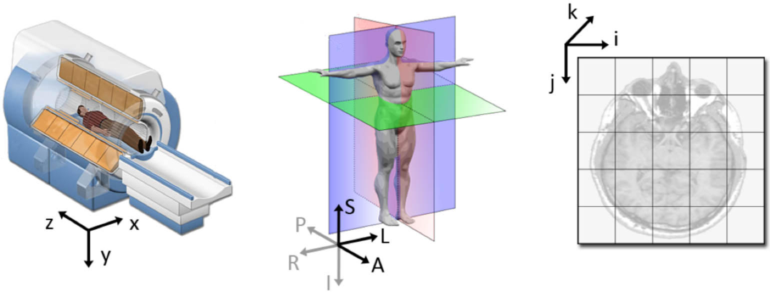


Coronal



Sagittal

Coordinate Spaces



Left to *Right*: World $\rightarrow$ Anatomical $\rightarrow$ Image

Coordinate Spaces

Meta information stored in (medical) images

In addition to the intensity value of a voxel at position (i, j, k), an image stores additional (meta) information.

Image origin

Position of the first voxel in the anatomical coordinate space, e.g.,

$$\text{origin} = [100\text{mm}, 50\text{mm}, -10\text{mm}]$$

Voxel spacing

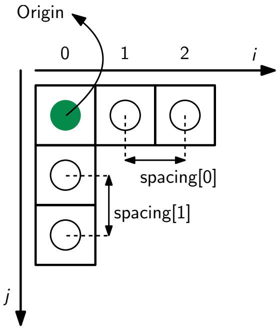
Distance between voxel, e.g.,

$$\text{spacing} = [1\text{mm}, 1\text{mm}, 0.9\text{mm}]$$

Coordinate Spaces

Some notes on image coordinates

Illustration for the first two dimensions (i, j):



Note that we can use origin & dimension to compute the position of a voxel in the anatomical coordinate space!

Tools

The following is a short listing of tools / applications that are very handy when you start working with medical imaging data:

- 3D Slicer https://www.slicer.org
- ITK-Snap http://www.itksnap.org
- ITK/SimpleITK www.simpleitk.org
- Paraview www.paraview.org
- Convert3D http://www.itksnap.org
- OsiriX Lite https://www.osirix-viewer.com/

Radiography

X-Ray Imaging [1]

[1] G. Dougherty. *Digital Image Processing for Medical Applications*. Cambridge University Press, 2009.

X-Ray Imaging

In short, an X-ray tube produces X-Rays by focusing a beam of high energy electrons onto a tungsten target.

X-rays are *absorbed* or *scattered* as the beam passes through the human body, resulting in

- a reduction, or
- attenuation

of the beam.

Visual appearance

Less dense tissue $\rightarrow$ less attenuation $\rightarrow$ darker appearance.

X-Ray Imaging

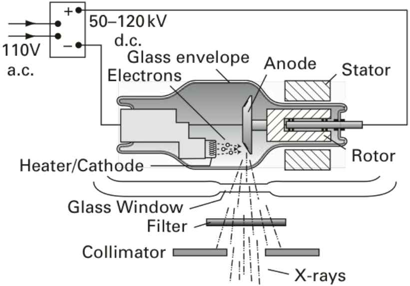
Example

Below is an example of a horse hoof (here: bone vs. soft-tissue)

LV ... “links vorne” (front left leg)

X-Ray Imaging

Physics – Principles



Sketch of working principle

Heating of tungsten ("Wolfram") filament (cathode) $\rightarrow$ electrons are emitted. Positive current at the anode $\rightarrow$ electrons accelerate and travel towards the (rotating, tungsten) anode $\rightarrow$ they enter the material and produce three different kinds of radiation.

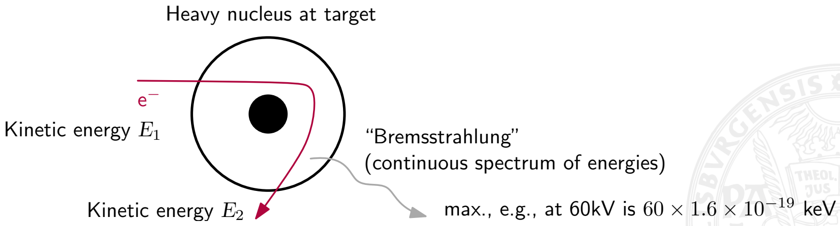
X-Ray Imaging

Physics – Types of emitted radiation

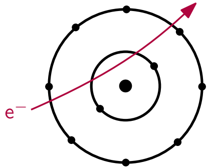
Upon contact with the anode material, electrons loose energy ($\approx 99\%$ as heat); about 1% convert into either

1. "Bremsstrahlung"
2. Characteristic X-Rays
3. ("Lilienfeld" radiation)

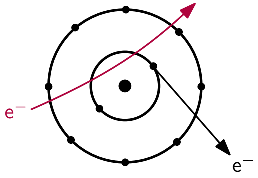
Bremsstrahlung



Characteristic X-Rays



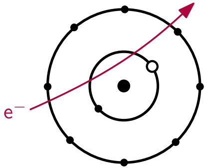
Characteristic X-Rays



X-Ray Imaging

Physics – Types of emitted radiation

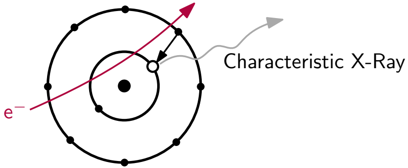
Characteristic X-Rays



X-Ray Imaging

Physics – Types of emitted radiation

Characteristic X-Rays



The (discrete) energy of the characteristic X-Ray photon results from the excess energy of an electron falling into the vacancy caused by an ejected inner shell electron.

X-Ray Imaging

Physics

X-Rays are further filtered (e.g., using a thin sheet of aluminum) to get rid of low-energy photons (would be absorbed by body).

Example

Say, we consider a maximum energy X-Ray photon with 60keV. Hence,

$$E = 1.6 \cdot 10^{-19} \cdot 60000 = 9.6 \cdot 10^{-15} \frac{kg\ m^2}{s^2} \quad .$$

We know that $E = hf$ where $h = 6.626 \cdot 10^{-34}\ kg\ m^2/s$ (this is the Planck constant), so

$$f = \frac{E}{h} = 1.44 \cdot 10^{19}\text{Hz} \quad .$$

We also know that $f\lambda = c$ with $c = 3 \cdot 10^8\text{ms}^{-1}$ (light speed). Hence, $\lambda = \frac{c}{f} = 2 \cdot 10^{-11}\text{m} = 0.02\text{nm}$.

Example (contd.)

In comparison, the wavelength (λ) of visible light is 400nm - 700nm $\rightarrow$ lower energy.

Why? Lets do the calculations[2]: $f = \frac{c}{\lambda} = 7.5 \cdot 10^{14}$Hz. Hence,

$$E = hf = h \times 7.5 \cdot 10^{14}\mathbf{s}^{-1} \approx 5 \cdot 10^{-19} \frac{kg\ m^2}{s^2} \quad .$$

This is the reason why X-Ray photons penetrate our body and visible light does not.

[2] On https://www.wolframalpha.com use: `Planck constant * 7.5 * 10^14 s^-1`

X-Ray Imaging

Physics – Interactions with human tissue

Loss of energy leads to a loss of intensity (I, energy per unit area). Different tissue types affect the beam differently, i.e.,

$$I = \boxed{I_0} \cdot e^{-\mu t} \tag{3.1}$$

Initial intensity

with attenuation coefficient μ and material thickness t. (cf. Beer-Lambert law)

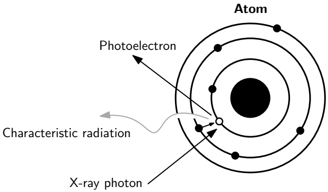
X-Ray Imaging

Physics – Interactions with human tissue (Causes of attenuation)

X-Rays interact with (human) tissue, either by

1. Photoelectric absorption
2. Compton scattering

Photoelectric absorption (related to the "radiation dose")

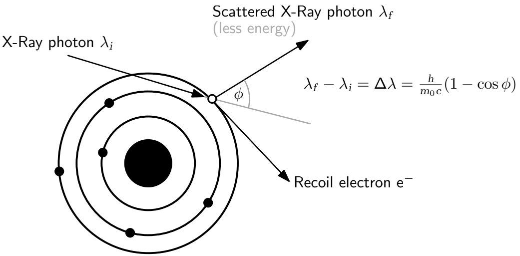


The energy of the photon is transferred to the electron which is ejected and a positively charged atom (ion) remains.

X-Ray Imaging

Physics – Interactions with human tissue (Causes of attenuation)

Compton scattering



X-Ray photon ejects outer shell electron e$^-$ and looses energy. It is deflected (by angle ϕ) and travels further. The reduced energy means greater wavelength. Again, an ionized atom remains.

X-Ray Imaging

Physics – Interactions with human tissue

Both, photoelectric absorption and Compton scattering contribute to μ, as $\mu = \tau + \sigma$ with

$$\tau \propto \rho \frac{Z_{eff}^3}{E^3} \quad \text{and} \quad \sigma \propto \frac{\rho}{E}$$

where

- Z_{eff} is the effective atomic number of the material
- ρ is the electron density of the material

Some Z_{eff} are 13.3 (bone), 7.4 (water, muscle), or 6.4 (fat) $\rightarrow$ bone has a higher attenuation coefficient (with photoelectric absorption as the dominant interaction).

X-Ray Imaging

Image acquisition

In *projection* X-Ray radiography, the image is a simple 2D projection of a 3D object.

Projection radiography includes

- Film-screen radiography (e.g., chest, abdominal, mammography)
- Computed radiography (storage phosphors replace film)
- Digital radiography (semiconductor sensors)
- Fluoroscopy (real-time, using an image intensifier tube)

X-Ray Imaging

Film-screen radiography

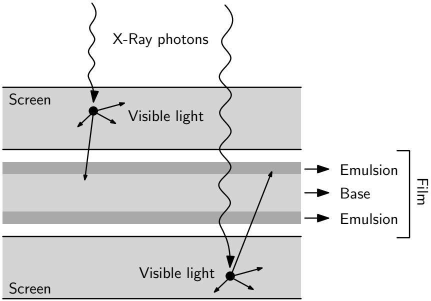
P $\rightarrow$ A view; *Left*: Normal, *Right*: tubercolosis

Note: always viewed so that you seem facing the patient.

X-Ray Imaging

Film-screen radiography

Sensitivity of photographic film to X-Rays is low. Only $\approx 2\%$ of X-ray photons are captured by film (*quantum efficiency*)!



Use fluorescent intensifying screen(s) with phosphor particles $\rightarrow$ converts X-Ray photons into visible light which exposes film.

X-Ray Imaging

Film-screen radiography

This increases efficiency to $\approx 25\%$ $\rightarrow$ better for patient, because we need fewer X-Ray photons and thus less dose.

Trade-Off

- Thicker screen $\rightarrow$ better absorption, but image quality degrades!

  (due to diversion of photons before they reach the film)

- Faster screen (i.e., larger phosphor particles) $\rightarrow$ higher sensitivity, but also increased unsharpness!

  (since, larger particles cause more blur)

All these contributions to unsharpness are summarized under the term detector unsharpness.

X-Ray Imaging

More on “unsharpness”

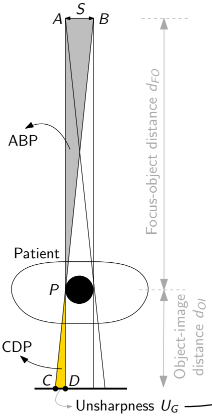
Other sources affecting the sharpness of the images:

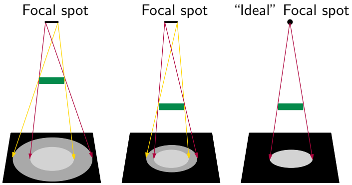
- Width of X-Ray beam
- Patient movement
- Patient *close* to detector
- Patient *far away* from X-Ray source

X-Ray Imaging

Geometric Unsharpness – aka “Penumbra”, or “Edge Gradient”

Cause: the focal spot is *not* an ideal point source!





$$\frac{U_G}{S} = \frac{d_{OI}}{d_{FO}} \Rightarrow U_G = S \cdot \frac{d_{OI}}{d_{FO}}$$

(Comparison of similar triangles)

X-Ray Imaging

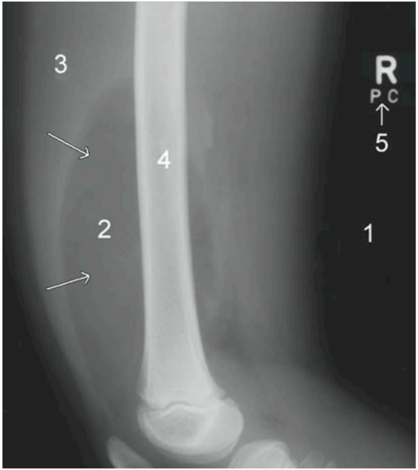
Radiographic densities

The five principal densities, recognized in a radiograph are:

1. Air/Gas (black): e.g., lungs, bowel, stomach
2. Fat (dark gray): e.g., subcutaneous tissue layer
3. Soft tissue / water (light gray): e.g., heart, blood vessels
4. Bone (off-white)
5. Contrast material (bright white): e.g., metal

X-Ray Imaging

Radiographic densities – Example



1. Air
2. Fat
3. Muscle
4. Bone
5. Metal

X-Ray Imaging

Some notes on mammography

In mammography, we look for (1) subtle differences in tissue, (2) very small objects and (3) minimization of radiation dose!

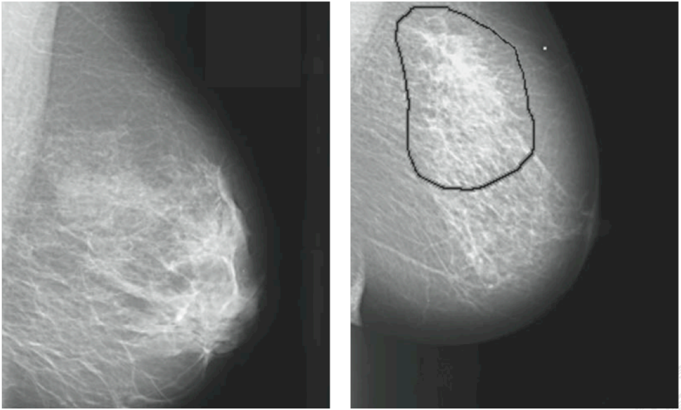
Achieved with ...

- special tubes operating at 25-30keV

  (attenuation is greater $\rightarrow$ larger contrast differences in soft-tissue)
- replace tungsten with molybdenum targets (to get 15-20keV)
- angle target to achieve small focal-spot size (0.1-0.3mm)
- large focal-spot to film distance (45-80cm)
- compression of the breast (less scatter, more uniform exposure)
- usually, single-emulsion film + one intensifier screen

  (reduces detector unsharpness, but requires larger dose)

X-Ray Imaging
Mammography – Example



Left: Normal breast; *Right*: dense opacity, spiculated mass (possibly malignant lesion);