Principles and State of the Art of Medical Imaging Systems

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Motto:
One image is better than thousand words

All images were adopted from webpage http://www.medical.toshiba.com
How to start?

• Maybe by question(s) or quiz or test!
• By what question(s)?
• What does it mean imaging?
• What is the simplest imaging system?
• Why are the imaging systems so important?
What does it mean imaging?

Imaging is the representation or reproduction of an object's outward form; especially a visual representation.

the formation of an image
Answers

• What is the simplest imaging system?

• The **camera obscura** (Latin *veiled chamber*) is an optical device used, for example, in drawing or for entertainment.

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From courses.essex.ac.uk/lt/lt204/GERMAN.HTM
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From "*Encyclopédie, ou dictionnaire raisonné des sciences, des arts et des métiers*, 1772"
Answers

• What are the imaging systems so important?
• Medical imaging systems have an important role from the point of view of the early diagnostics and the following treatment without invasive approach.
Lecture motto

• One sentence is better than thousand characters

• One image is better than thousand words

• One videosequence is better than thousand images
Essential parts of a medical imaging system

Acquisition = building the image = applying energy + sensing a response

reflection, transmission
Medical imaging systems

- conventional
  - X-ray, X-ray TV, DSA, DR, (IR), NM

- tomographical (tomography)
  - US

- tomographical (computed tomography)
  - CT, MR, SPECT, PET, (EIT)
## Chart of the Electromagnetic Spectrum

<table>
<thead>
<tr>
<th>Wavelength ($\lambda$) (m)</th>
<th>Wavenumber ($cm^{-1}$)</th>
<th>Electron Volt (eV)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10$^3$</td>
<td>10^{-5}</td>
<td>10^{-9}</td>
<td>10$^5$</td>
</tr>
<tr>
<td>10$^2$</td>
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<td>10$^6$</td>
</tr>
<tr>
<td>10</td>
<td>10^{-3}</td>
<td>10^{-7}</td>
<td>10$^7$</td>
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<tr>
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<td>10^{-2}</td>
<td>10^{-6}</td>
<td>10$^8$</td>
</tr>
<tr>
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<td></td>
<td>10^{-4}</td>
<td>10$^{10}$</td>
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<td>10$^{11}$</td>
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<tr>
<td>10$^{-14}$</td>
<td></td>
<td>10^{7}</td>
<td>10$^{21}$</td>
</tr>
</tbody>
</table>

### Bands

- **Radio Spectrum**
  - Broadcast and Wireless
  - Microwave

- **Terahertz**
  - Far IR
  - Mid IR
  - Near IR

- **Infrared**
  - Far IR
  - Mid IR
  - Near IR

- **Ultraviolet**
  - Extreme UV
  - Soft X-ray
  - Hard X-ray

- **X-ray**
  - Medical X-rays
  - Cosmic ray observations

- **Gamma**

### Sources and Uses of Frequency Bands

- **AM radio**: 600kHz-1.6MHz
- **FM radio**: 88-108 MHz
- **Mobile Phones**: 900MHz-2.4GHz
- **Radar**: 1-100 GHz
- **Ultrasound**: 1-20 MHz
- **TV Broadcast**: 54-700 MHz
- **Wireless Data**: ~2.4 GHz
- **MRI-MRS**: 60-1000MHz
- **Microwave Oven**: 2.4 GHz
- **Screening**: 0.2-4.0 THz
- **Remotes**: 850 nm
- **MRI**: 0.1-0.01 Å
- **PET imaging**: 0.1-0.01 Å

**Visible wavelengths (nm)**
- Fiber telecom: 0.7-1.4 μm
- Dental Curing: 200-350nm
- Visible Light: 425-750 THz
- Suntan: 400-290 nm
- Night Vision: 10-0.7 μm
- Microscope: "mm wave""sub-mm"

**$X = 3 \times 10^8 / \text{freq} = 1/(\text{wn}^{*}100) = 1.24 \times 10^{-6} / \text{eV}$**
Image acquisition modalities

• the various technologies and protocols used to acquire image data
Projection X-ray (radiography)

- Different absorption characteristics allow to distinguish different material (and provide contrast) in the image.
- X-ray attenuation is measured by the linear attenuation coefficient ($\mu$).
- Projection X-rays (radiographs) are 2D projections of 3D data
Conventional X-ray (projection radiography)
Conventional X-ray (X-ray tube)
Conventional X-ray (mamograph)
Conventional X-ray TV (C arm with II)
Conventional X-ray TV (image intensifier)
Conventional X-ray TV (TV pick-up tube)
**Ultrasound**

- US imaging employs **HF sound energy** to image the interface between differing tissue types.
- When the sound wave strikes an interface, some energy moves across the interface and some energy is reflected backwards.
- The **reflected energy** is detected by a receiver and is used to form the image.
Conventional US („tomography“)
Nuclear medicine

- **Radio-isotopes** are introduced into the body to "tag" specific physiologic functions.
- As the **tracer** accumulates in a particular anatomic location, it periodically **emits a particle** that can be observed and used to form an image.
- NM it can be used to form **functional** rather than structural images.
Conventional NM (Anger gamma camera)
Computed tomography (CT)

• CT is used to generate cross-sectional images (CT slices) from a set of projections images obtained at different angles.

• CT image pixels are reported in units called Hounsfield units (HU).

• The following reference points are useful to know:
<table>
<thead>
<tr>
<th>Material</th>
<th>CT number</th>
<th>$\mu$ [cm$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>808</td>
<td>0.38</td>
</tr>
<tr>
<td>Muscle</td>
<td>0</td>
<td>0.21</td>
</tr>
<tr>
<td>Water</td>
<td>-48</td>
<td>0.20</td>
</tr>
<tr>
<td>Fat</td>
<td>-142</td>
<td>0.18</td>
</tr>
<tr>
<td>Air</td>
<td>-1000</td>
<td>0.00</td>
</tr>
</tbody>
</table>
CT (history vs. present)
Magnetic resonance imaging

• MRI images proton density by using a permanent magnet with a pulsed radio frequency (RF) field.

• The RF field changes the spin orientation of protons (tilting them and causing them to precess as they spin) within the body.

• We form an image by listening to a signal emitted as the protons relax back to their original orientation.
MRI

• We apply energy to perturb the system, but the signal itself is generated from the tissue sample under study!
• This places some fundamental limitations on MR image acquisition.
Single photon emission computed tomography (SPECT)

• **SPECT** camera acquire multiple planar views of the radioactivity in an organ
• the data are then processed mathematically (**iterative reconstruction**)
• SPECT utilizes the single photon emitted by gamma-emitting radionuclides such as $^{99m}$Tc, $^{67}$Ga, $^{111}$In, and $^{123}$I
• this is in contrast to PET
SPECT
Positron emission tomography (PET)

- PET cameras are designed to detect the paired 511-keV photons generated from the annihilation event of a positron and electron.
- Following emission, any positron travels only a short distance before colliding with electrons in surrounding matter.
- The paired 511-keV annihilation photons travel in opposite directions (180° apart) along a line.
PET
Ionizing vs. non-ionizing radiation

- **Ionizing radiation** – applied energy is sufficient to ionize atoms (ejects an electron from orbit, creating a positively charged ion). (e.g., X-ray, CT, PET, SPECT)

- **Non-ionizing radiation** – insufficient energy to ionize atoms (MRI, US, optical)
Imaging structure and function

• **Structure**: tissue density, region size, shape, and orientation.

• **Function**: Activity (metabolic rate), perfusion, ventilation.

• **Challenge**: combining structural and functional information together in a synergistic presentation (ex. display blood flow distribution on top of a CT slice of lung).
Digital image processing

- **What is an image?**
- **Formal definition:** A digital image is a multi-dimensional signal that is sampled in space and/or time and quantized in amplitude. An image is often represented by a multi-dimensional matrix (array) of numbers.
- **Looser definition:** An image is a „picture“. The brightness value in the picture may represent distance, reflectivity, density, temperature, etc.
Digital image processing

• The image may be 2-D (planar), 3-D (volumetric), or N-D.

• Image elements: an image is composed of:
  2-D: pixels = picture x elements
  3-D: voxels = volume x elements
Analog image to digital image conversion

greyscale test image

TV camera including optical system

CCD

CCD detail

conversion of 3D scene (optical information) into the electrical signal

electrical signal (voltage)

conversion of electrical signal (voltage) into the number within the range from 0 to 255

A/D – analog to digital converter as a part of „frame grabber“ (FG – PC card)

A/D

PC

SW

recording (memory) medium
What do images represent?

- X-ray attenuation (density)  X-ray, CT
- Water (proton) density, relaxation times  MRI
- Acoustic impedance  US
- Brightness  TV
- Tracer uptake (distribution of radioactivity)  NM
- Heat  IR
- Electrical impedance  EIT
Transfer properties of imaging systems

- Why?
- Analogy with 1D cases.
- Key point: spatial frequency, contrast transfer
- How to measure quality?
- Set of transfer functions
Impulse response of imaging system - PSF

\[ g(x, y) = f(x, y) \ast h(x, y) \]
2D convolution

\[ f(x, y) = \delta(x - x', y - y') \quad \text{and} \quad g(x, y) = h(x - x', y - y') \]

\[ g(x, y) = f(x, y) * h(x, y) \]

\[ g(x, y) = f(x, y) * h(x, y) = \int f(\alpha, \beta) h(x - \alpha, y - \beta) \, d\alpha \, d\beta \quad \square^2 \]

\[ h_{\text{ideal}}(x, y) = \delta(x, y) \]
2D convolution – example 1

Video_1
2D convolution– example 2

Video 2
Transfer function of imaging system in frequency domain

\[ F \{ g(x, y) \} = F \{ f(x, y) * h(x, y) \} \]

\[ G(u, v) = F(u, v) H(u, v) \]
The resulting transfer function of imaging system

\[ h(x, y) = h_1(x, y) * h_2(x, y) * \ldots * h_n(x, y) \]

\[ H(u, v) = H_1(u, v) \cdot H_2(u, v) \cdot \ldots \cdot H_n(u, v) \]
Spatial frequency

\[ u = \frac{1}{X}, \quad v = \frac{1}{Y} \quad \text{cy/mm} \quad \text{Hz} \equiv \text{cy/s} \]

\[ \text{lp/mm} \quad \text{cy/mrad} \quad u_a = \frac{r}{X} = ru \]

Spatial period

Angle period

Distance

Place of observation

Spatial frequency

\[ u = 1/X \text{[cy/m]} \]

Spatial angle frequency

\[ u_a = r/X \text{[cy/rad]} \]
Relationships among transfer functions

\[ OTF \equiv \mathbf{F} \{ h(x, y) \} = |H(u, v)| e^{j\phi(u, v)} \]

\[ MTF \equiv |H(u, v)| \]

\[ PTF \equiv \Box H(u, v) = \phi(u, v) \]
**Modulation transfer function**

\[ M = \frac{A_{\text{max}} - A_{\text{min}}}{A_{\text{max}} + A_{\text{min}}} = \frac{ac}{dc} \]
CTF and MTF relationship

- **Object**
- **MTF**
- **Image**
- **CTF**

- **PSF**
- **OTF**

- **Impinging system**

- **Imaging system**

- **Zobrazovací soustava**

- **A**

- **u**
Phase transfer function (PTF)
Effect of PTF on distortion

Image

Object

Convolution

Convolution kernel

\[ k_{16} = \frac{1}{256} \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & 1 & \cdots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & \cdots & 1 \end{bmatrix} \]
Another transfer functions

Point source

Line source

Edge source

Imaging system

Imaging system

Imaging system

Bodový zdroj

Liniový zdroj

Zdroj hrany

Zobrazovací soustava

Imaging system

PSF $x, y$

LSF $x$

ESF $x$
Line spread function (LSF)

$$LSF(x) \equiv g(x, y) = f(x, y) \ast h(x, y) = \delta(x) \ast PSF(x, y)$$

$$MTF(u, 0) = |F \{LSF(x)\}| \quad f(x, y) = \delta(y) \quad MTF(0, v) = |F \{LSF(y)\}|$$

$$LSF(x) \neq PSF(x, 0)$$

Edge spread function (ESF)

$$LSF(x) = \frac{d}{dx} \left( \int_{-\infty}^{x} LSF(x') dx' \right) = \frac{d}{dx} (ESF(x))$$
Mathematical relationships among PSF, OTF, MTF, LSF, ESF

\[ \text{PSF}(x, y) \xrightarrow{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \text{PSF}(x', y) \, dy \, dx'} \text{ESF}(x) \]

\[ \text{OTF}(u, v) \xrightarrow{\int_{-\infty}^{\infty} \text{PSF}(x, y) \, dy} \frac{d}{dx} \text{ESF}(x) \xrightarrow{\int_{-\infty}^{\infty} \text{LSF}(x') \, dx'} \text{LSF}(x) \]

\[ \text{MTF}(u, v) \xrightarrow{\text{OTF}(u, v)} \text{OTF}(u, v = 0) \]

\[ \text{MTF}(u, v = 0) \xrightarrow{\text{MTF}(u)} \text{MTF}(u) \]

\[ \text{OTF}(u) \xrightarrow{\text{F}_{1D} \{\text{OTF}(u, 0)\}} \text{LSF}(x) \xrightarrow{\text{F}_{1D} \{\text{LSF}(x')\}} \text{MTF}(u) \]

\[ |\text{OTF}(u)| \xrightarrow{\text{F}_{1D} \{\text{OTF}(u)\}} \text{OTF}(u) \]
Aliasing

Sensed scene

Optical antialiasing filter

Spatial sampling

Reconstruction filter

Reconstructed image - aliasing

Reconstructed image - without aliasing

Brightness profile of sensed scene and reconstructed image

$\Delta x$ sampling period

Reconstructed image without aliasing

Samples of sensed scene

Reconstructed image with aliasing

Sensed scene
Magnetic resonance imaging

- MRI physics in brief
  - proton NMR physics
  - MR image formation
Basic NMR physics

- Magnetization
- Resonance
- Excitation and detection
- Rotating frame
- Dephasing
- T1 & T2 relaxation
Charge, mass and spin of the proton as nuclear particle

Video 1
### NMR parameters of common nuclei

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Gyromagnetic ratio [MHz/T]</th>
<th>Relative sensitivity</th>
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</thead>
<tbody>
<tr>
<td>$^1$H</td>
<td>42.570</td>
<td>1.000</td>
</tr>
<tr>
<td>$^{13}$C</td>
<td>10.700</td>
<td>0.015</td>
</tr>
<tr>
<td>$^{19}$F</td>
<td>40.050</td>
<td>0.833</td>
</tr>
<tr>
<td>$^{31}$P</td>
<td>17.235</td>
<td>0.066</td>
</tr>
<tr>
<td>$^{23}$Na</td>
<td>11.230</td>
<td>0.092</td>
</tr>
</tbody>
</table>

Only isotopes with an odd number of protons or neutrons have a non zero spin.
Bulk magnetization

Video 2
Detection of magnetization (induction)

Video 3
RF pulses (spin excitation)

Video 4
NMR signal (spin-echo pulse sequence)

Video 5
The motions of the magnetization vector

- part 1 – laboratory frame point of view
- part 2 – magnetization+turntable+camera in synchrony
- part 3 – view of the rotating frame camera

Video_6
Tissue MR properties

- Proton density (PD)
- Spin-lattice relaxation (T1)
- Spin-spin relaxation (T2)
- Susceptibility effects (T2*)
- Motion
Addition of magnetization vectors

Vectors in-phase maximum magnitude

Out-of-phase smaller magnitude
The resulting magnetization vector

Video 7
The resulting magnetization vector for laboratory and rotating frame

Video 8
The MR system demodulation of the NMR signal

Video 9
Dephasing in laboratory and rotating frame

Video 10
Total dephasing in laboratory and rotating frame

Video 11
Total dephasing in laboratory and rotating frame – T2* decay time

Video 11 2
MNR signal decay (spin-echo)

- Constant spin dephasing
- Spin-echo will remove
Spin-spin interactions

- Changing spin dephasing
- Due to spin-spin coupling
- Measure T2 with spin-echo
Spin-echo
Details of the spin-echo sequence

• part 1 - the behavior of spin dephasing and RF pulses during the sequence
• part 2 - NMR signal for different echo times TE
• part 3 - detailed view of the transverse magnetization components alone

Video 12
The spin echo - T2 summary (MNR signal vs. the time TE)
Typical T2 values in the head

<table>
<thead>
<tr>
<th>Tissue</th>
<th>T2 (ms)</th>
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<tbody>
<tr>
<td>Grey matter</td>
<td>87</td>
</tr>
<tr>
<td>White matter</td>
<td>74</td>
</tr>
<tr>
<td>CSF</td>
<td>250</td>
</tr>
<tr>
<td>Thalamus</td>
<td>75</td>
</tr>
<tr>
<td>Putamen</td>
<td>71</td>
</tr>
<tr>
<td>Internal capsule</td>
<td>67</td>
</tr>
<tr>
<td>Corpus callosum</td>
<td>69</td>
</tr>
<tr>
<td>Caudate nucleus</td>
<td>76</td>
</tr>
</tbody>
</table>
T2 modulation of image contrast
Spin-lattice (T1) relaxation
Spin-lattice (T1) relaxation - animation

Video_13
Spin-lattice relaxation values for various tissues (sample T1 relaxation times)

<table>
<thead>
<tr>
<th>Tissue</th>
<th>T1 (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grey matter</td>
<td>871</td>
</tr>
<tr>
<td>White matter</td>
<td>515</td>
</tr>
<tr>
<td>CSF</td>
<td>1900</td>
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<tr>
<td>Thalamus</td>
<td>703</td>
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<td>Putamen</td>
<td>747</td>
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<tr>
<td>Internal capsule</td>
<td>559</td>
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<tr>
<td>Corpus callosum</td>
<td>509</td>
</tr>
<tr>
<td>Caudate nucleus</td>
<td>822</td>
</tr>
</tbody>
</table>
T1 modulation on image contrast
Summary of T1 and T2 relaxation (relaxation effects)

**T1 Relaxation**
- spin-lattice interactions
- dissipation of energy
- 200-2000 ms time constant

**T2 Relaxation**
- spin-spin interactions
- loss of spin phase (order)
- 25-250 ms time constant
Overview of lecture on the physics of image formation (MR imaging)

- Image structure
- Fourier representation
- Magnetic field gradients
- Moving through K-space
- Collecting K-space data
- MRI sequence summary
Structure of MR images

Find the Location/Brightness of each Pixel
The question of localization (How do we localize the signal?)

MR Signals originate from all tissues, not a pixel
The spatial location task

Find pixel location in x, y & z
Techniques for spatial localization

Z - Selective Excitation
X - Frequency Encoding
Y - Phase Encoding
Selective excitation: The ingredients

Combines effects of:
- NMR resonance
- Magnetic Field Gradient
- RF excitation frequency
Selective excitations: An analogy - resonance

A - 440 Hz

440 Hz

F G A B C
Selective excitations and NMR resonance
A uniform magnetic field (magnetic field gradients)
A magnetic field gradient (Gz - in Z direction)
Selective excitation and a Gx gradient
The effect of RF pulses in selective excitation
In plane localization

**X - Frequency Encoding**
Measures NMR signal in the presence of a gradient in the X direction

**Y - Phase Encoding**
Induces a different gradient to induce a phase twist in the Y direction.
The relation between the MR system and image formation
Image space vs. K-space
A one dimensional problem (Fourier transform)

1D object

How is this object represented in terms of simple functions?

distance
A crude Fourier approximation

![Graph showing amplitude vs. distance with frequency labels]

- Frequency $freq = 0$
- Frequency $freq = 1$
A better Fourier approximation
The definition of K-space
Successively better approximation
Successively better approximation
Two dimensional K-space and image space (space and image domains)
The meaning of various points on K-space (Fourier transform representation)
The question of How stripes are made in MRI? (MR image formation)

How does MR imaging make
- stripes?
- variable spatial frequency?
- variable orientation?
Return to the relation of the MR system and image formation.
Gradient in X (gradient X direction)
Gradient in Y (gradient Y direction)
An alternative representation for magnetization

Video_14
The effect of a gradient on an array of magnetization balls
The effect of a gradient on an array of magnetization balls (animation)

Video_15
Creating vertical stripes

Video_16
Creating horizontal stripes

Video_17
Creating blique stripes and K-space

Video_18
Oblique stripes: A summary
How does the MRI system measure the K-space signals?

Video_19
A simple (but incomplete) MRI pulse sequence
The four quadrants of K-space (symmetric 2D K-space)
A more complete MRI pulse sequence
Fourier reconstruction of K-space: part A

Video_20
Fourier reconstruction of K-space:
part B

Video_20_2
Conclusion I (MR image formation)

- Spatial location by application of three orthogonal gradients
- **Selection excitation** defines slice location and width
- In-plane locations done by: Frequency Encoding  
  Phase Encoding
Conclusion II (MR image formation)

- Frequency Encoding
  - Measures location in one direction
  - MR signal measured with gradient on
  - MR signal vs time measures the K-space data
Conclusion III (MR image formation)

- **Phase-encoding** defines Y position
- Incremented phase-encoding gradient generates Ky data
- Combined phase/frequency encoding defines all K-space data
- Requires many RF/gradient pulses to fill all K-space