Medical Imaging Modalities
Principle and Image Quality of CT scans

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Medical Imaging Modalities - An Introduction

Contents

→ Imaging – purpose?
→ Overview about common imaging modalities
→ CT principle 1: Xrays
→ CT principle 2: Image reconstruction
→ Image viewing and image quality
Medical Imaging Modalities - An Introduction

Aims

→ You know the common clinical imaging modalities
→ You know some clinical applications of CT
→ You are able to describe the basic principle of CT
→ You can explain 1-2 methods for image quality assessment
Imaging - Purpose?

Different questions – different modalities:

- Diagnostic: Imaging of anatomy and physiology!
- Image guided therapy: Interventional radiology and radiotherapy
- Theranostics: Tracer with isotopes for functional imaging and therapy
Overview about common imaging modalities

Different questions – different modalities:

Diagnostic: Imaging of anatomy and physiology:

- Xray projection radiography (XR), Xray fluoroscopy (XRF)
- Computer tomography (CT)
- Xray angiography (XRA), CT angiography

X-rays

Nuclear medicine

- Positron Emission Tomography (PET)
- Single Photon Emission Tomography (SPECT)

Non-ionising radiation

- Ultrasound / Sonography
- Magnetic Resonance Tomography / Imaging (MRI)

(mechanical waves, Radio frequency EMW)
PET & SPECT: Tomography in Nuclear Medicine

Applications / Indications:

→ Metabolic information (tracer principle)
→ $^{18}\text{F}$-FDG for PET brain imaging or cancer metastasis search
→ $^{99}\text{mTcO}_4$ for bone microfractions or metastasis search
→ Theranostics
PET & SPECT: Tomography in Nuclear Medicine

Principle of tracer and imaging:

→ Tracer (specific molecule defines biokinetics)
→ Tracer accumulates in certain structures (e.g., metastasis or active brain region)
→ Isotope defines radiation energy and characteristics: For PET, a positron emitter has to be used
PET & SPECT: Tomography in Nuclear Medicine

How to get an Image?:

→ Radiation detection with a szintillation detector
→ Gamma (Anger-) cam: Collimation of radiation (scatter = bluring; no or less collimation needed for PET)
→ For tomography: measurements at different angles / posistions → Projections!
SPECT: Single Photon Emission Tomography

How to get an Image?:

→ For tomography: measurements at different angles / positions → Projections!
SPECT-CT
PET: Positron Emission Tomography
Image Fusion: PET and MRI
MRI: Magnetic Resonance Imaging

Applications / Indications:

→ Soft tissue (not bones due to lack of signal)
→ Anatomic and functional / physiological information
→ fMRI, blood flow
→ Spectroscopy
→ Cerebral diagnostics
→ Cardiology
→ ...

![MRI Image]
Input: Puls Sequ

Output: (FID) Signal
In a MR image, different measures can be converted to grey scale and displayed: Weighting in different images

- **PDw**
  - TR/TE=5500/14ms

- **T₁w**
  - TR/TE=500/10ms

- **T₂w**
  - TR/TE=5500/101ms
SONO/US: Ultra Sound

Applications / Indications:

→ Soft tissue (not bones due to high impedance)
→ Endosonography
→ Echocardiography
→ Doppler sonography
→ Vascular system by using contrast media
→ Advantage: non-ionizing radiation!
→ ... and gives 2-dim. slices through patients anatomy
Endosonography
SONO/US: Ultra Sound

Principle of image generation:

→ Mechanical waves emitted into patients body
→ Frequency 1-20 MHz
→ Reflected waves are detected
Xrays – toward an insight into patients anatomy

Steps to modern diagnostics:

→ 1895: Discovery of Xrays by C.W. Röntgen
→ End of 19th Century: first medical applications (diagnostics)
→ Early 20th Century: first therapeutic applications
→ 1969 / 72 first CTs (Hounsfield, first commercial scanner by EMI)
Xrays – toward an insight into patients anatomy

Principles of Xray generation:

→ High voltage ($U$) between anode and cathode (40-140 kV for diagnostics; 20-300 kV for therapy)

→ Acceleration of electrons between cathode and anode

→ Electron transport toward anode (tube current, mA)

→ Collision of electrons with anode (Bremsstrahlung, characteristic lines)
The Xray Source

Tube Voltage
(40 - 150 kV)

Transformer
(230 V)

Heating Circuit
(12 - 100 V)

Wagner, 2007: Biomed Imaging Interv J

Hip Imaging ...

after coronary Angiography

after CT Angiography
Conventional Xray – Projection Radiography

What can be seen?
(densities):

→ Air
→ Fat
→ Muscle
→ Bone
→ Metal
→ High contrast produced by Photo-electric effect
XRF:
Flouroscopy

XRA:
Angiography (+ Contrast media)

DSA:
Digital Subtractions-Angiography
(Contrast-enhanced image – native image)
Detectors

Task: Convert Xrays into a signal, for CT:

- Gas-filled ionisation chambers
- Szintillators & photo multipliers
- CMOS
CdTe-Detektor

CdTe-Sensor Technology vs. Conventional CCD/CMOS

**AJAT CdTe-Sensor**

- X-rays
- CdTe (X-rays converted to electrical signals)
- Electric Circuit
- Sharp Image

**CCD/CMOS**

- X-rays
- Phosphor Screen (X-rays converted to light)
- Optical lens
- Electric Circuit
- Image
Detectors

Information width:

→ Small for photographic system (film with fluorescent screen)
→ Large for CT: typical resolution 12 bit, special monitors for displaying medical Xray images 10 bit
CT: Computer Tomography

Applications / Indications:

→ 2D- (slice) or 3D- view (rendered contours) available
→ DVT: Dental Volume Tomography and CBCT
→ Soft tissue contrast clearly better than with conventional (projection-) radiography
→ CT angiography
→ Fast reconstruction algorithm allowing 4D-CT (tracking)
→ RT planning
CT - based Radiation Therapy Planning
EMI-Scanner
1972
Dental Volume Tomography DVT
CT: 2D or 3D?
CT: How To Get An Image (Slice)

Basic Principle:

→ Projection: Absorption of radiation can be detected as relief
→ Reconstruct 2-dim. Image from $n$ 1-dim projections
→ $n \to \infty$ for ideal image ($n > 36$ for real image)
Image matrix 80x80 Pixles (1974)

Image matrix 512x512 Pixles (2000)

imbie.meb.uni-bonn.de/epileptologie/staff/lehnertz/CT1.pdf
CT: How To Get An Image (Slice)

Basic Principle:

→ Real image is a pixelized image
→ Every pixel represents a grey scale corresponding to the tissue density (resolution 12 bit)
→ Task: find the density of a pixel based on $n$ projections
CT: How To Get An Image (Slice)

Basic Principle:

→ Task: find the density of a pixel based on $n$ projections

→ The absorption contribution from a specific direction to every pixel is defined by the sum of contributions of every path element
CT: How To Get An Image (Slice)

Basic Principle:

→ The absorption contribution from a specific direction to every pixel is defined by the sum of contributions of every path element

→ The signal strength $P$ in a projection is given by the detected intensity $I$

→ For absorption, the Beer-Lambert law is assumed

$$
I = I_0 e^{-\int ds \cdot \mu(x,y)}
$$

$$
\Rightarrow P(\varphi) = \ln \left( \frac{I_0}{I} \right)
$$

$$
= \int_s ds \cdot \mu(x,y)
\approx \sum_i \mu_{ik}
$$
**CT: How To Get An Image (Slice)**

Algebraic approach:

→ All projections are defining a system of (linear) equations

→ The projection values $P(\phi)$ are known

→ Rearrange equations to find the contributions $x$
$N = 180$
Reconstruction Algorithms

Different approaches:

→ Arithmetic (slow)
→ FFT: A projection in the real space corresponds in the k-space (frequency domain) to a slice; FFT of projection, add all k-space slices, reverse FFT
→ Filtered back projection: Convolution of real space projections with filter function (e.g. Shepp Logan Kerner)
→ Iterative reconstruction: estimation of the real pixel value by a statistical / physical model
*) courtesy of University of Erlangen, Germany
Scanning-Techniques
Scanning-Techniques

Pencil-Beam-Geometry

- Parallel beams needed for reconstruction
Scanning-Techniques

Fan-Beam-Geometry

• Divergence in slice
Scanning-Techniques

Fan-Beam-Geometry

- Divergence in slice
- Parallel beams (rays) in different projections
Scanning-Techniques

Fan-Beam-Geometry

- Divergence in slice
- Parallel beams (rays) in different projections
- Reassembly of parallel beams
Scanning-Techniques: Axial / Sequential vs. Spiral Scans
IAEA HUMAN HEALTH REPORTS
No. 5: STATUS OF COMPUTED TOMOGRAPHY DOSIMETRY FOR WIDE CONE BEAM SCANNERS
CT: Image Content and Window

\[
HU = \frac{\mu_x - \mu_{Wasser}}{\mu_{Wasser}} \cdot 1000
\]
CT: Image Content and Window

Window

+1000
+ 800
+ 600
+ 400
+ 200
  0
- 200
- 400
- 600
- 800
- 1000

HU

Center

+148
+ 120
+ 100
+ 80
+ 60
+ 40
+ 20
  0
- 20
- 40
- 60
- 80
- 100
- 108

Displayed grey scale 8-10 bit
soft tissue and lung window

W 400 HU
C +45 HU

W 750 HU
C -720 HU
CT Image Quality

Parameters

→ Low contrast detectability: contrast, noise
→ (High contrast) resolution: spatial resolution, MTF

Artefacts

→ Partial volume
→ Beam hardening
→ «object generation / modification» by AI! (reco using machine learning / deep learning)
Why are we trying to measure Image Quality?

Different reasons – different tasks:

→ Performance: system suitable for clinical tasks?
  Clinical relevant quality (Model Observer)
→ Optimisation: system working at optimal point (ALARA)?
  Comparison of quality with applied dose (e.g. DDC with CTDI)
→ Quality control: Change in systems performance?
  Comparison of a measure representing systems performance
  with the base line (e.g. DQE, NPS, MTF etc.)
From Quality to Quantity?

- Observer impression
- Visual Grading Analysis VGA
- Receiver Operating Characteristics ROC
- Alternative Force Choice AFC
- CDC / DDC
- Line pair TO
- MTF, NNPS DQE, SNR CNR
Low-Contrast-Detectability: Contrast – to – Noise Ratio CNR

Simple approach: Difference of SNR in two compared ROI’s

→ Usefull for relative signal detection with threshold?

\[
CNR = \frac{\langle HU \rangle_{Pos2} - \langle HU \rangle_{Pos1}}{s_{nm,Pos2}(HU) - s_{nm,Pos1}(HU)} = \Delta_{12}SNR
\]
Low-Contrast-Detectability: Contrast – to – Noise Ratio

\[ \text{CNR} = -0.007 \]

\[ \text{CNR} = 0.03 \]
Modulation Transfer Function MTF

\[ MTF(\nu) = \left| \int_{-\infty}^{\infty} L(x) \cdot e^{-2\pi i x \cdot \nu} \, dx \right| \]
Modulation Transfer Function MTF
Gaussian filter $r = 12$ pixels

Initial image

Gaussian filter $r = 4$ pixels

Gaussian filter $r = 12$ pixels

MTF high C

MTF vs. Frequency

Position / pixel

Grey Value

Reihe1
Reihe2
Reihe3
Reihe4
Reihe5
Reihe6
Reihe7
Reihe8

lp / pixel

MTF

Reihe1
Reihe2
Reihe3
Reihe4
Reihe5
Reihe6
Reihe7
Reihe8
Gaussian filter $r = 12$ pixel

Initial

Gaussian filter $r = 4$ pixels

Gaussian filter $r = 12$ pixel

MTF high C

MTF

Grey Value

Position / pixel

lp / pixel

Reihe1
Reihe2
Reihe3
Reihe4
Reihe5
Reihe6
Reihe7
Reihe8
Modulation Transfer Function MTF: Iterative Reconstruction

\[ M_{total} \neq \prod_{k} MTF_k \]


<table>
<thead>
<tr>
<th>Abdomen (Siemens Force Abdomen 2.0 Br36)</th>
<th>MTF 50</th>
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<tbody>
<tr>
<td>3)</td>
<td>0.227</td>
</tr>
<tr>
<td>4)</td>
<td>0.239</td>
</tr>
<tr>
<td>5)</td>
<td>0.2435</td>
</tr>
</tbody>
</table>
Alternative Approach

Contrast-detail curve [1, 2, 3]
Alternative Approach

![Graph showing the relationship between contrast (Δ CT), object size (mm), and dose with arrows indicating higher spatial resolution and greater dose. The shape depends on scan parameters (mA, kV etc) and reconstruction parameters (recon. alg.).]
Alternative Approach

More noise

Smooth algorithm (. . . less noise)