ETH zürich | University of Zurich[UZH]

Biomedical Imaging

X-Ray Imaging (III)

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Today's Learning Objectives

- **Recap FT and FPB reconstruction in reciprocal spaces**
- **Relate FT and FBP reconstruction to algebraic reconstruction**
- **Explain spiral CT principle and reconstruction**
- **Derive relation between SNR and experimental settings**
- **Implement noisy CT experiment and filtering** (Exercise)

Image reconstruction

CT – Image reconstruction

- Inverse transform (III)

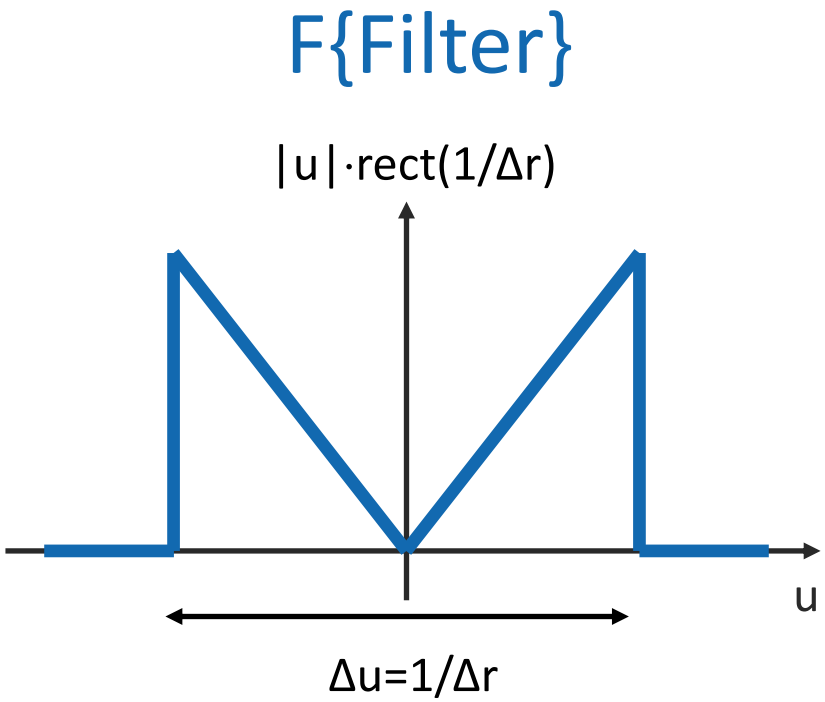
F{Filter}

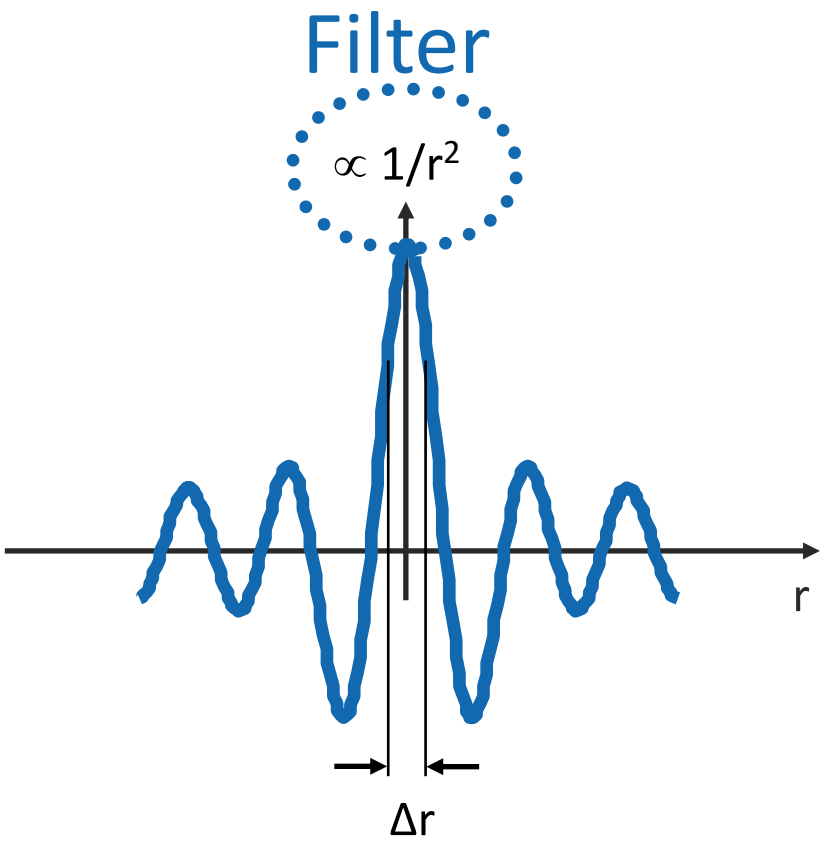
$$\mu(x,y) = \frac{1}{4\pi^2}\int_0^{\pi}\int_{-\infty}^{+\infty} F\{P_\varphi(u)\}\, e^{iur}\,|u|\,du\,d\varphi$$

$$\text{Image} = \text{Filter} * \text{Object} \leftrightarrow F\{\text{Image}\} = F\{\text{Filter}\} \cdot F\{\text{Object}\}$$

Filter ?

CT – Image reconstruction



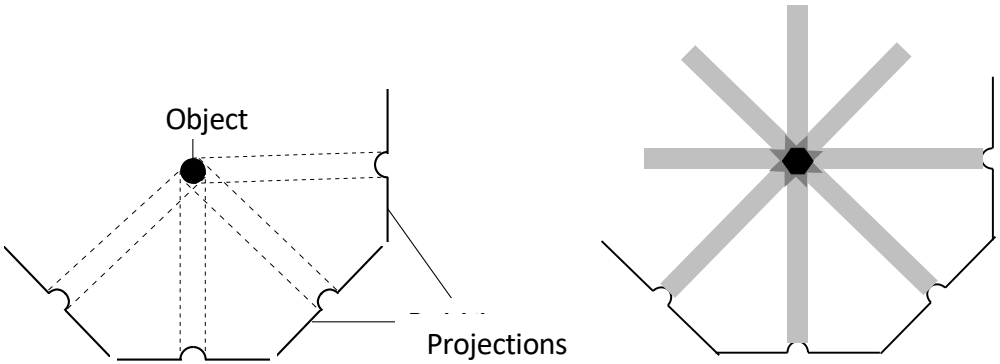


"Ramachandran & Lakshminarayanan"
="Ram-Lak"

CT – Filter

Point object

Image



"Ideal" Filter:
1) $\text{radius}_{\text{object}} \rightarrow 0$
2) number of projections $\rightarrow \infty$
3) number samples per projection $\rightarrow \infty$

$$\text{Filter} \propto \left|\frac{1}{r^2}\right|$$

Ram-Lak Filter

"Real" Filter:
1) $\text{radius}_{\text{object}} \rightarrow 0$
2) number of projections $\rightarrow \infty$
3) number samples per projection $\rightarrow N_r$

$$\text{Filter} \propto \left|\frac{1}{r^2}\right| * \text{sinc}\left(\frac{r}{2\Delta r}\right)$$

CT – Beam geometries

Scan efficiency

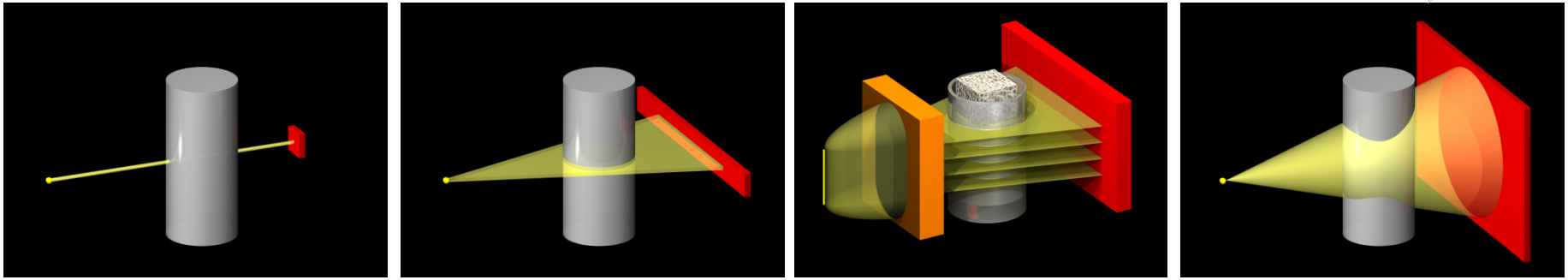
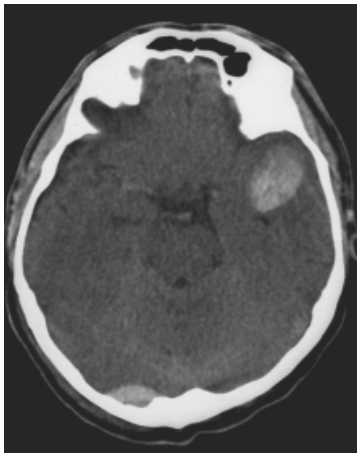
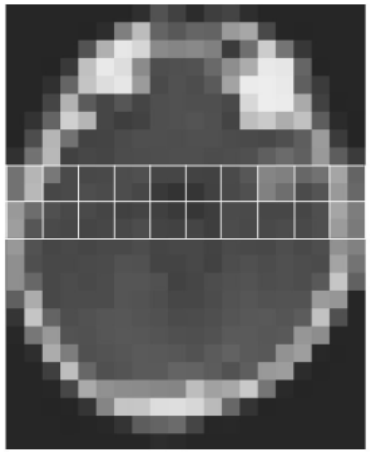


Image reconstruction complexity

CT – General approaches to reconstruction

	ReconObject O(x,y)	Measurement	Measured data P(φ,r)
■ Analytical	continuous	continuous	continuous
■ Algebraic	discrete	linear	discrete

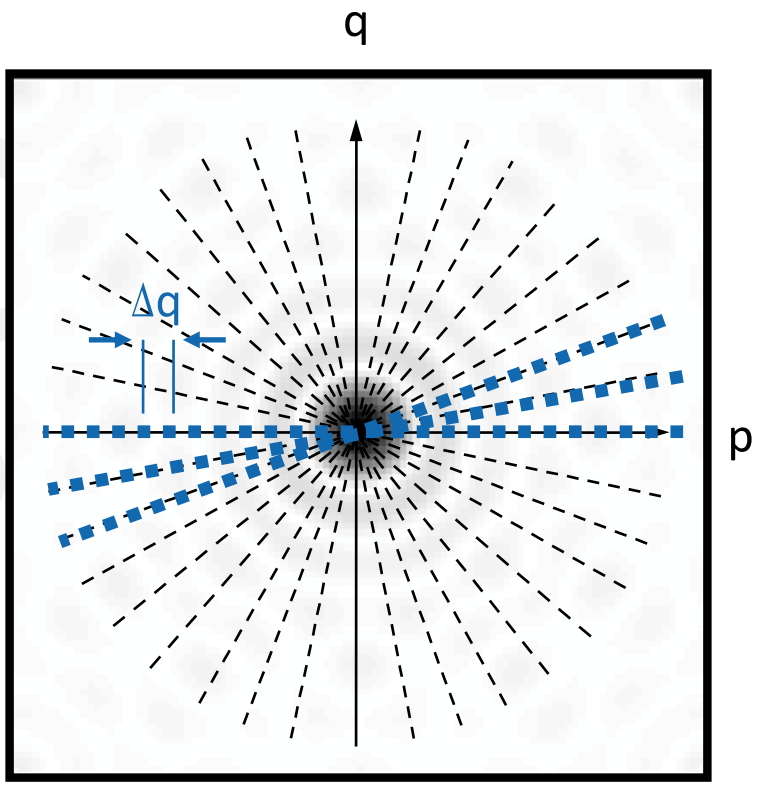




Clicker Activity (5 min)

How many projections does one need to collect in order to fulfill the Nyquist sampling criterion if the number of sample points per projection is N according to the Nyquist rate Δq?

- N different projections are required
- 2*N different projections are required
- pi/2*N different projections are required
- pi*N different projections are required

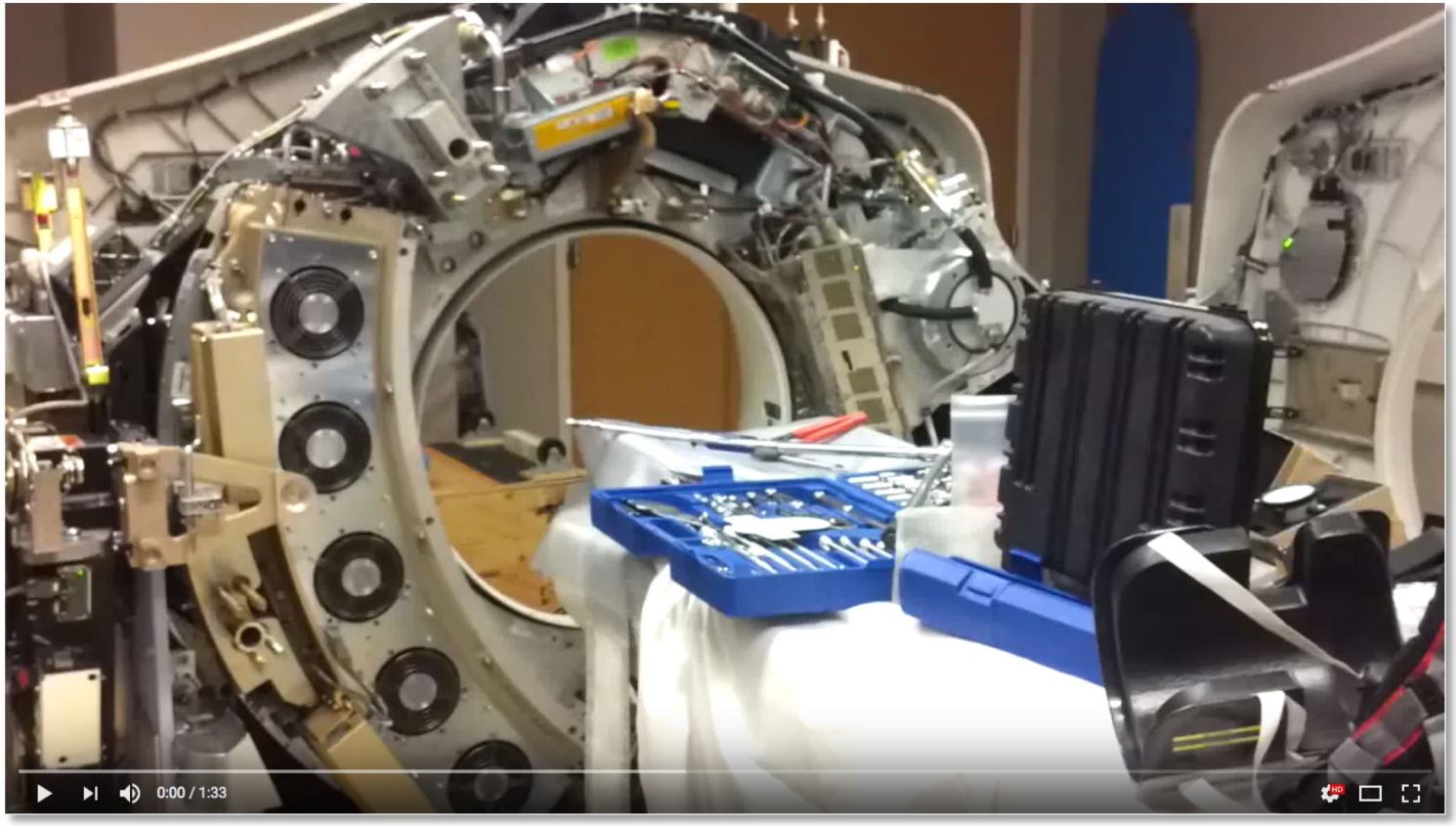


ETH Edu

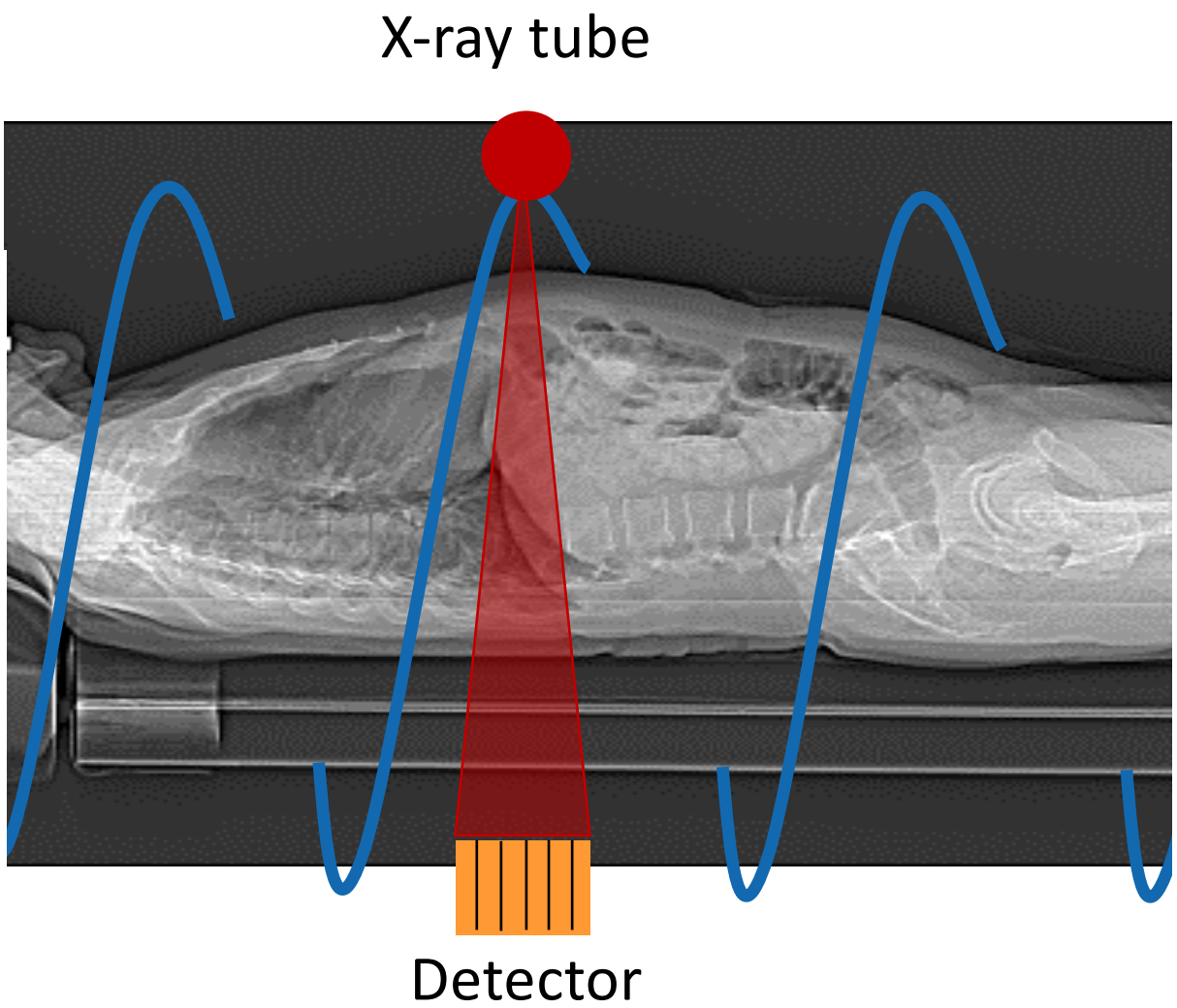
Clicker Activity (Notes)

Spiral CT

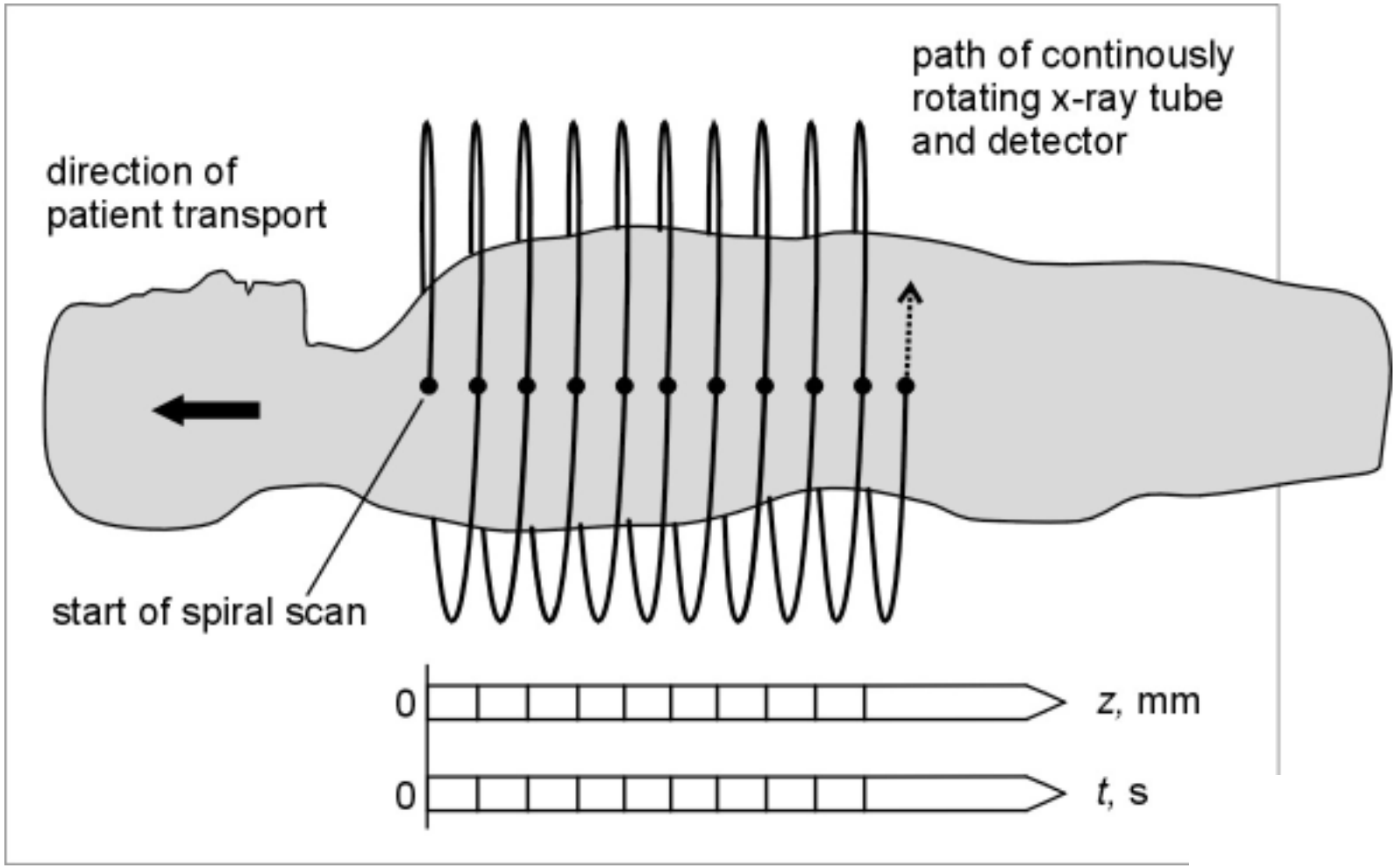
Spiral CT



Spiral CT



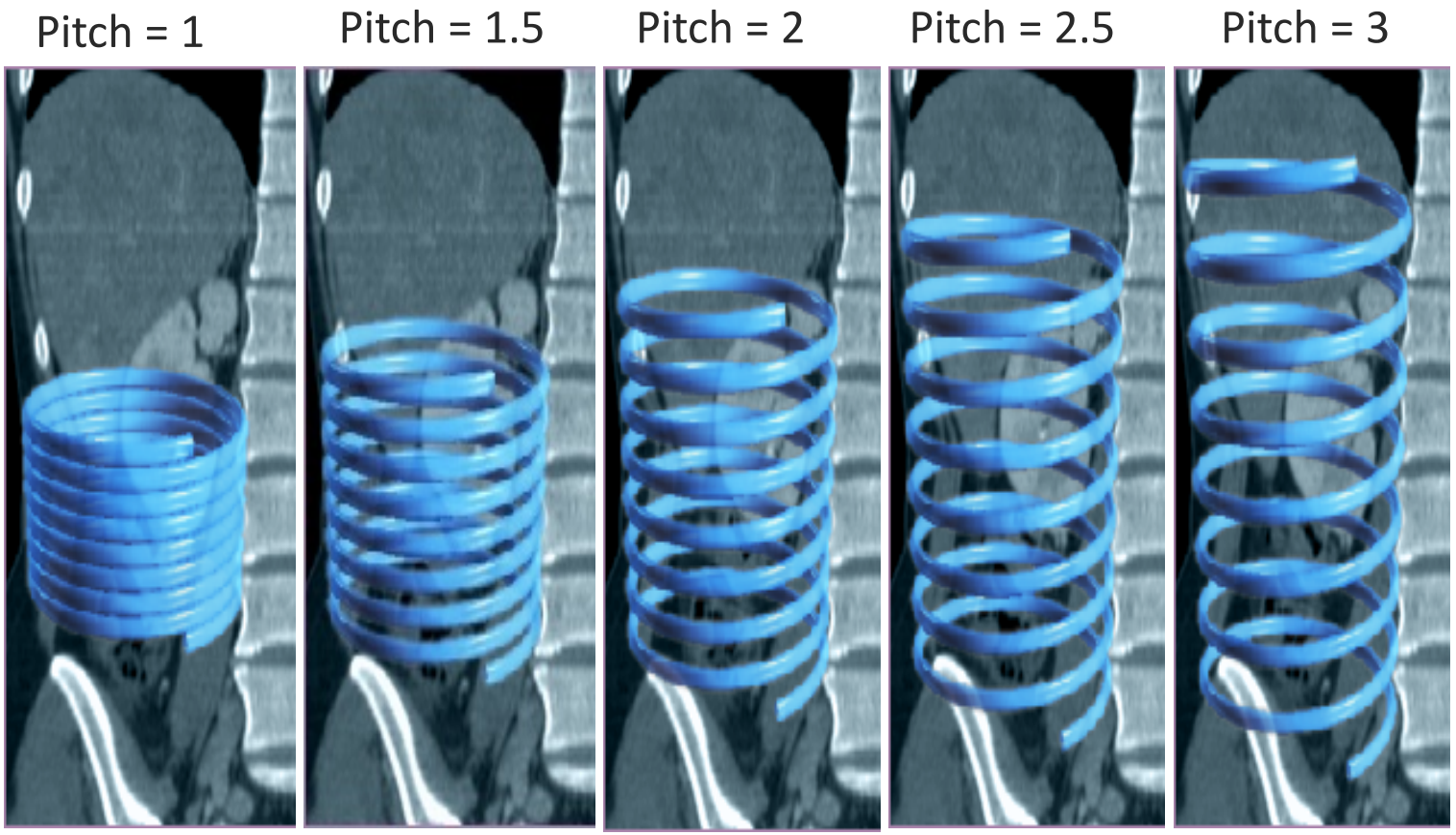
Spiral CT



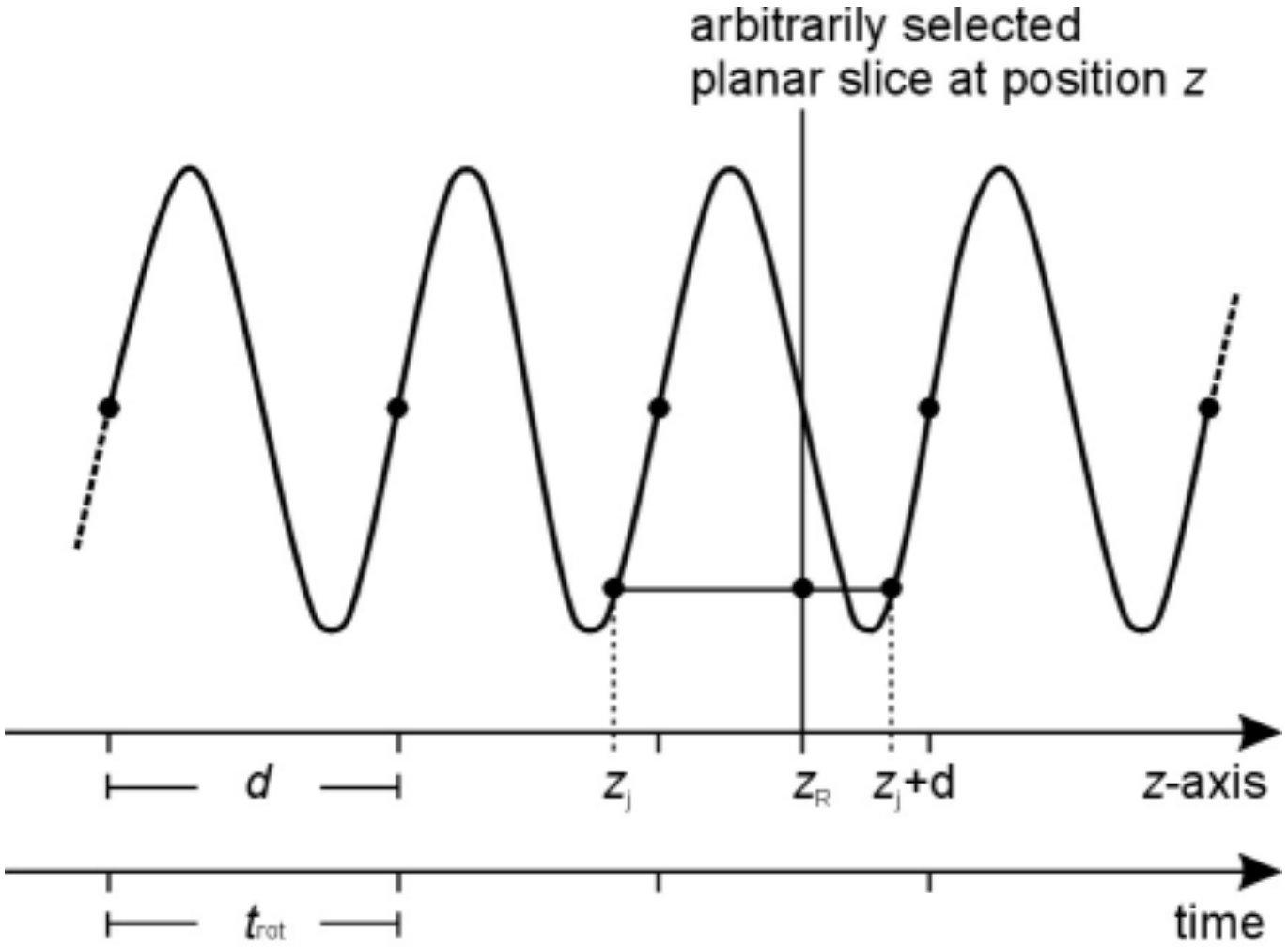
Adapted from Kalender WA, Computed Tomography, ISBN 3-89578-216-5

Spiral CT

- Pitch = table movement per rotation/slice collimation



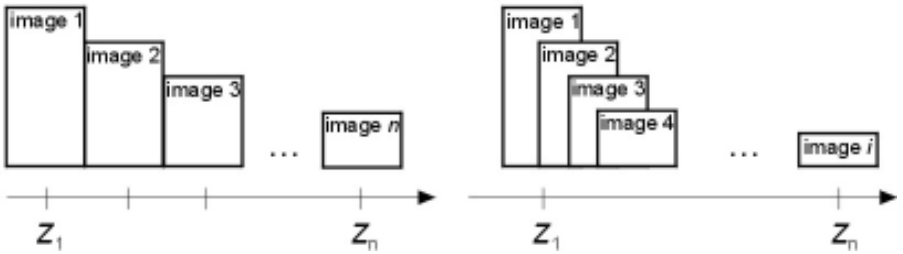
Spiral CT



Adapted from Kalender WA, Computed Tomography, ISBN 3-89578-216-5

Spiral CT

	Conventional CT	Spiral CT
scanning	n 360° scans at positions z_1 *to* z_n	one scan of $n \cdot 360°$ from position z_1 to z_n
	⇩	⇩
preprocessing	corrections	corrections
	⇩	⇩
intermediate step	-	*z*-interpolation
	⇩	⇩
image reconstruction	convolution and backprojection	convolution and backprojection
	⇩	⇩
result	*n* images at positions z_1 *to* z_n	images at arbitrary positions from z_1 to z_n



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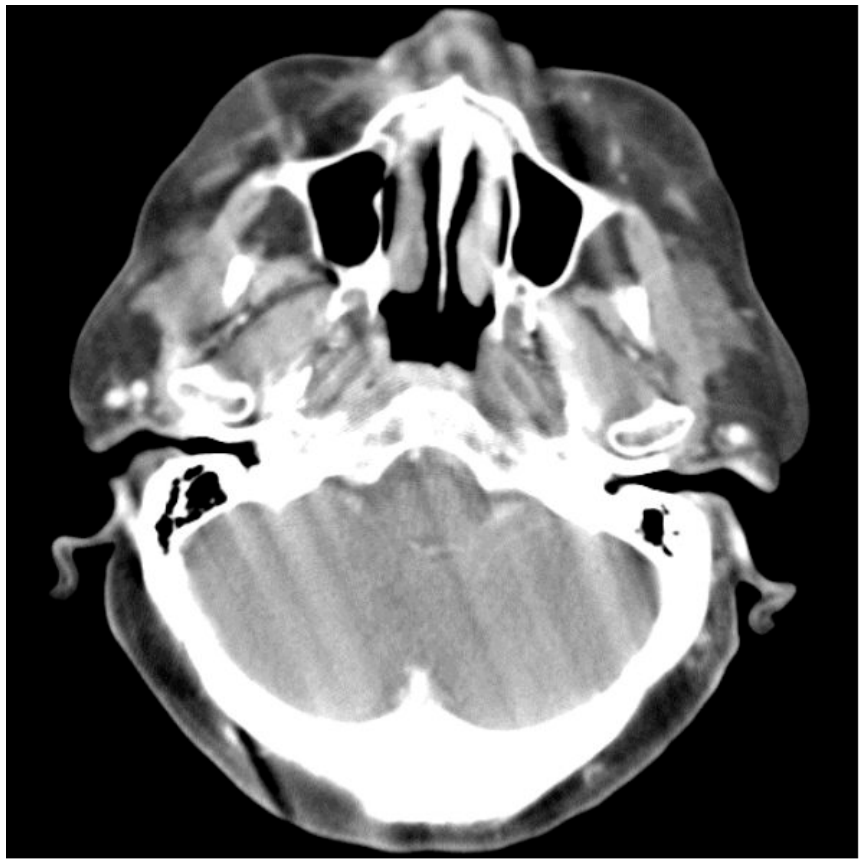
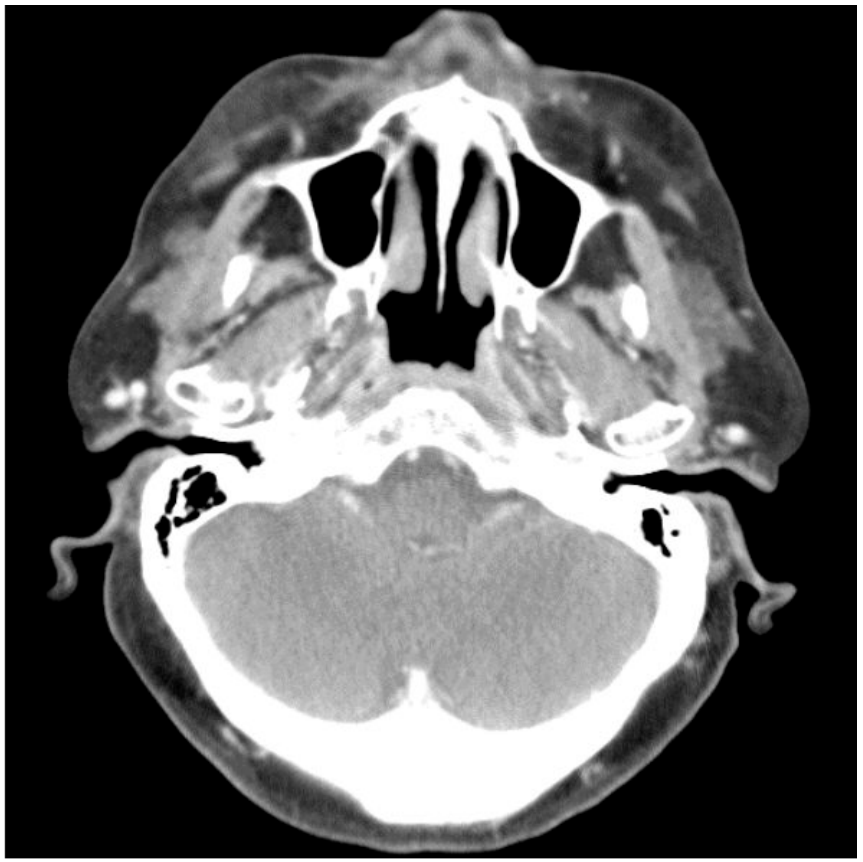
Spiral CT

Without z-Interpolation



With z-Interpolation



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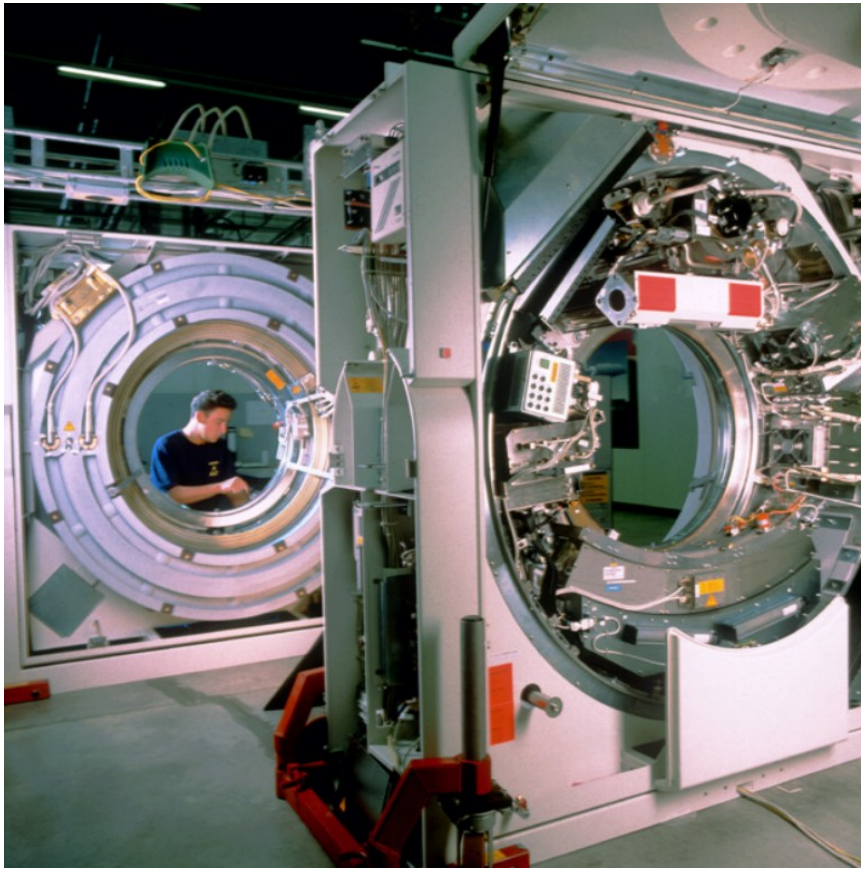
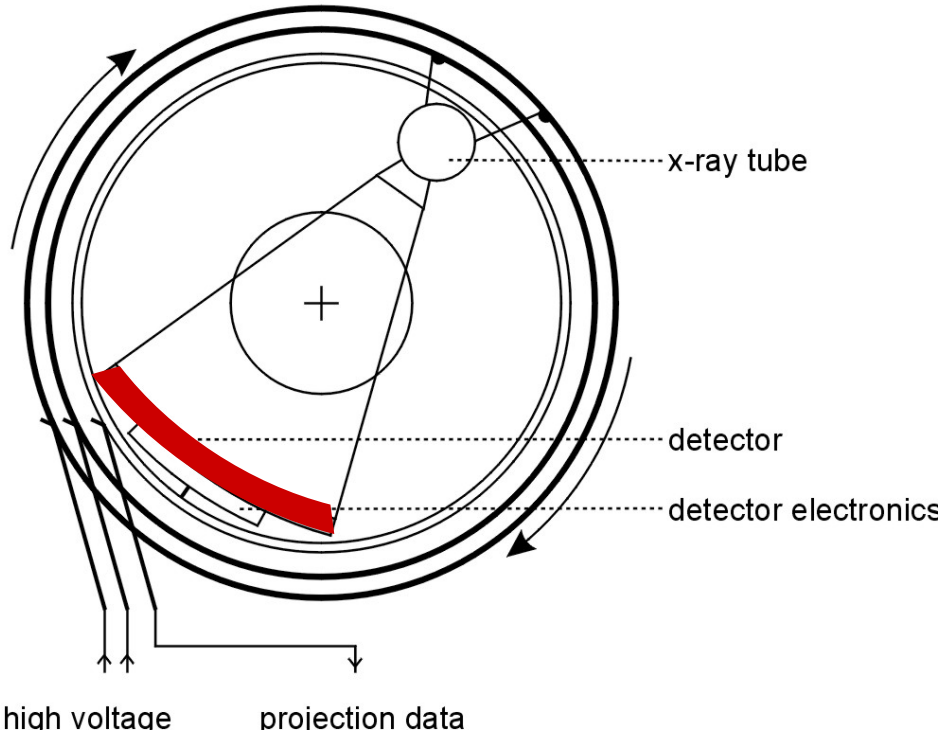
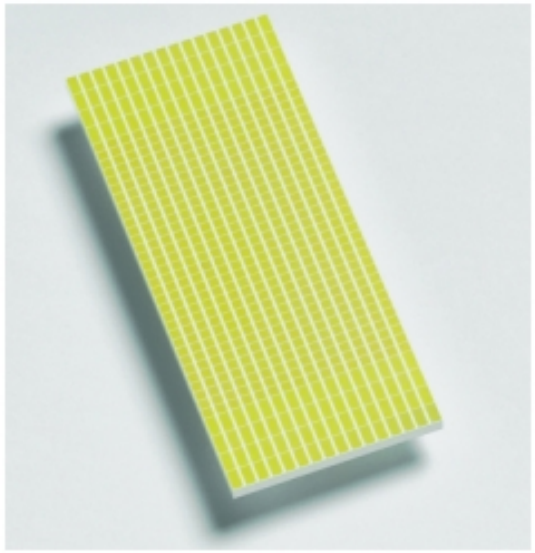
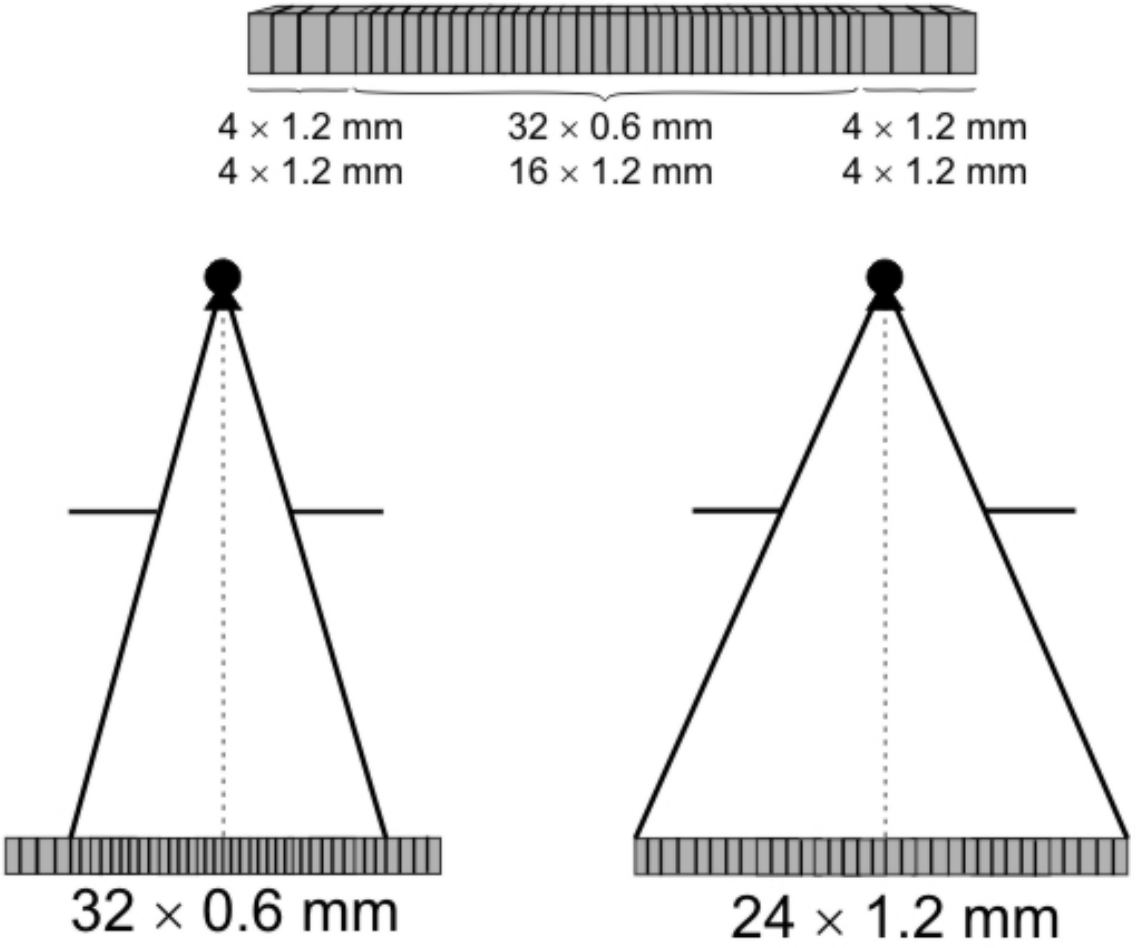
Multi-slice CT





Multi-slice CT





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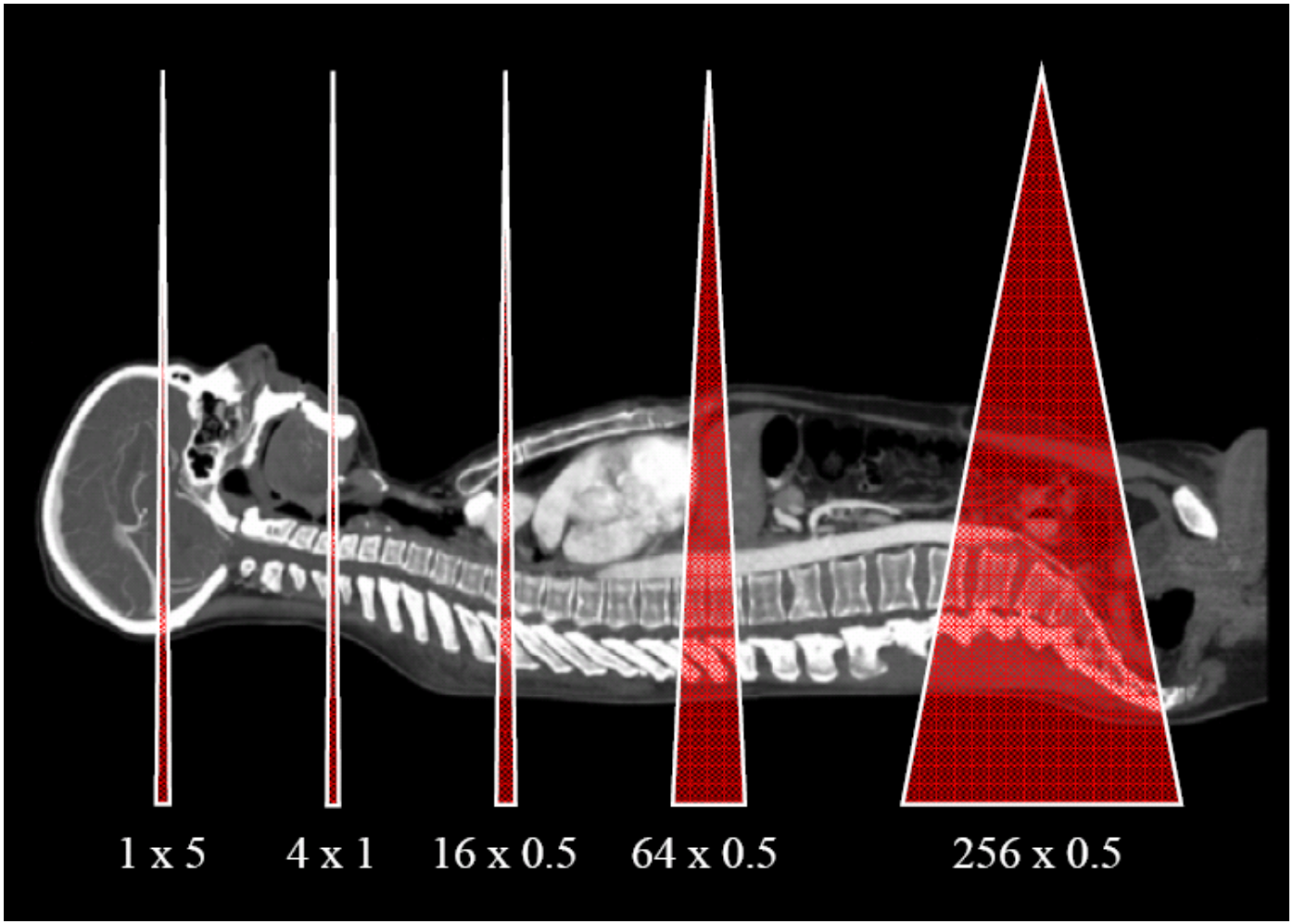
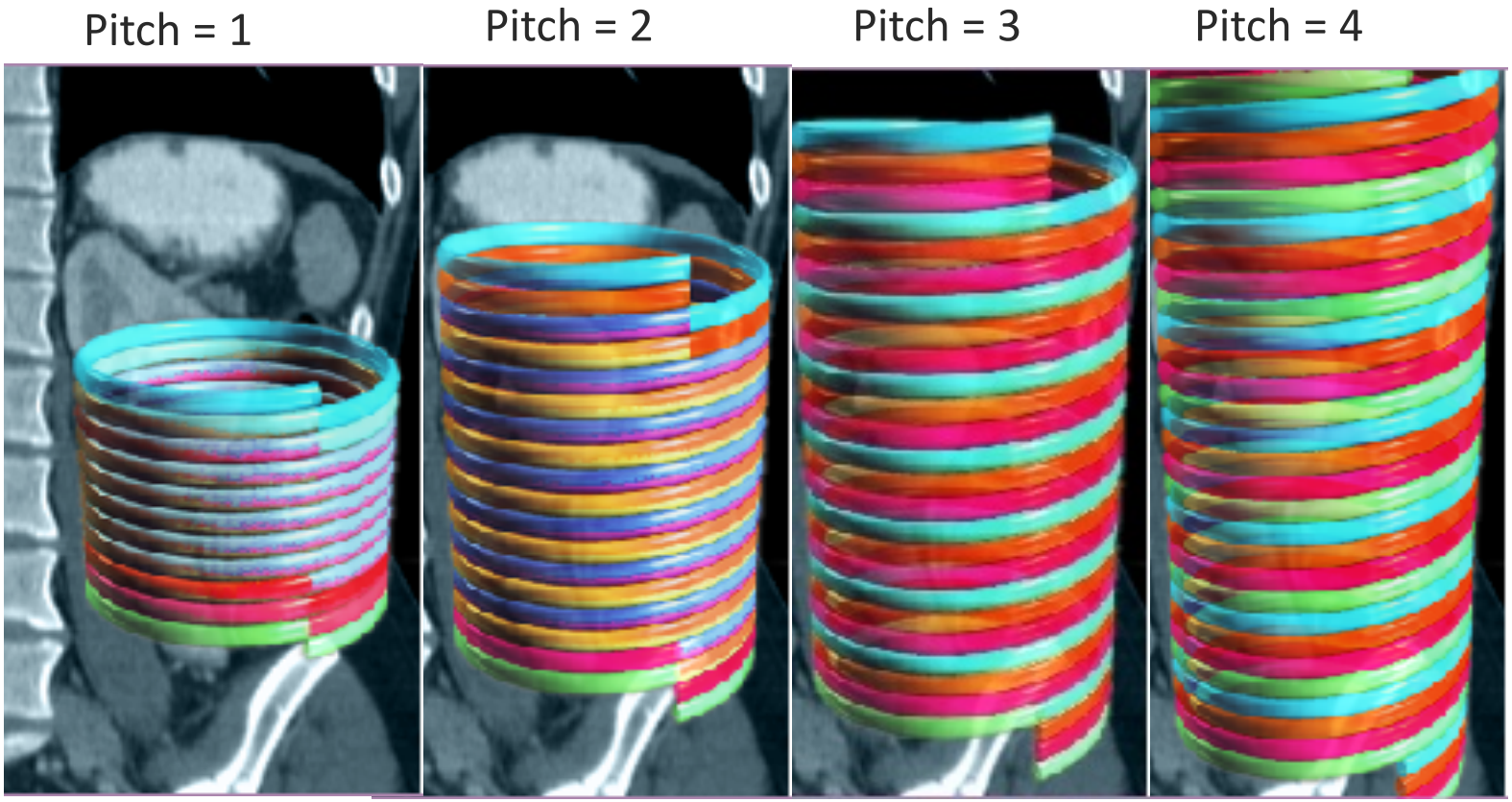
Multi-slice CT



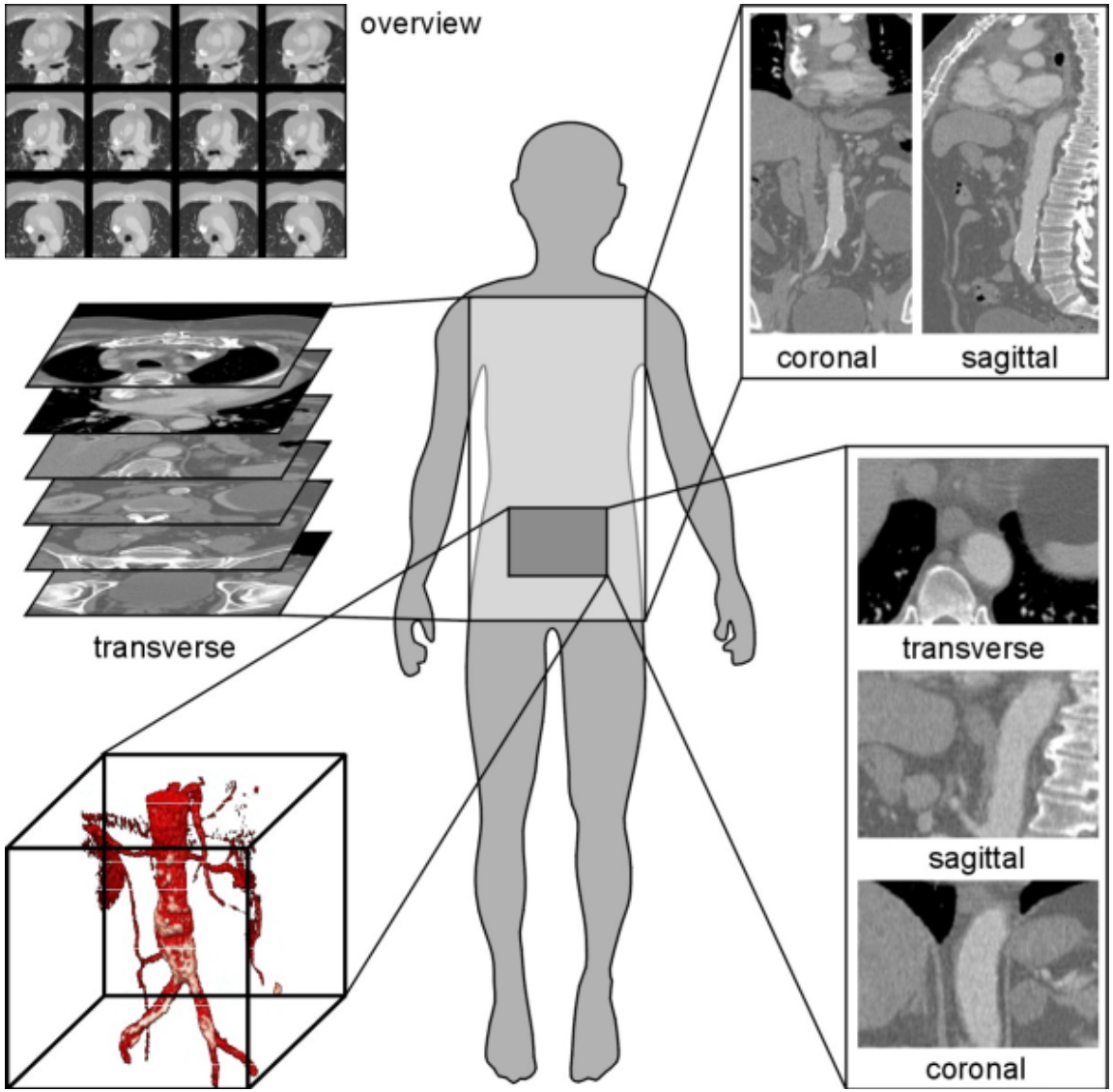
Multidetector/Multislice Spiral CT

- Pitch = table movement per rotation/slice collimation



Applications

CT – Applications



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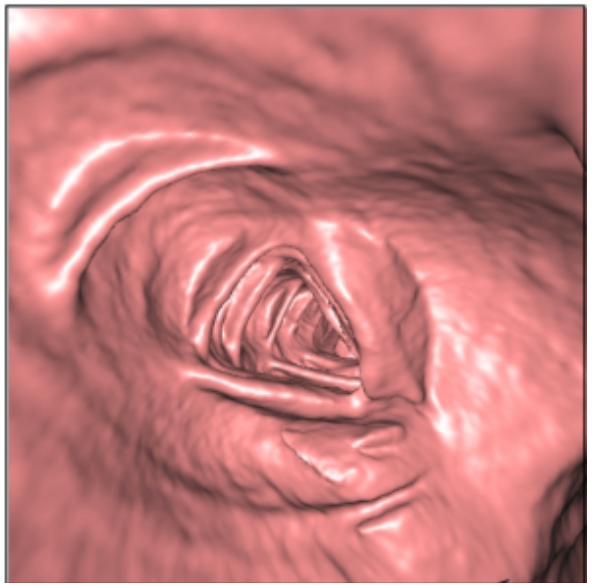
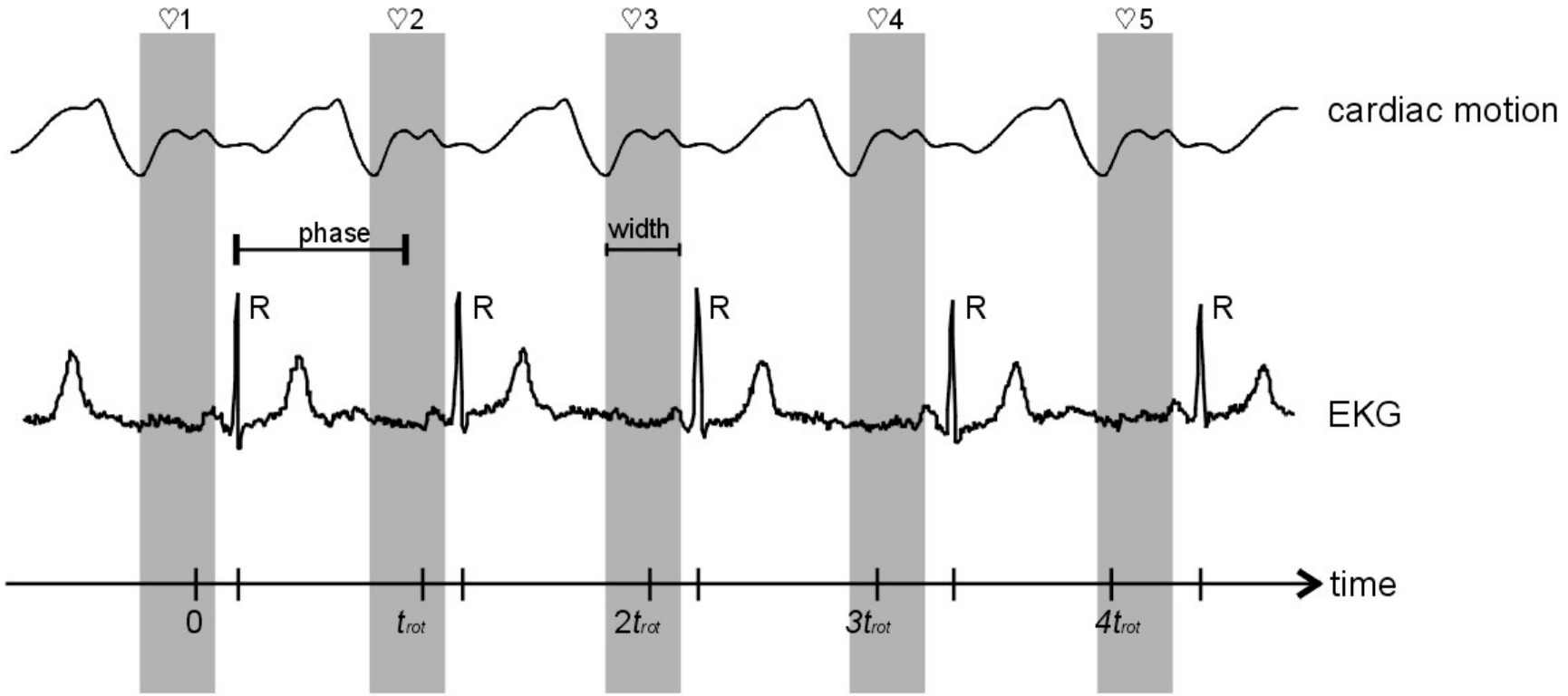
CT – Applications



CT – Applications



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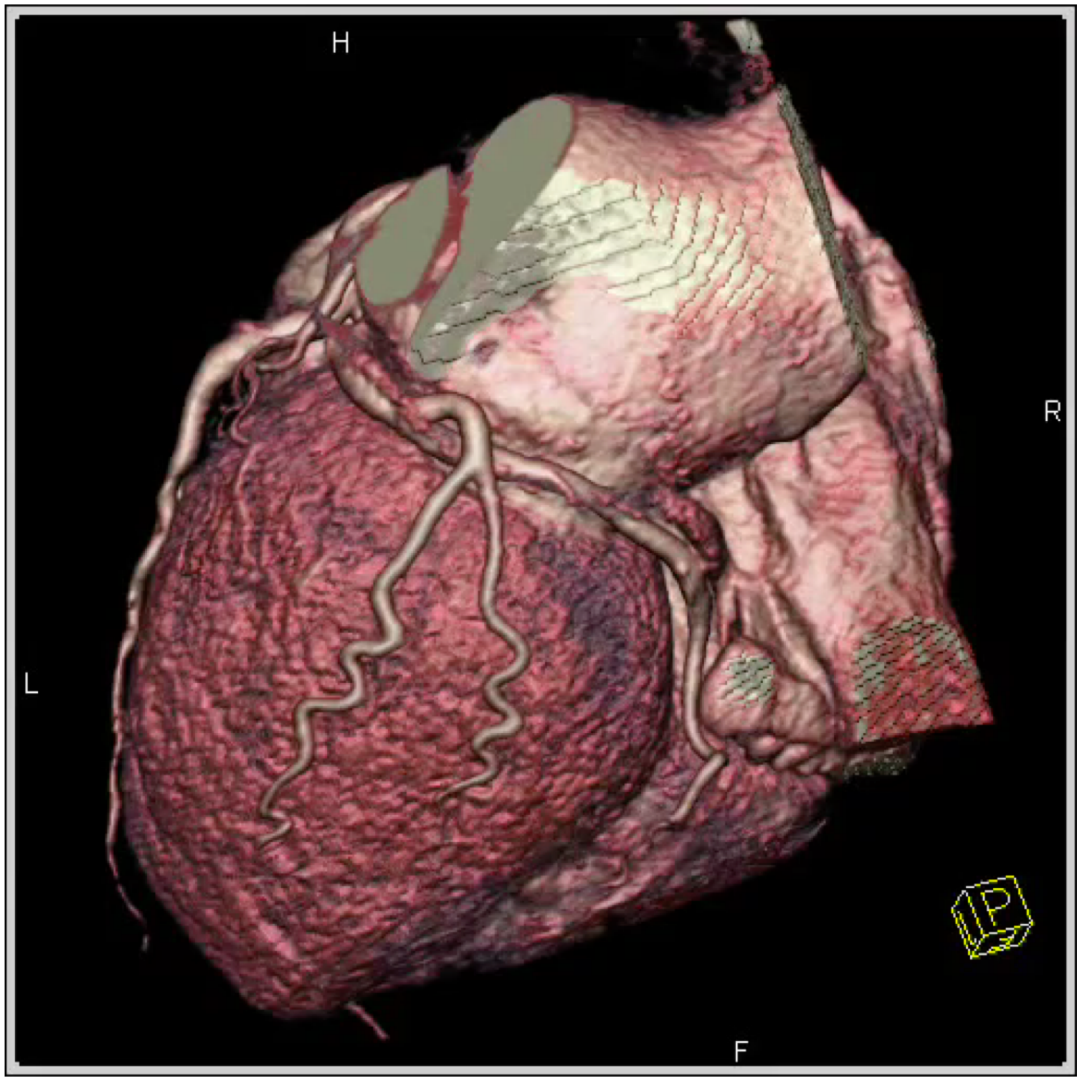
CT – Applications



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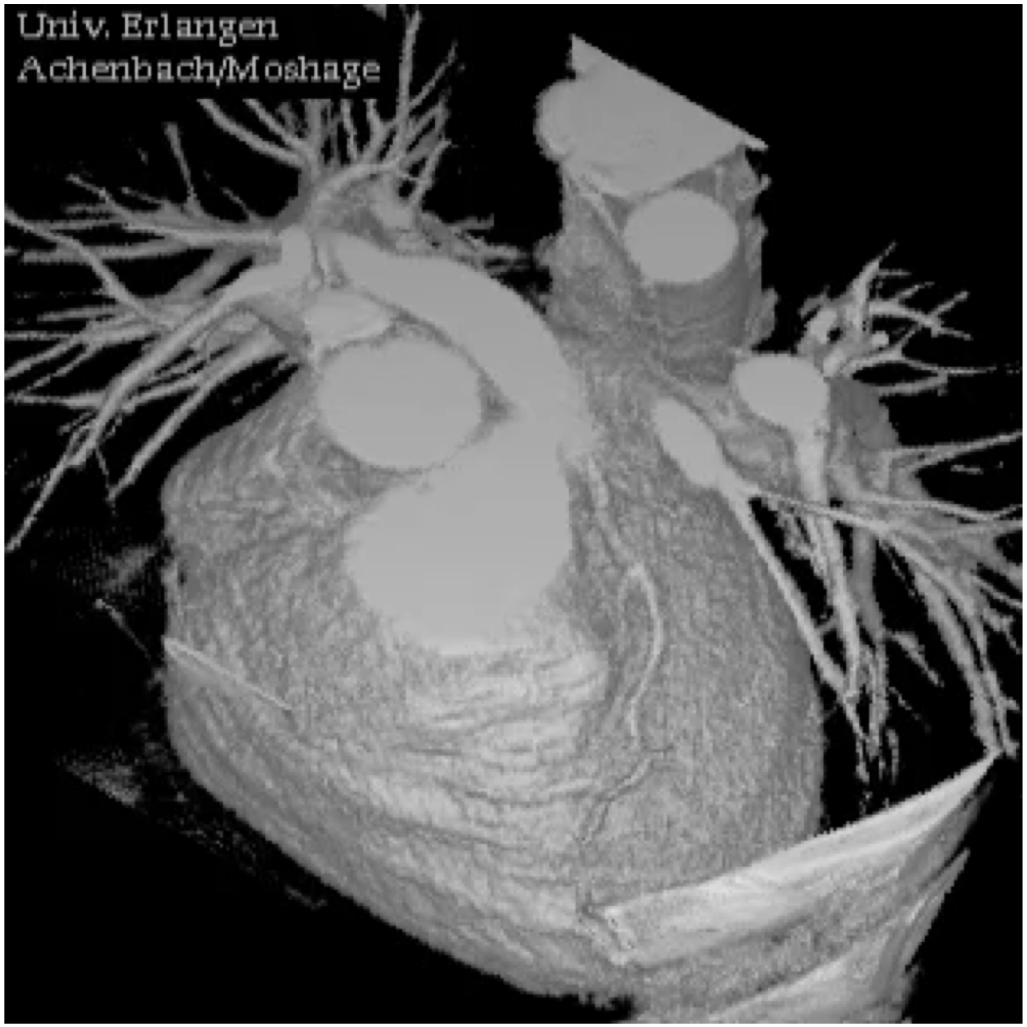
CT – Applications



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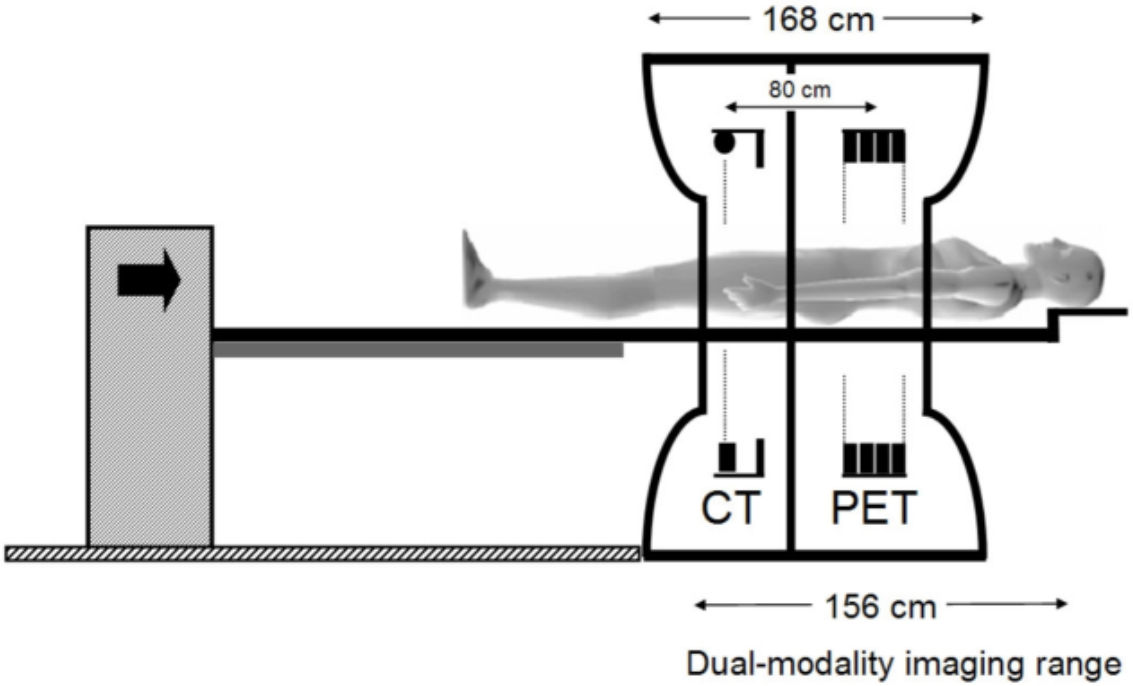
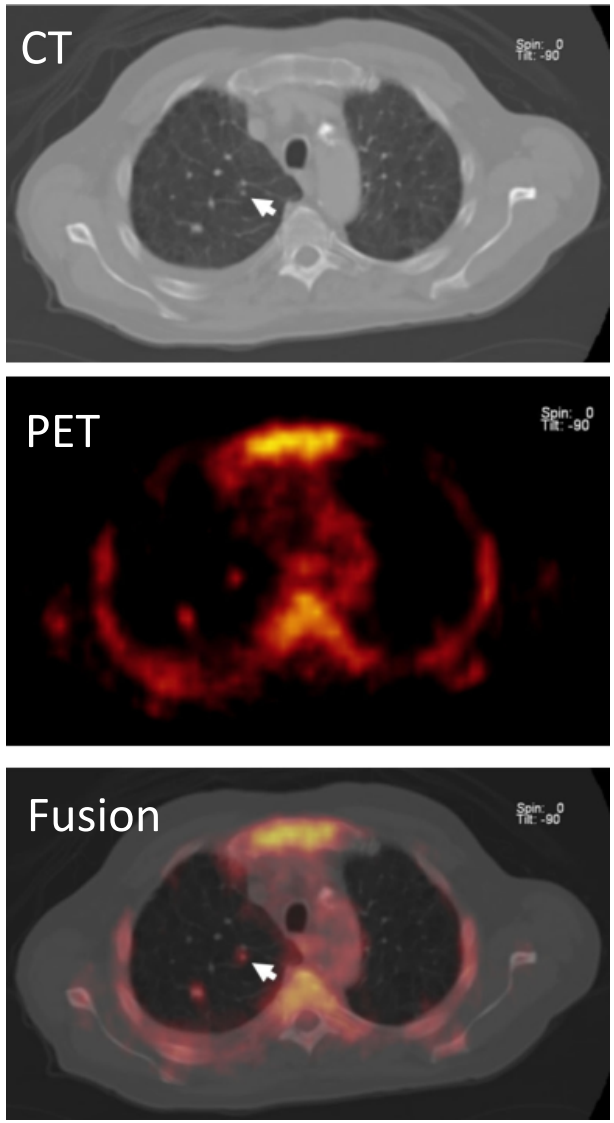
CT – PET



Dual-modality imaging range



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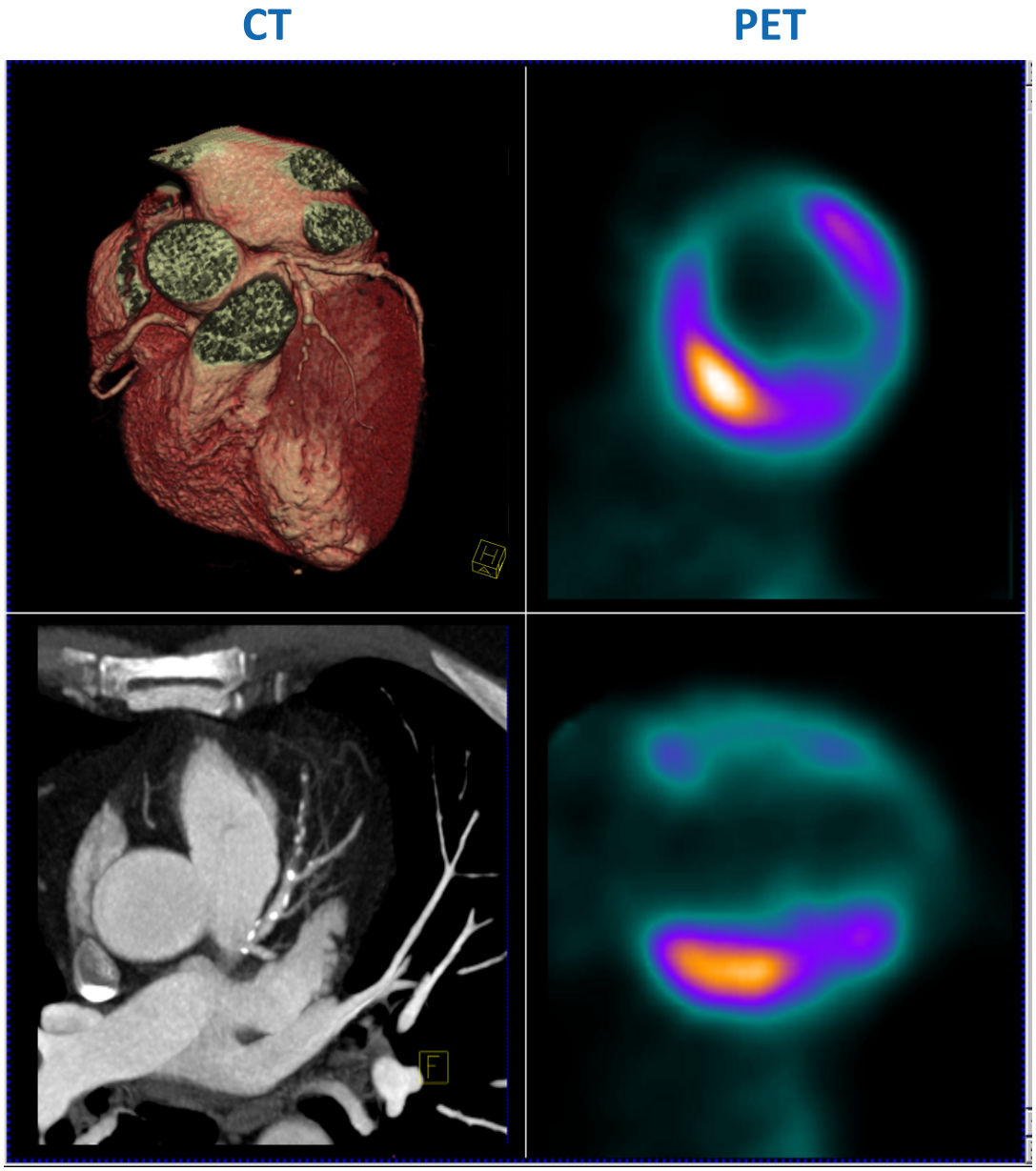
CT – PET

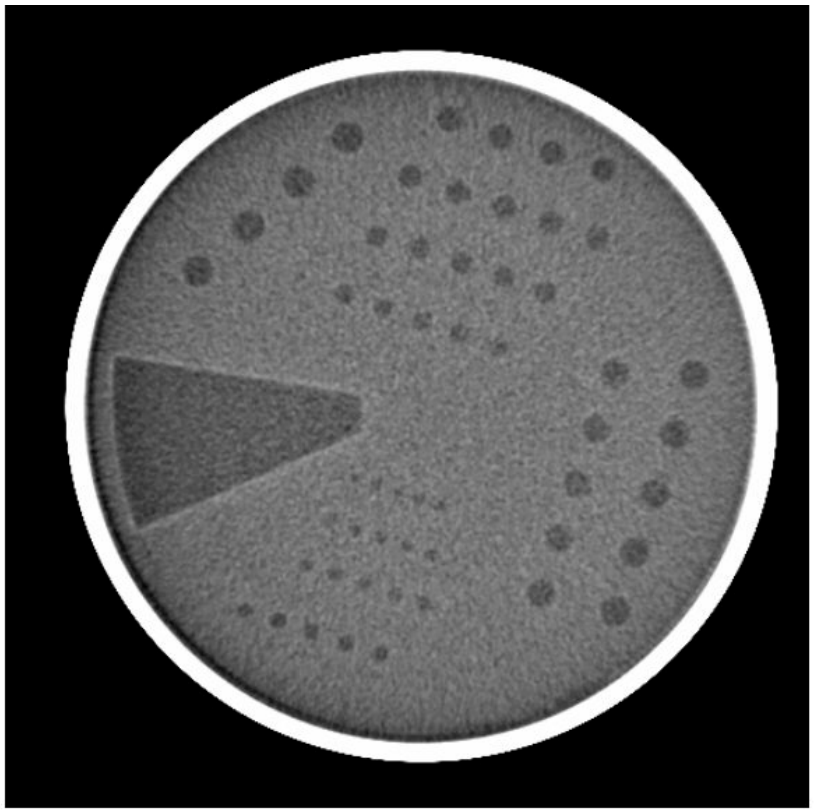


Chapter
1.4-1.6, 2.8

Image quality

Image quality

High-dose scan (e.g. brain)



Low-dose scan (e.g. bone)

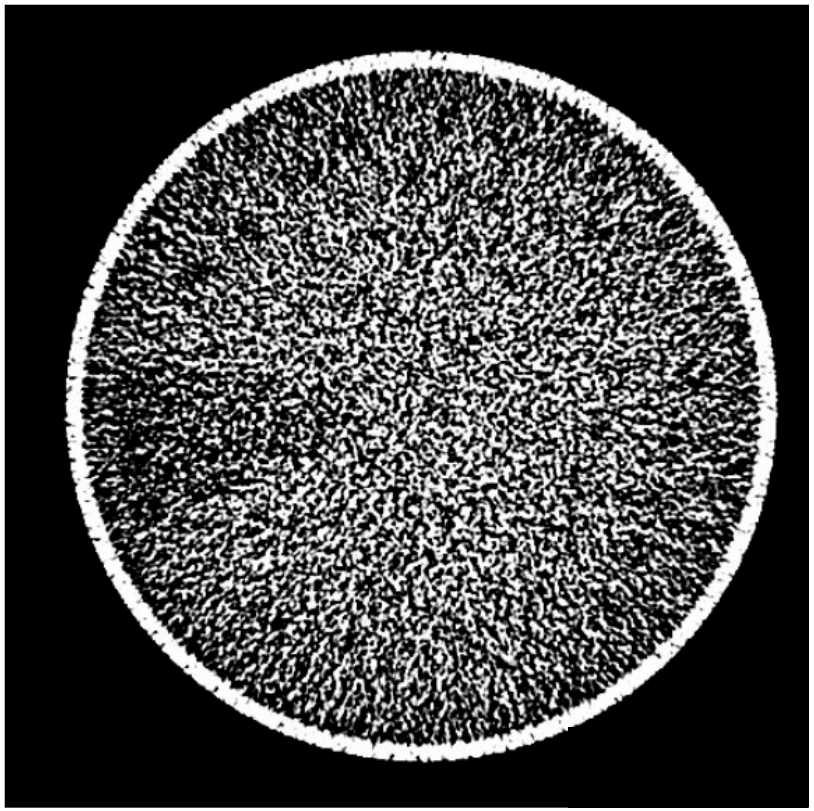


Image quality

$$I(x,y,z) = C(E) \cdot O(x,y,z) * PSF(x,y,z) + noise + artifacts$$

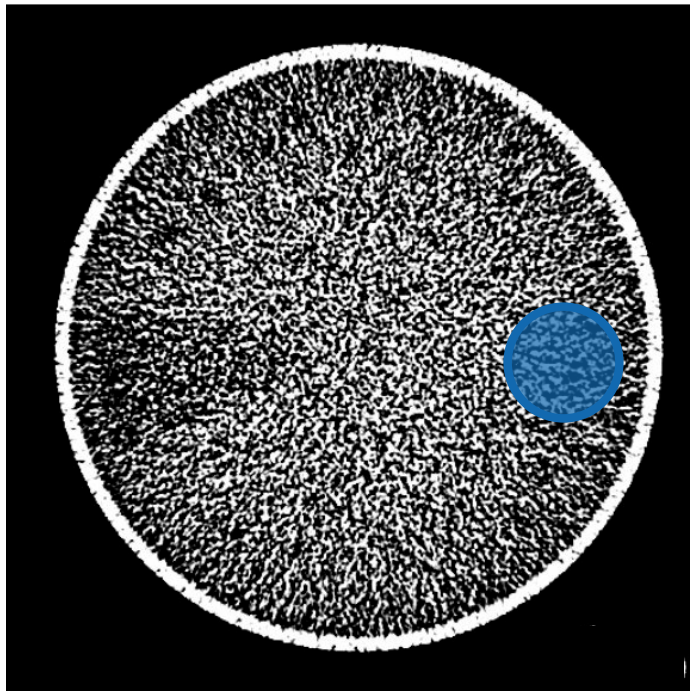
$$I(x,y,z) \propto O(x,y,z) * PSF(x,y,z) + noise$$

"spatial blurring" "uncertainty"

- Quantum noise ($\rightarrow$ Poisson distribution): $\sigma \propto \sqrt{\bar{N}}$

$\bar{N}$: mean number of x-ray quanta registered by detector

Image noise



region-of-interest (ROI)

- Pixel noise:

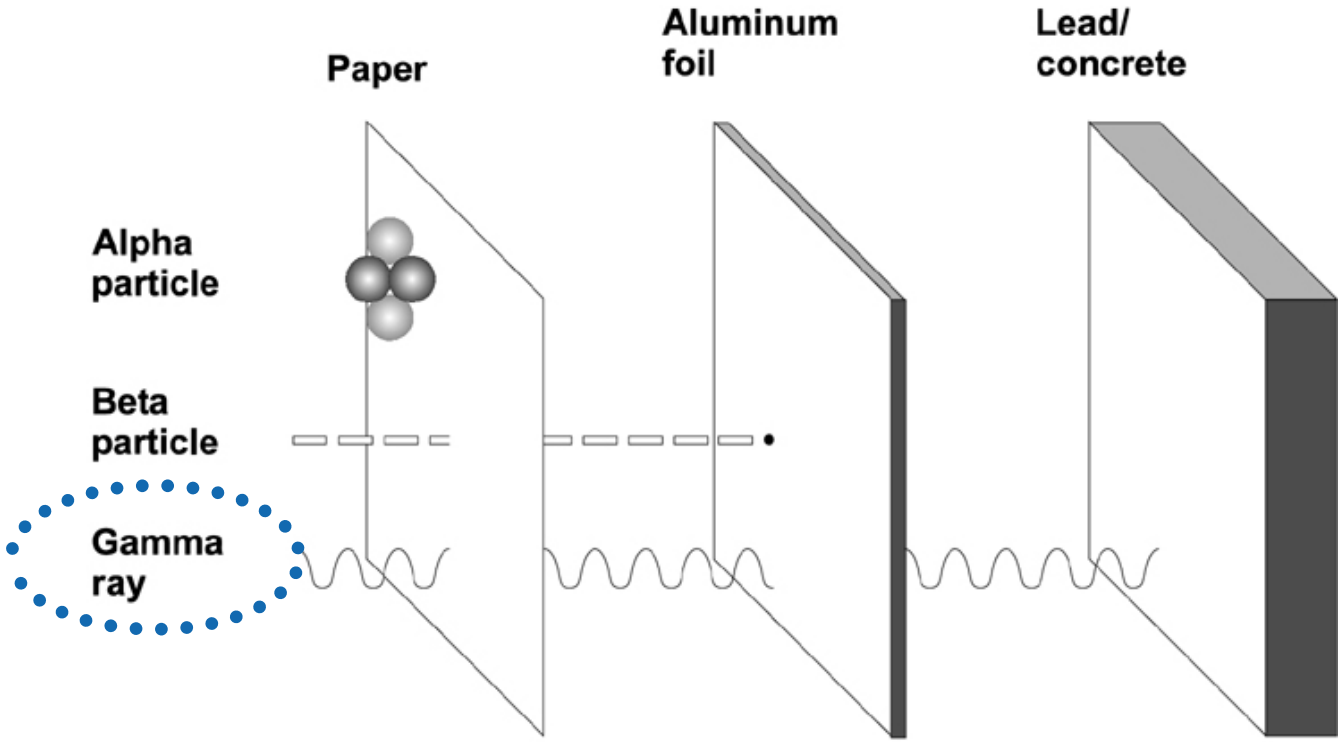
$$\sigma = \sqrt{\frac{1}{M-1}\sum_{i=1}^{M}\left(I_i - \bar{I}\right)^2}$$

$$\sigma = \sqrt{\frac{1}{Q\Delta z}}$$

Q: Tube current * scan time; Δz: detector thickness

Dose

Radiation basics



Radiation basics

- Several reaction mechanisms of cell if hit by radiation:
  - Cell repair
  - Interaction with nearby cells (bystander effect)
  - Genomic instability
  - Cell death
- Cells that grow out of control become cancers
- Non-cancer effects of radiation include blood disorders, circulatory problems, liver disease, thyroid disease, others

Radiation basics

- Absorbed dose (=energy deposited per unit mass)

$$1\,\text{Gray} = 1\,\text{Gy} = 1\,\text{J/kg}$$

Note: the absorbed dose is not a good indicator of the likely biological effect.

- Equivalent dose (=reflects biological in contrast to physical effect)

$$1\,\text{Sievert} = 1\,\text{Sv} = 1\,\text{J/kg}$$

Note: the equivalent dose to a tissue is found by multiplying the absorbed dose, in grays, by a dimensionless "quality factor" Q, dependent upon radiation type, and by another dimensionless factor N, dependent on all other pertinent factors.

Radiation basics

- Equivalent dose

$$1\left[\mathrm{Sv}\right] = Q \cdot N\left[\mathrm{Gy}\right]$$

Quality factor Q

Photons, all energies	Q = 1
Electrons and muons, all energies	Q = 1
Neutrons (energy dependent)	Q = 5-20
Protons, energy > 2 MeV	Q = 5
Alpha particles	Q = 20

Pertinent factor N

Bone marrow, colon, lung, stomach	N = 0.12
Bladder, brain, breast, kidney, liver	N = 0.05
Muscles, pancreas, intestine, uterus	N = 0.05
Bone surface, skin	N = 0.01

Radiation basics

- Equivalent dose

- mean dose received by atomic bomb survivors was 0.2 Sv

- low dose radiation regime less than 0.1 Sv

- the average nuclear worker is exposed to 0.02 Sv

- **average background exposure** to radiation is **0.0025 Sv per year**

- **average dose per CT scan 0.02 Sv**

Dose considerations

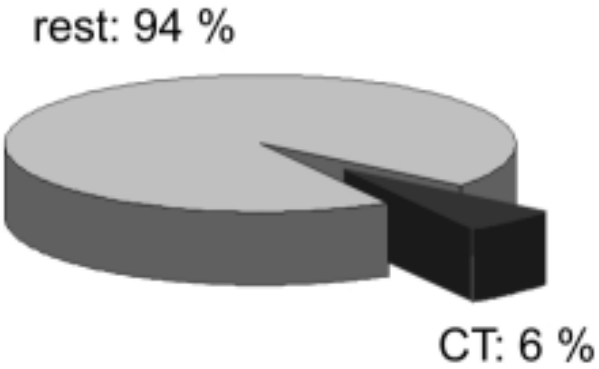
- Radiological exams

Type	Dose [mSv]	Equivalence
PI – Thorax	0.02	3 days
CT – Head	2.3	1 year
CT – Thorax	10	4.4 years
CT – Abdomen	15	6.5 years
CT – Heart	20	8.7 years

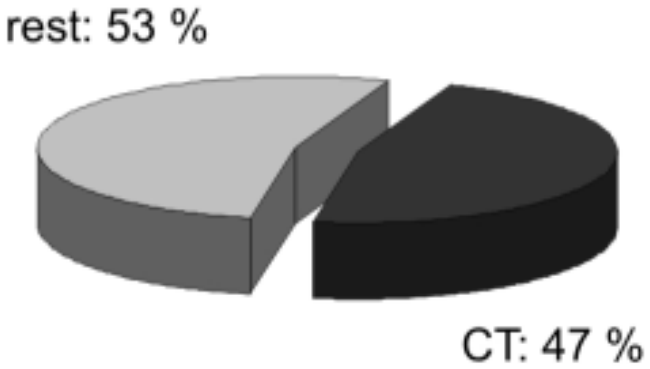
Data from 90's, in 2004 average already 20 mSv!

Dose considerations

frequency of radiological examinations



proportions of collective effective dose



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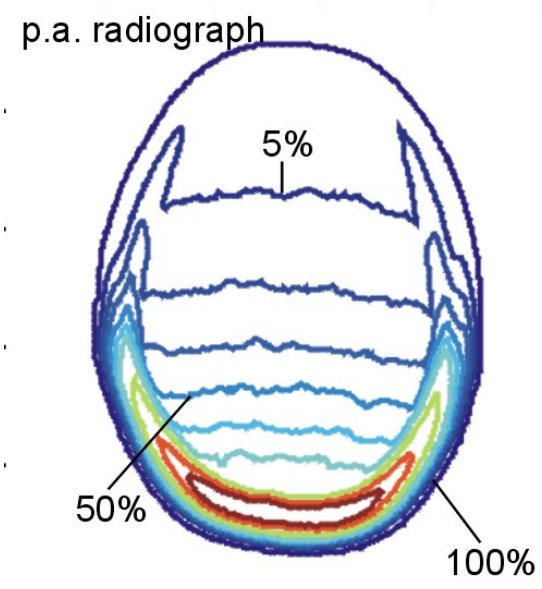
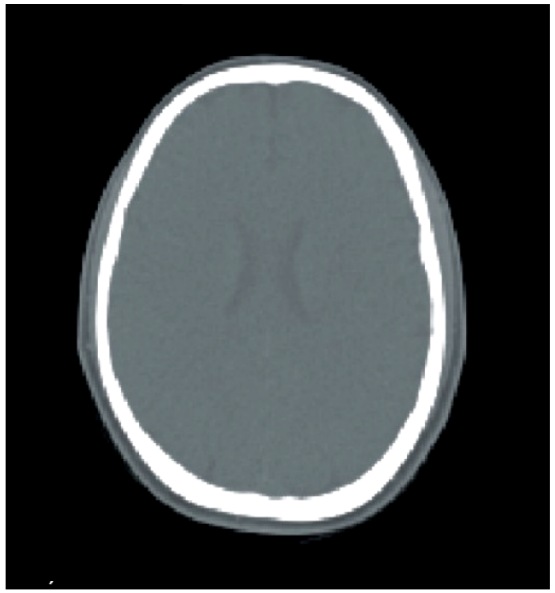
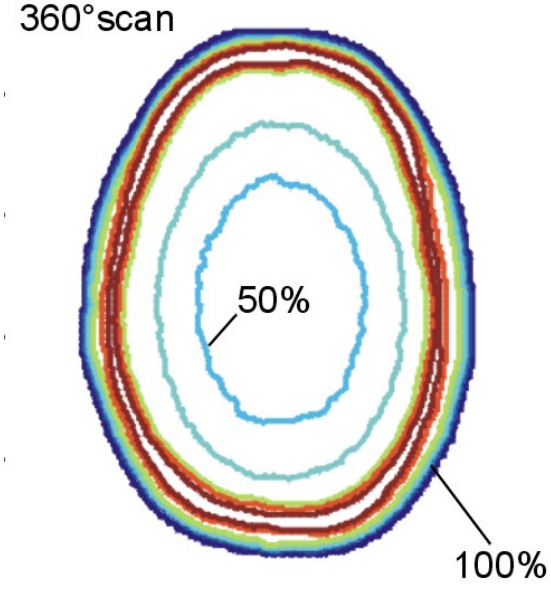
Dose distribution

Projection imaging



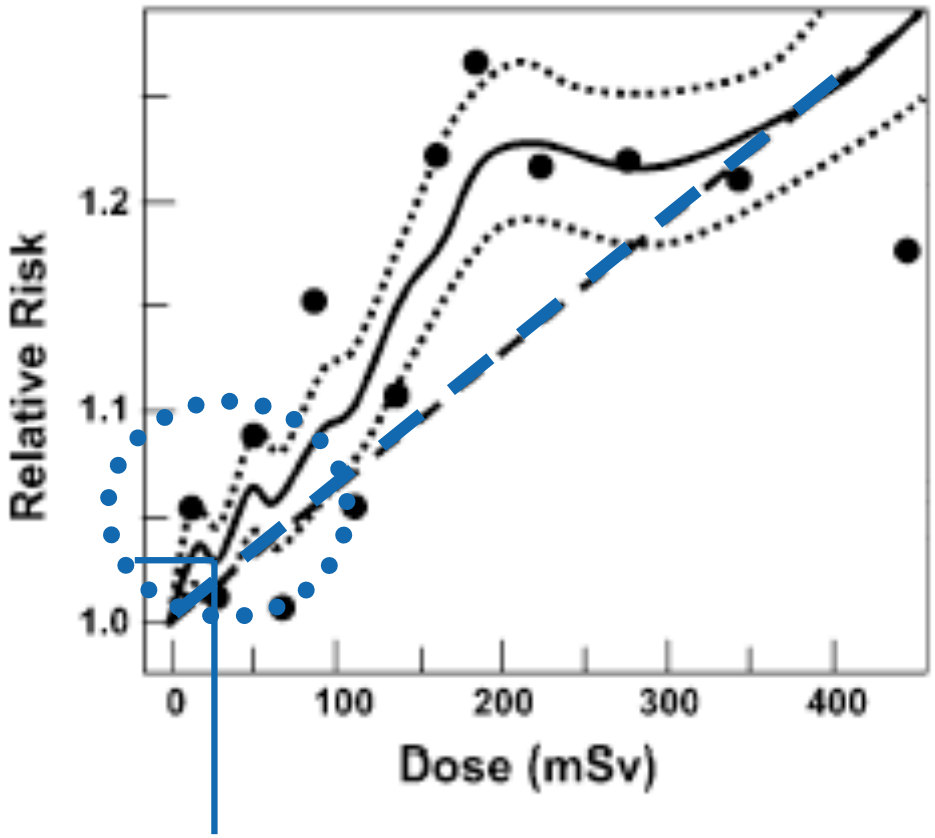


Tomographic imaging



Dose considerations

- Incidence of solid cancer (atomic bomb survivors)



Effective dose from 1 CT scan

Brenner DJ et al. 2003. Cancer risks attributable to low doses of ionizing radiation: Assessing what we really know. Proc Natl Acad Sci USA 100(24):13761-6.

Dose considerations

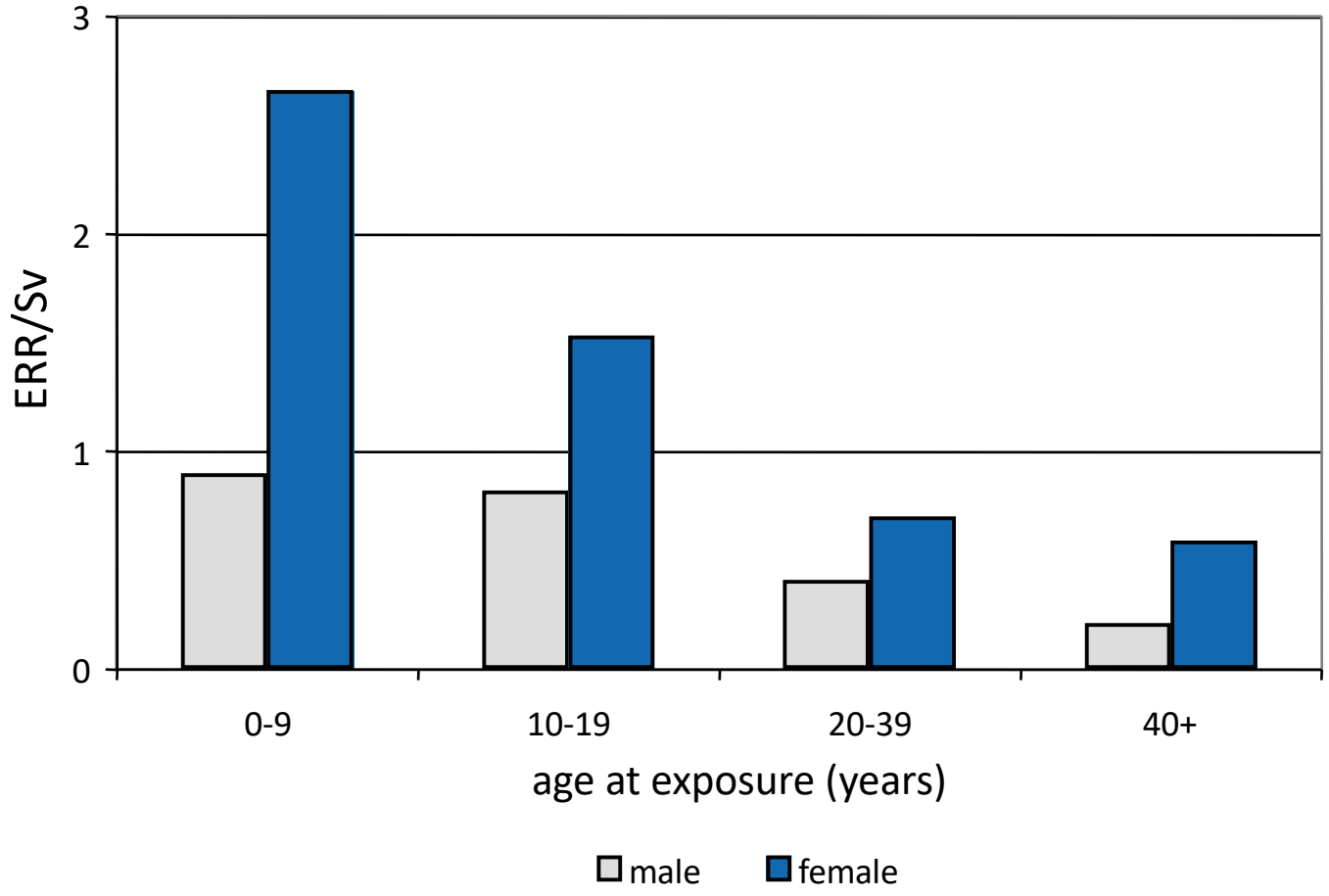
- Atomic bomb survivors vs. nuclear workers

	Atomic bomb survivors (Preston et al. 2003)	Nuclear workers (Cardis et al. 2005)
Mean dose	20 mSv (colon)	20 mSv (colon)
ERR solid cancer	0.93/Sv	0.87/Sv

ERR: Excess Relative Risk

Dose considerations

- Gender and age differences



Dose considerations

- Health effects

  - Radiation **increases the risk** of cancer and other diseases

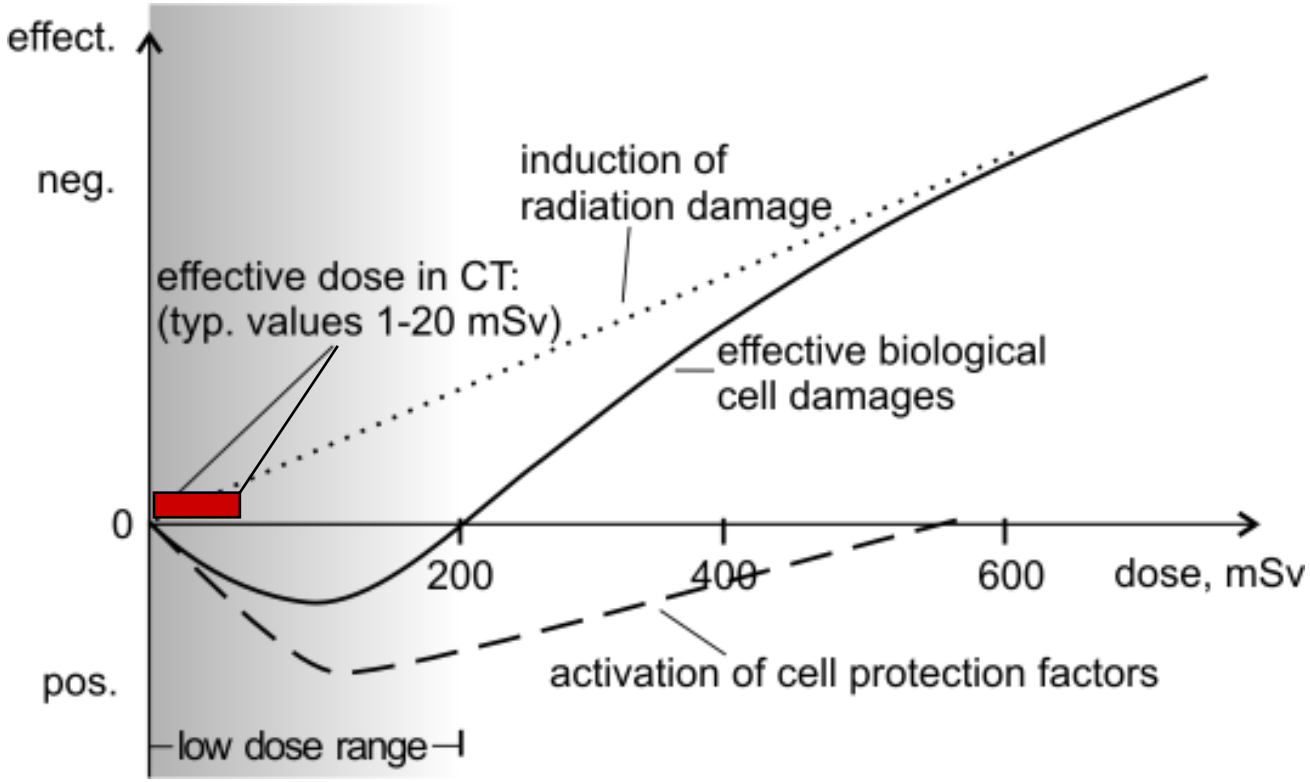
  - There is **no "safe" dose** of radiation

  - Risk is related to dose

  - **Women and children** are more sensitive to radiation than men

Dose considerations

- CT vendor's view



From Kalender WA, Computed Tomography, ISBN 3-89578-216-5

Dose considerations

- Scientific literature

European Heart Journal Advance Access published September 9, 2010

European Heart Journal
doi:10.1093/eurheartj/ehq298

VIEWPOINT

Ionizing radiation risks of cardiac imaging: estimates of the immeasurable

As CT coronary angiographies can now be achieved with a radiation dose <1 mSv,[16] the estimated risk of inducing a fatal malignancy (*Table 2*) is now in the range of the lifetime odds of dying from a lightning strike.[7]

CT coronary angiogram (64-slice)	
Without tube current modulation	20
With tube current modulation	12
Prospective triggering	2
Prospective triggering with high-pitch spiral	1
CT chest	7
CT abdominal	8
Diagnostic invasive coronary angiogram	7

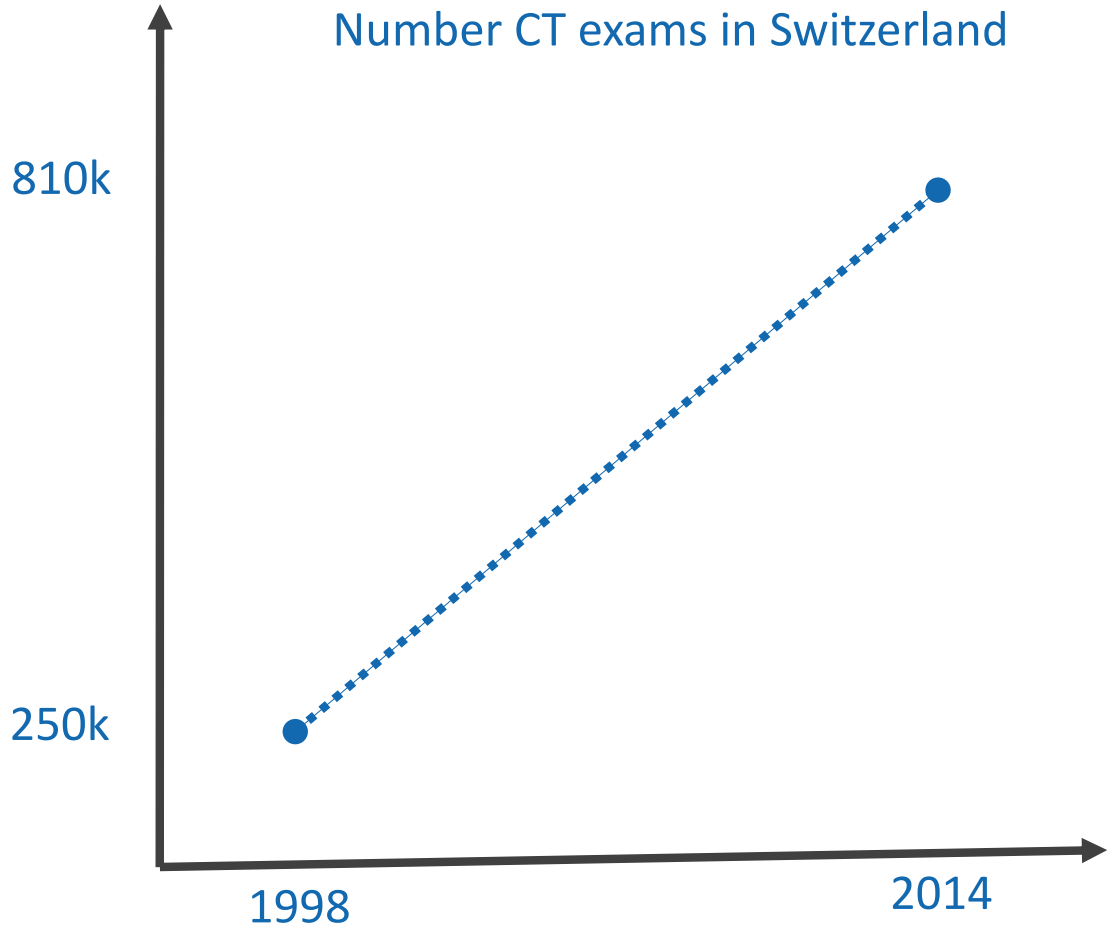
Dose considerations

- Swiss Federal Office for Public Health (BAG data 2010)

		CTDI [mGy]					
		#	Min.	25. Perz.	Median	75. Perz.	Max.
1	Schädel / Hirn	210	12	47	58	69	275
2	Hirn (Gefässe)	55	17	39	57	65	118
3	Sinus	147	3	12	18	25	61
4	Felsenbeine	48	13	35	45	67	143
5	Hals / HWS	98	4	14	20	28	60
6	Hals (Gefässe)	45	6	12	15	20	41
7	Schulter	62	3	14	20	35	104
8	Thorax (Gewebe)	128	1	7	10	13	26
9	Thorax (Gefässe)	152	2	8	12	15	28
10	Thorax + Oberbauch	95	2	8	12	16	24
11	Abdomen (Oberb.)	66	2	10	12	16	28
12	Abdomen (Gefässe)	47	1	10	12	16	24
13	Abdomen / Becken	193	1	10	12	15	41
14	Abd. / Becken (Gef.)	47	1	11	13	18	41
15	Becken (ossär)	87	2	11	15	20	61
16	Becken (Gefässe)	34	2	9	12	23	37
17	Thorax/Abd./Becken	121	2	9	13	16	49
18	LWS	23	9	16	23	30	92
19	Untere Extremitäten	31	4	8	13	17	35
20	Herz (Angio-CT)	27	7	27	39	65	114
21	Herz (Kardio-CT)	14	3	4	8	11	74

Dose considerations

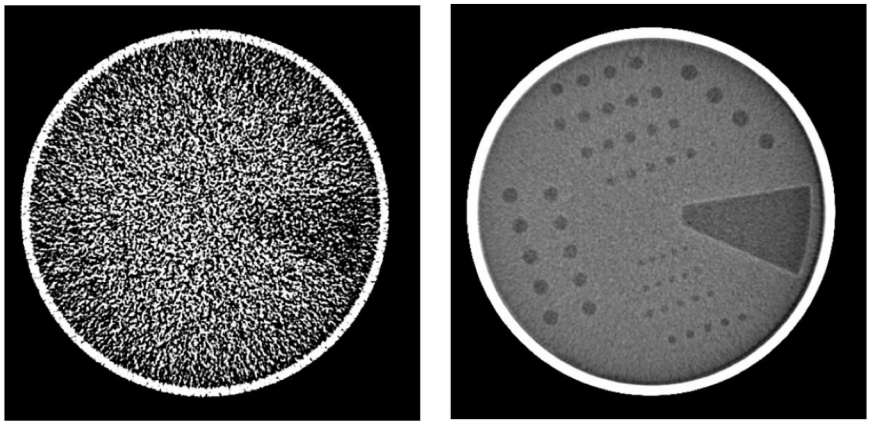
- Swiss Federal Office for Public Health (1998-2014)



Clicker Activity (5 min)

If the product of tube-current and scan time doubles, the signal-to-noise ratio (SNR) of a CT image

- is increased by a factor of 2
- is increased by a factor of sqrt(2)
- remains unchanged
- is reduced by a factor 2



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Clicker Activity (Notes)

Biomedical Imaging

Imaging Mode: X-ray Imaging

- Probe: X-ray photons
- Wavelength: 10 pm – 10 nm
- Matter interaction: absorption, scatter
- Modalities: Projection imaging
  Digital Subtraction Angiography (DSA)
  Computed tomography
- Resolution: 50 µm – 1 mm
- Applications: Mammography, body, neuro, lung, cardiac, angio
- Advantages: Very fast, high throughput, 3D
- Limitations: Dose, contrast agent, functional information

"The most important slides"

CT – Image reconstruction

- Inverse transform (III)

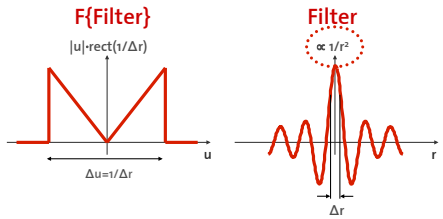
$$\mu(x,y) = -\frac{1}{4\pi^2}\int_0^{\pi}\int_{-\infty}^{+\infty} F\{P_\varphi(u)\}\, e^{iux}\,|u|\,du\,d\varphi$$

F{Filter}

$$\text{Image} = \text{Filter} * \text{Object} \leftrightarrow F\{\text{Image}\} = F\{\text{Filter}\}\cdot F\{\text{Object}\}$$

Filter ?

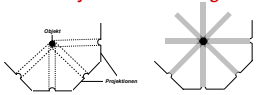
CT – Image reconstruction



"Ramachandran & Lakshminarayanan"
="Ram-Lak"

CT – Image reconstruction

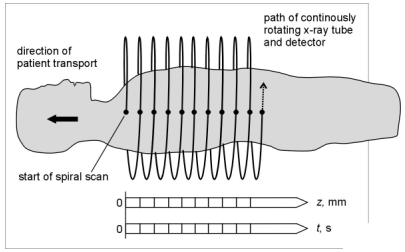
Point object Image



"Theoretical" PSF: 1) radius$_{object}$ → 0
2) number of projections → ∞
3) number samples per projection → ∞

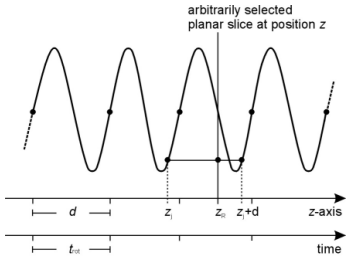
"Corrected" PSF: 1) radius$_{object}$ → 0
2) number of projections → ∞
3) sample distance → Δr

Spiral CT



Adapted from Kalender WA, Computed Tomography, ISBN 3-89578-216-5

Spiral CT



Adapted from Kalender WA, Computed Tomography, ISBN 3-89578-216-5

Image quality

$$I(x,y,z) = C(E)\cdot O(x,y,z) * PSF(x,y,z) + \text{noise} + \text{artifacts}$$

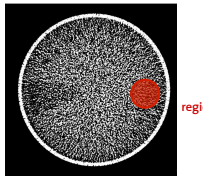
$$I(x,y,z) \propto O(x,y,z) * PSF(x,y,z) + \text{noise}$$

"spatial blurring" "uncertainty"

- Quantum noise (→ Poisson distribution): $\sigma \propto \sqrt{\bar{N}}$

$\bar{N}$: mean number of x-ray quanta registered by detector

Image quality



region-of-interest (ROI)

- Pixel noise: $\sigma = \sqrt{\frac{1}{M-1}\sum_{i=1}^{M}(I_i - \bar{I})^2}$

$$\sigma \propto \sqrt{\frac{I_0/I}{Q\Delta z}}$$

Q: Tube current * scan time; Δz: slice thickness

Radiation basics

- Equivalent dose

$$1[\text{Sv}] = Q\cdot N[\text{Gy}]$$

Quality factor Q

Photons, all energies	**Q = 1**
Electrons and muons, all energies	Q = 1
Neutrons (energy dependent)	Q = 5-20
Protons, energy > 2 MeV	Q = 5
Alpha particles	Q = 20

Pertinent factor N

Bone marrow, colon, lung, stomach	**N = 0.12**
Bladder, brain, breast, kidney, liver	**N = 0.05**
Muscles, pancreas, intestine, uterus	**N = 0.05**
Bone surface, skin	**N = 0.01**

Dose considerations

- Gender and age differences