Lecture 8 – CT instrumentation

This lecture will cover:

– Instrumentation of CT *(CH2.12-2.13)*

- Source
- Detectors
- Helical CT (螺旋CT)
- Pre-processing data corrections

– Image characteristics of CT images

- CT number *(CH2.14.1)*
- Resolution, Noise, Contrast *(Fundamental of MI CH3 P49-50)*
- Image artifact *(Fundamental of MI CH3 P50-53)*

Source

- The X-ray tube is similar to planar radiography, and the typical operating parameters are
  - kVp: 140 kV (effective X-ray energy: 70-80 keV)
  - Tube current: 70-320mA
  - Focal spot size: 0.6-1.6 mm
  - Fixed with a heavy gantry for fast rotation
- Two collimators: perpendicular to each other
  - Same as radiography: restrict beam to an angular width of 45-60°
  - Direction of head/foot: restrict beam to desired slice thickness (层厚，1-5 mm)

Detectors in CT

- Energy integrating detector

X-ray $\xrightarrow{\text{Scintillator}}$ Visible light $\xrightarrow{\text{Photodiode}}$ Electric current $\xrightarrow{\text{DAS}}$ Voltage $\xrightarrow{\text{A/D}}$ Digital image

- Photon counting detector (光子计数探测器):

X-ray $\rightarrow$ Electronic charge

  - Count numbers of photon
  - 10 times conversion of scintillator/photodiode
  - Increase CNR by 10-20%
  - Measuring the energy of X-ray photon for multi-energy CT
  - Challenge: stability and count rate limits

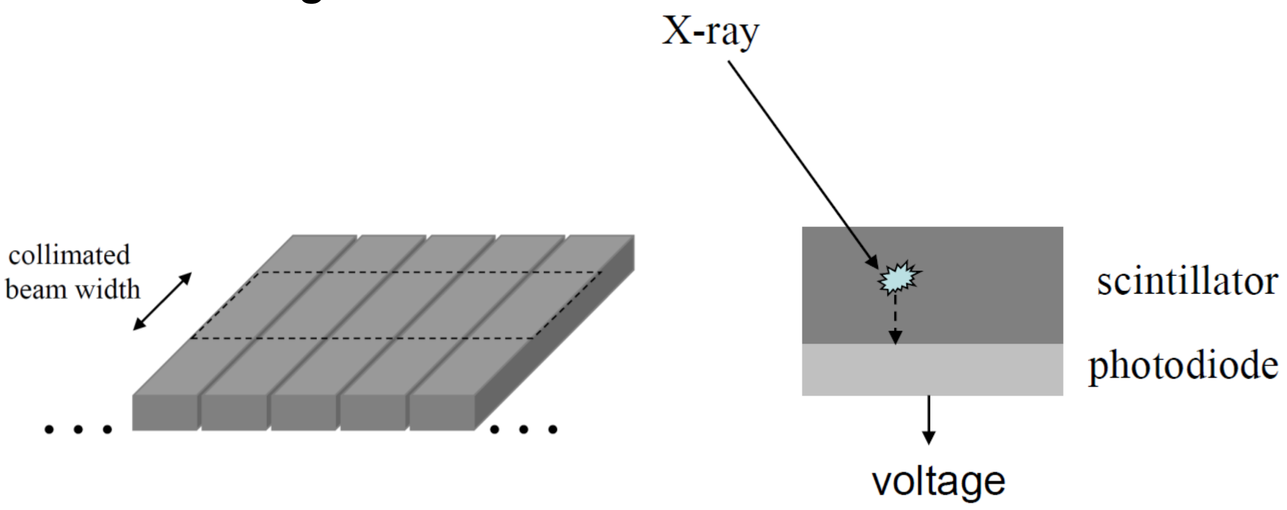


Fig. (left) A single row detector array. (right) For each solid-state detector the incident X-ray energy is converted into an electrical signal via a scintillator and photodiode.

Detectors in multi-slice CT

- 2D detector array consisting of multiple detector rows;
- Detector size can be same, or smallest close to center of the array;
- Slice thickness is determined by the size of the detector

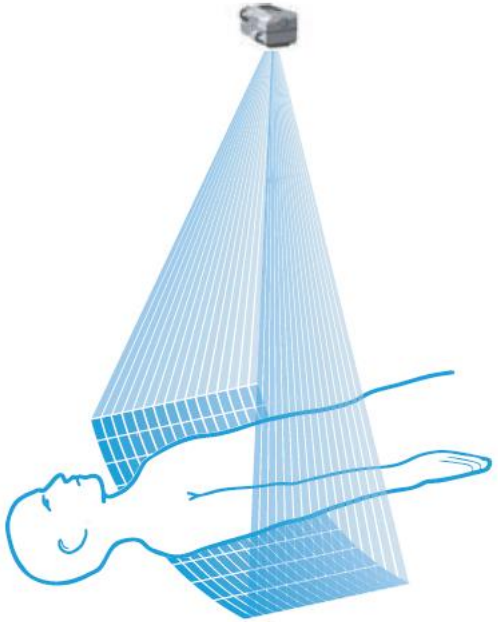


Fig. (left) Multi-slice CT detectors, with up to 320 rows for the largest detector at the back. (right) multi-slice CT: a multi-slice CT scanner can acquire multiple slices simultaneously by using multiple adjacent detector arrays..

Helical CT (螺旋CT)

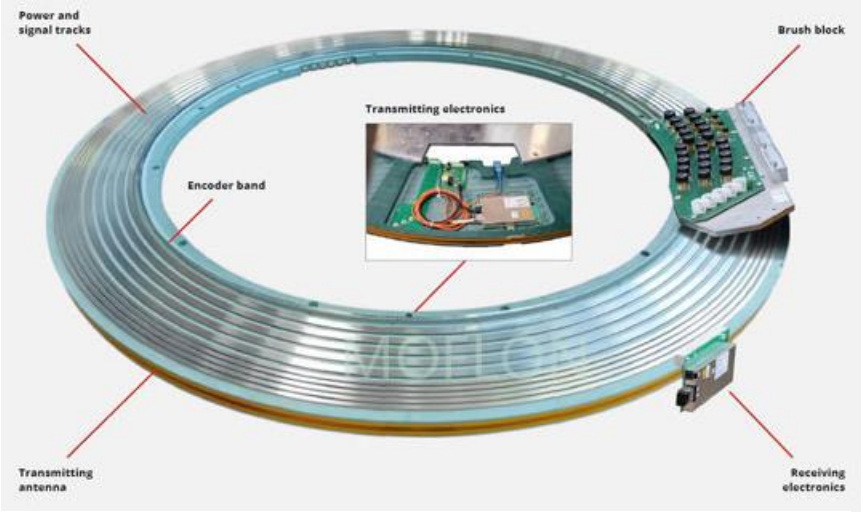
- **Continuous power and signal transmission**
  - Multiple slip-rings: circular contact with sliding brushes
  - Contactless slip ring
- **Continuous operating of X-ray tube**
  - Anode heating problem
  - High heat-capacity
  - Efficient cooling system
- **Modified image reconstruction algorithms**

$$p = \frac{d}{s}$$

where p : pitch (螺距)

d : table feed (床进速度, mm/circle)

s : slice thickness (层厚)



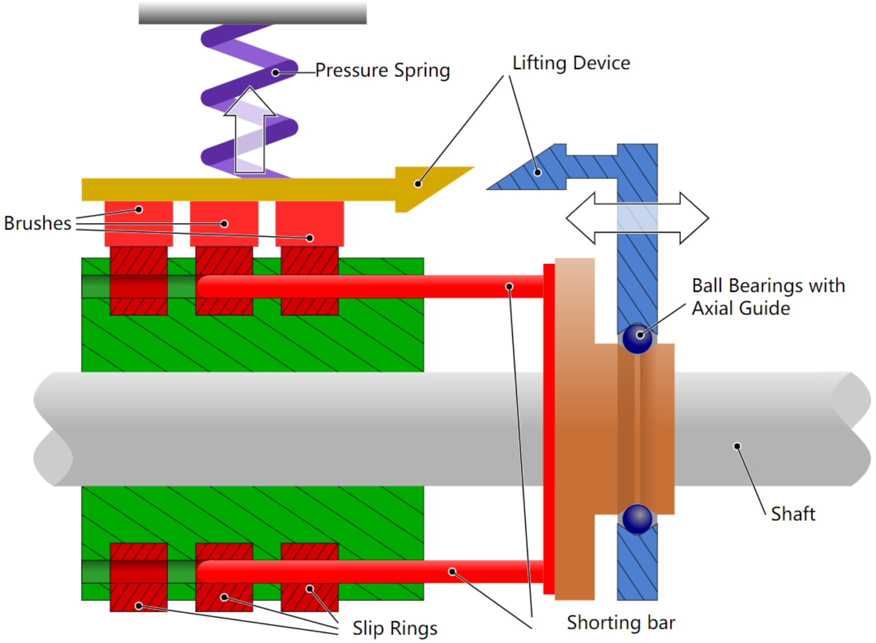


Fig. The slip-rings of a helical CT scanner.

CT instrumentation

Pre-processing data corrections

- **Beam hardening**
  - bowtie filter;
  - correction algorithms by travelled distance
- **Sensitivity of individual detectors and detector channels**
  - Phantom calibration : using an object with uniform attenuation coefficient

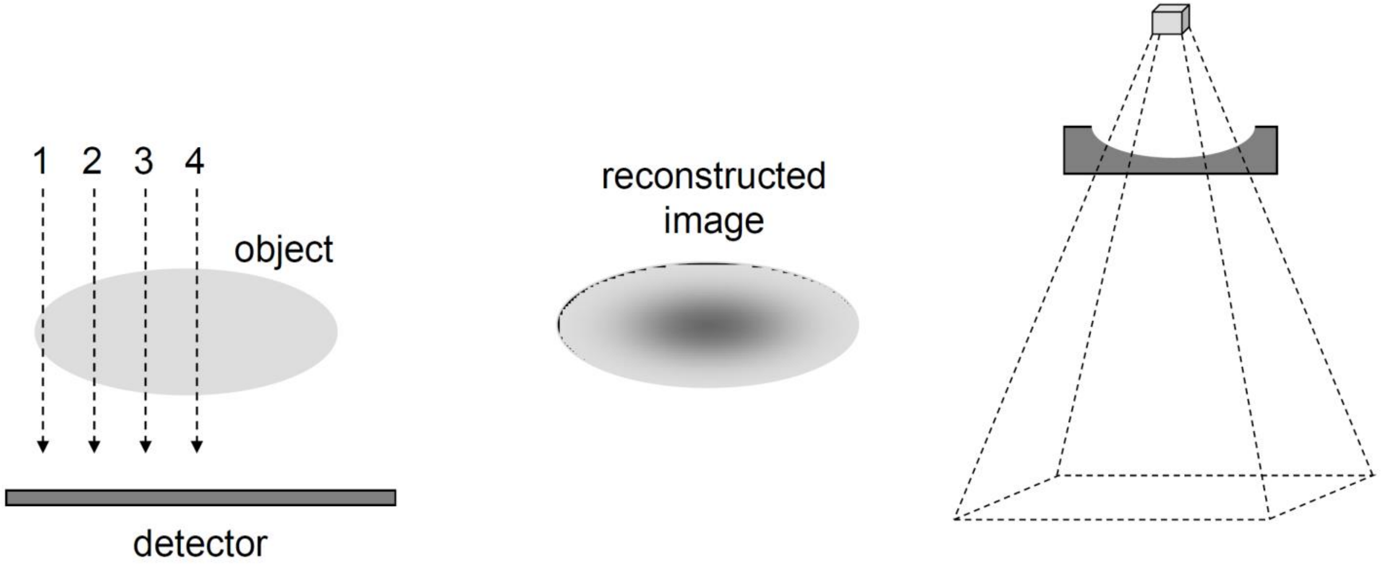


Fig. (left) Four parallel X-ray beams pass through an elliptical object with spatially uniform attenuation coefficient. The effective energy of beam 4 increases as it passes through the object to a greater degree than for beams 3, 2 and 1 since it has to travel the furthest distance through the object. This effect is known as beam hardening. An image reconstructed using filtered backprojection (centre) shows a reduced CT number in the centre of the object. (right) The effect of beam-hardening can be reduced by the use of a 'bow-tie' filter made of a metal such as aluminium, which also reduces the dose to extremities such as the arms..

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  - CT number
  - Resolution, Noise, Contrast
  - Image artifact

CT number

$$\text{CT number} = \frac{\mu - \mu_{H_2 0}}{\mu_{H_2 0}} \times 1000$$

Where μ is the linear attenuation coefficient, and the unit of CT number is Hounsfield units (HU)

Table 2.1: CT numbers of different tissues at 70 keV

Tissue	CT number (Hounsfield units)
Bone	1000–3000
Muscle	10–40
Water	0
Lipid	−50 to −100
Air	−1000
Brain (white matter)	20 to 30
Brain (grey matter)	35 to 45
Blood	40

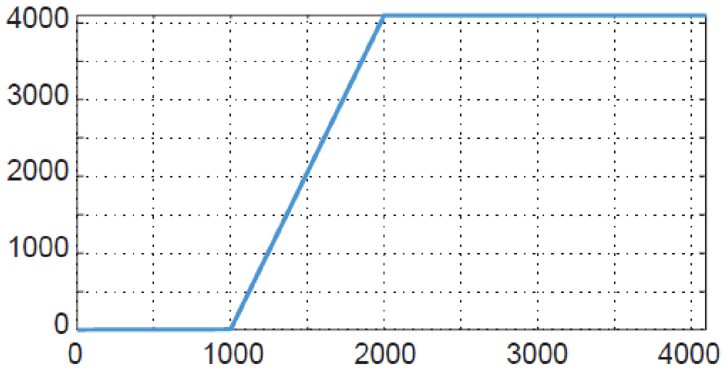
Window/level operation (窗口技术)

$$g_{l,w}(t) = \begin{cases} 0 & \text{for } t < l - \frac{w}{2} \\ \frac{M}{w}\left(t - l + \frac{w}{2}\right) & \text{for } l - \frac{w}{2} \le t \le l + \frac{w}{2} \\ M & \text{for } t > l + \frac{w}{2}, \end{cases}$$

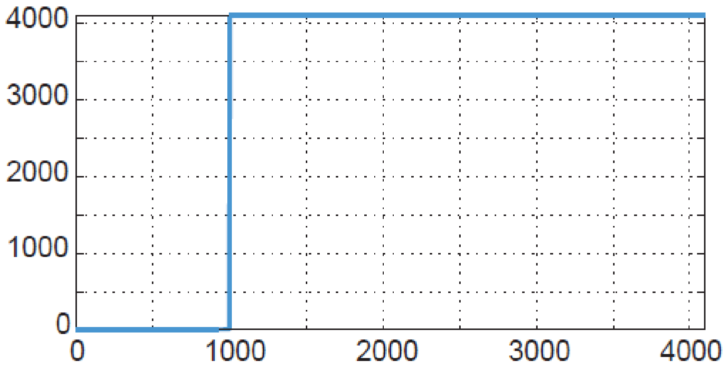
Where M: maximal available gray value

l : window level (窗位)

w : window width, (窗宽)



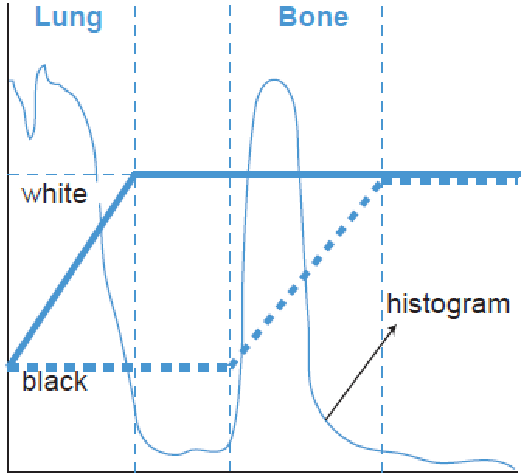
(a)



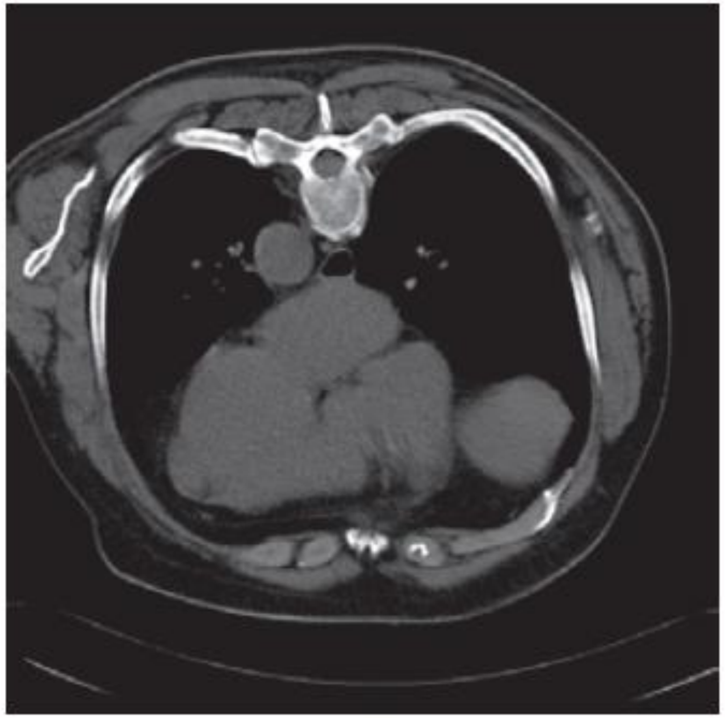
(b)

Window/level operation (窗口技术)

(a)



(b)



(c)

(d)

Fig. (a) Original CT image of the chest; (B) Window level setting; CT image of the chest with different window/level settings: (c) for the bone (window 900 and level 1500), and (d) for the lung (window 0 and level 500).

Resolution

The spatial resolution in a CT image depends on

- The size of the focal spot
- The size of the detector channels
- The slice thickness – axial resolution
- The continuous rotation of the tube-detector – azimuthal blur
- The reconstruction kernel or convolution filter – high frequency components
- The interpolation process inherent to backprojection - helical pitch
- The voxel size

Noise

- **Three types of noise distinguished in CT**
  - Quantum (Statistical) noise: result from the statistical nature of X-ray
  - Electronic noise
  - Round-off (quantization) noise – dynamic range of the detector
- **The amount of noise depends on**
  - The total exposure
  - The patient attenuation
  - The reconstruction algorithm

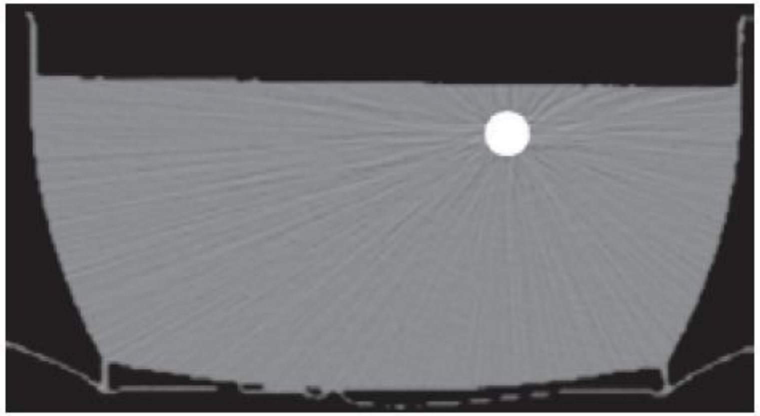


Fig. Reconstruction of a simulated water bowl with iron rod after noise was added to the simulated sinogram.

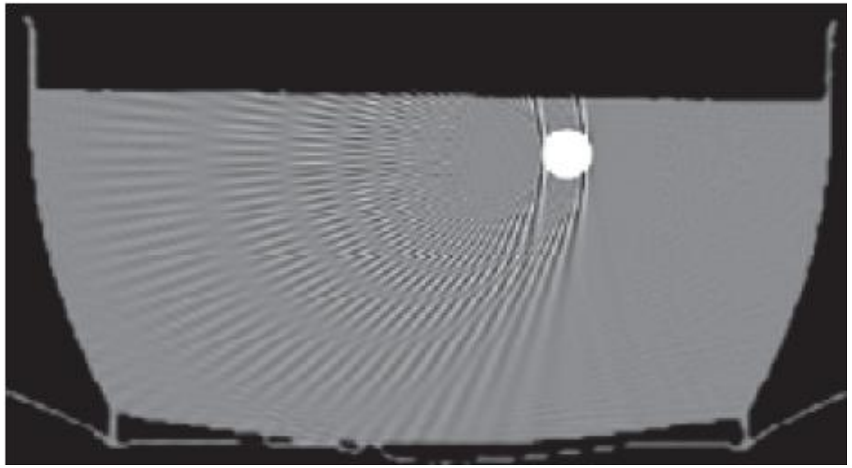
Contrast

- **Primarily depends on the respective attenuation properties and physical factors**
  - X-ray spectrum
  - Beam hardening and scatter
  - Detection nonlinearity
- **Better detecting ability on low-contrast details in CT**
  - CT – thin body slice
  - Radiography – superimposed multiple structures

Image artifact by Undersampling

Undersampling (欠采样) caused by

- Small number of detector sampling - aliasing
- Small number of views – alternative streaks in the peripheral region



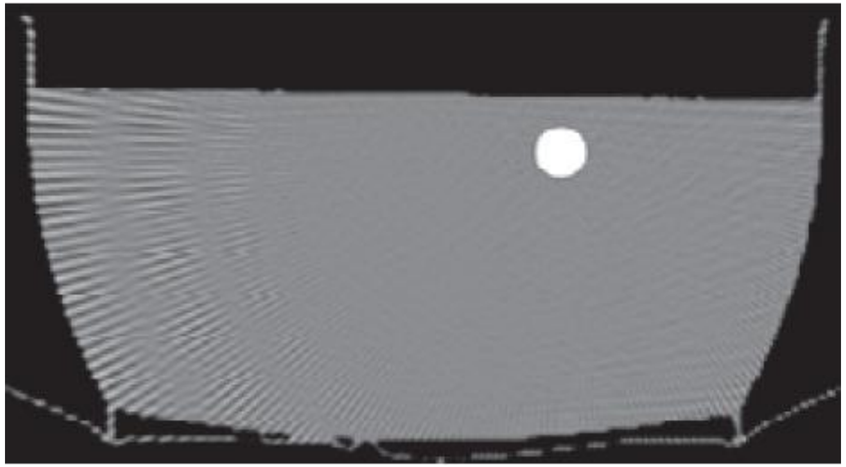


Fig. (Left) Aliasing artifacts occur when the number of detector samples is too small. (Right) Peripheral streaks occur when the number of views is too small.

Image artifact by Beam hardening

- The same pixel experiences different degree of beam hardening when following different paths.
- Reduced attenuation toward the center of an object (cupping)
- Streaks that connect objects with strong attenuation

Fig. (Left) Artifact-free reconstruction of a plexiglass plate with three amalgam fillings. (Right) Beam hardening artifacts occur when a polychromatic spectrum is simulated.

Nonlinear partial volume effect

The larger the attenuation difference across the beam width → the larger underestimation of the integrated averaged attenuation

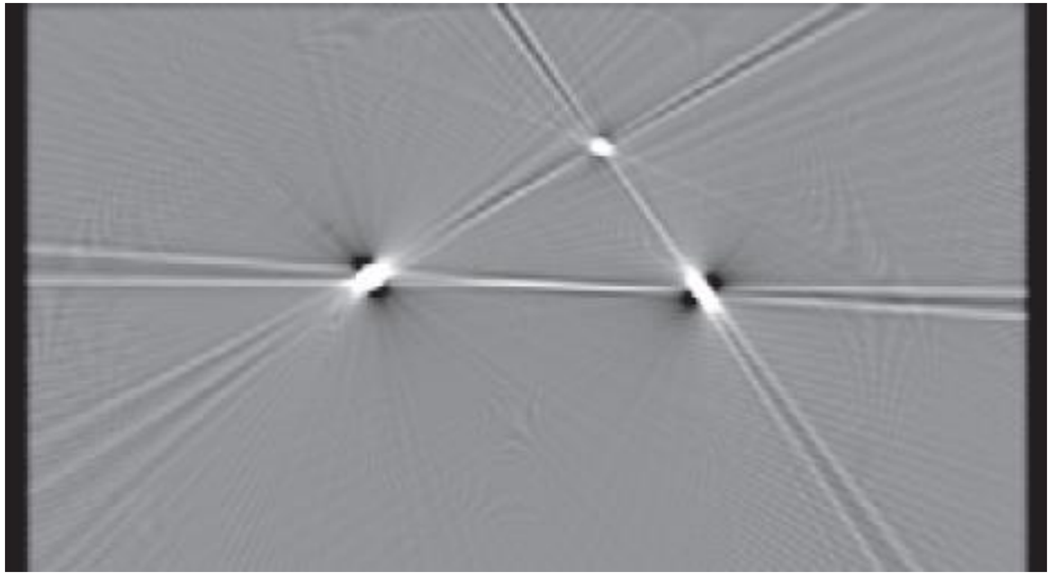


Fig. Strong gradients in the image result in partial volume artifacts. This effect was artificially eliminated in all the other images.

Image artifact by Motion

- **A short movement results in two streaks connecting**
  - the object and the position of the X-ray tube at the moment the object moves
  - The object and the X-ray tube at its start-stop position
- **Gradual movement results in a blurred representation of the moving parts**

Fig. Motion artifacts caused by a short movement of the iron rod.

Image artifact by Helical interpolation

➢ **Stairstep artifact occurs when**

- Helical pitch is too large
- The reconstruction interval is too small

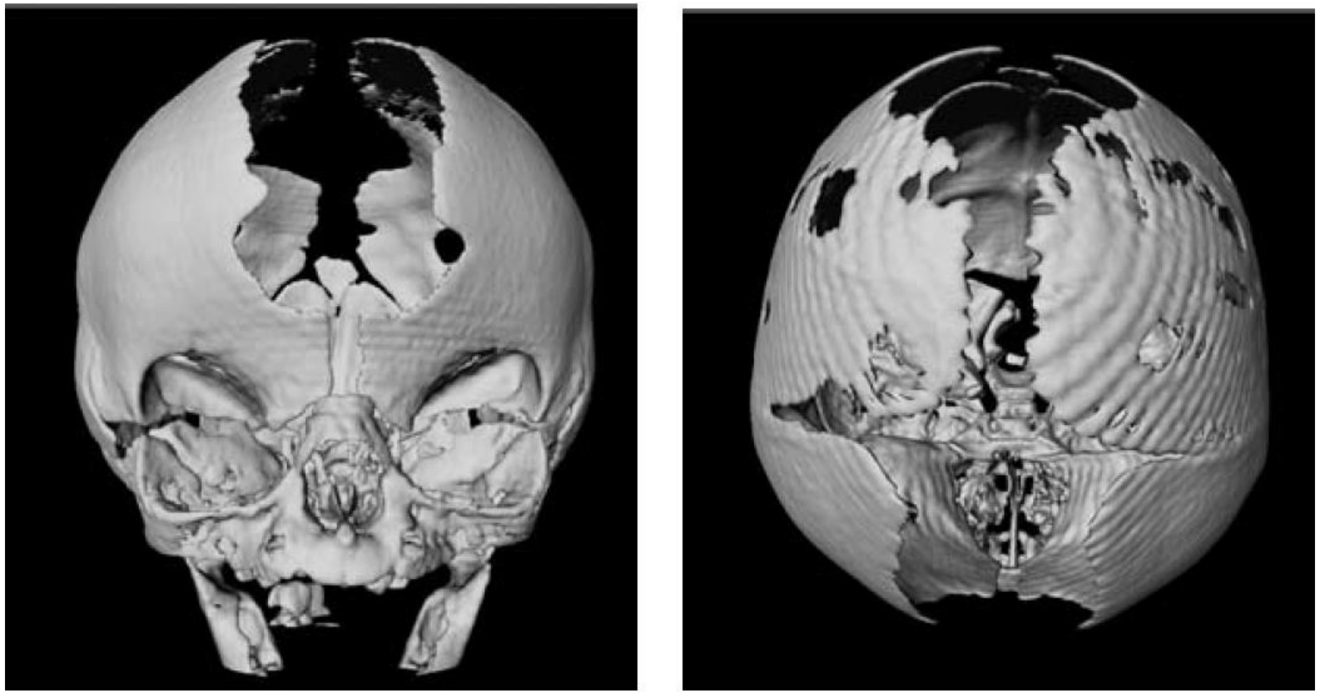


Fig. The stairstep artifact is visible in 3D images as a helical winding along inclined surfaces.

Image artifact by System inaccuracy

➢ **Due to poor calibration or system failure**

- Noisy calibration
- A change of detector efficiency between calibration and actual measurement
- Detector failure
- Irregular table translation
- Mechanical instability of the tube detector unit

Combination of artifacts

- A metal artifact can be caused by beam hardening, scatter, nonlinear partial volume effect and noise

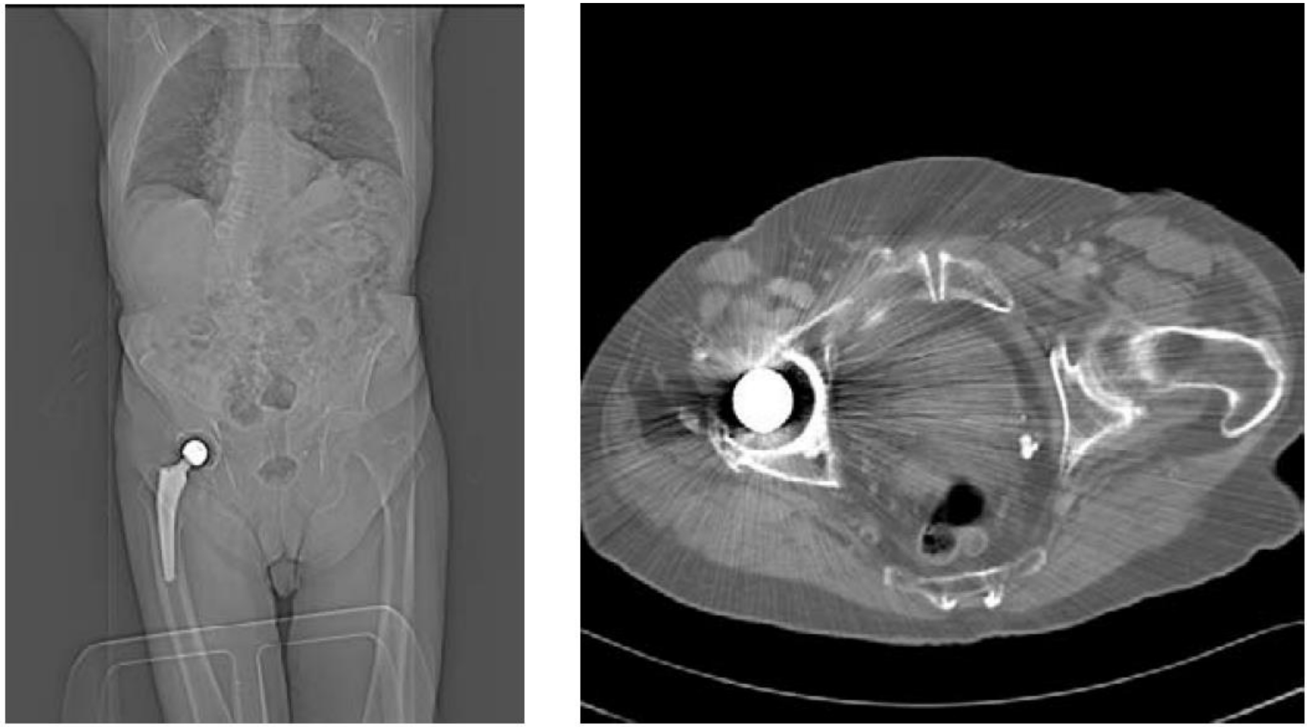


Fig. CT scan of a patient with a prosthetic hip implant, obtained with a multi-slice CT scanner. (left) Topogram, that is, an image of the projections $p_\theta(r)$ for a particular angle θ and varying depth z. This image looks like a radiograph. It is typically used as an overview image to define the region for subsequent scanning. (right) CT image of a slice through the prosthesis showing streak artifacts due to the metallic implant.