Lecture 6 – CT instrumentation & application

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)*
- Equipment *(Fundamental of MI CH3 P53-58)*
- Clinical application

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 —Scintillator→ **Visible light** —Photodiode→ **Electric current** —DAS→ **Voltage** —A/D→ **Digital image**

➢ Photon counting detector (光子计数探测器):

X-ray → **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

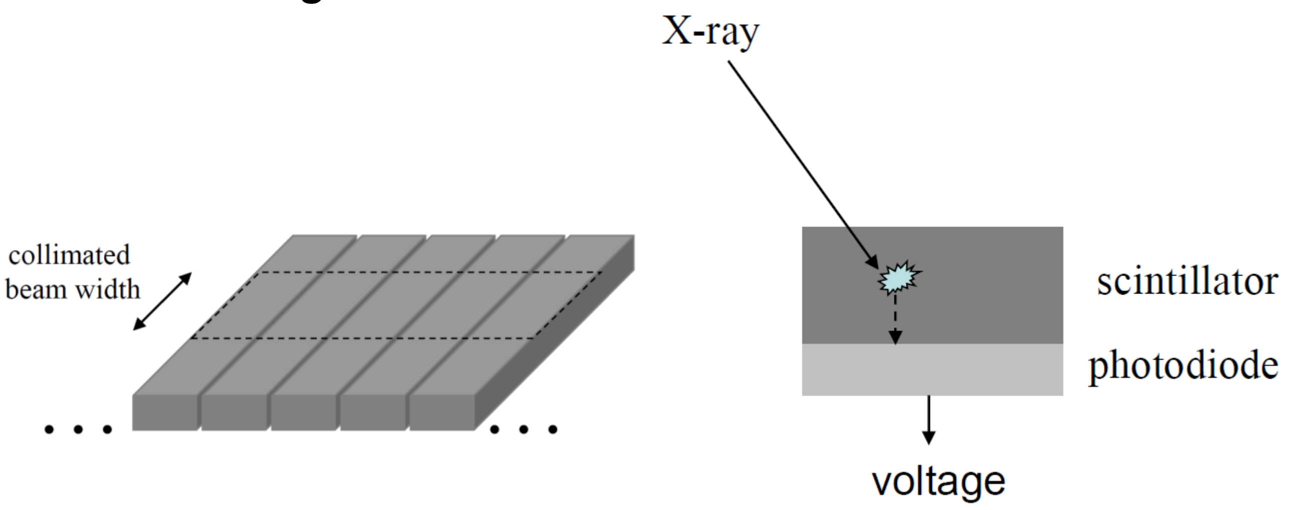


Fig. (left) A single row detector array. (right) For each solid-state detector the incident X-ray energy is converted into an electrical signal via a scintillator and photodiode.

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

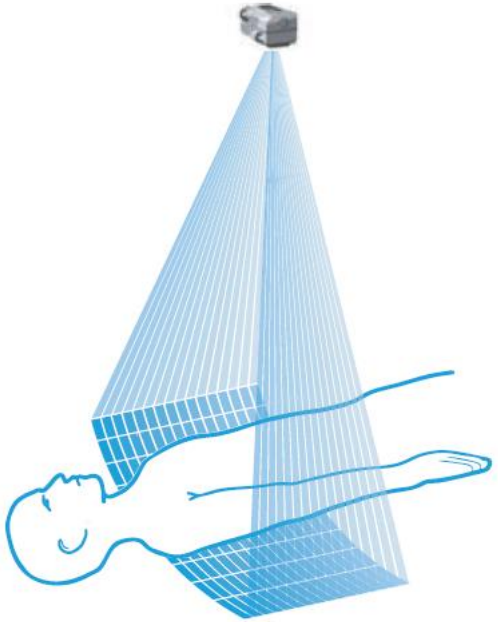


Fig. (left) Multi-slice CT detectors, with up to 320 rows for the largest detector at the back. (right) multi-slice CT: a multi-slice CT scanner can acquire multiple slices simultaneously by using multiple adjacent detector arrays..

Helical CT (螺旋CT)

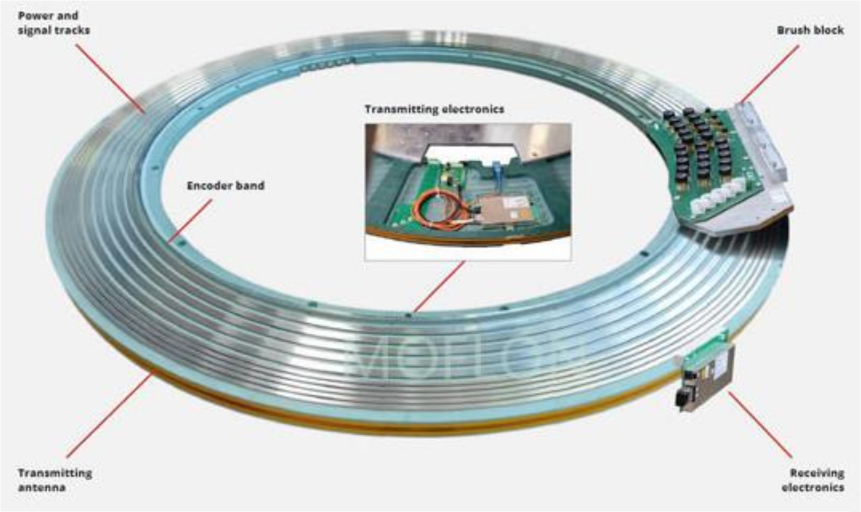
- **Continuous power and signal transmission**
  - Multiple slip-rings: circular contact with sliding brushes
  - Contactless slip ring
- **Continuous operating of X-ray tube**
  - Anode heating problem
  - High heat-capacity
  - Efficient cooling system
- **Modified image reconstruction algorithms**

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

where p : pitch (螺距)

d : table feed (床进速度, mm/circle)

s : slice thickness (层厚)



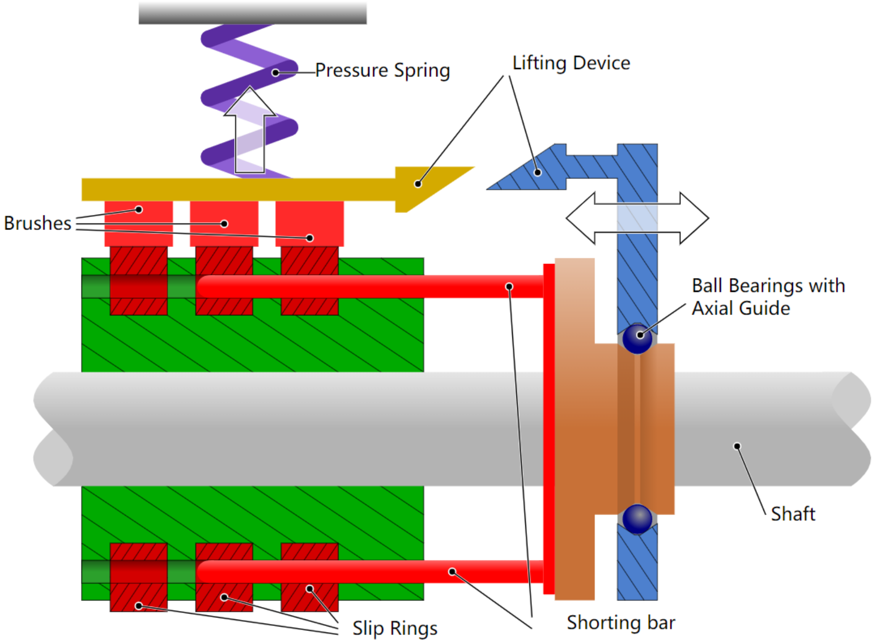
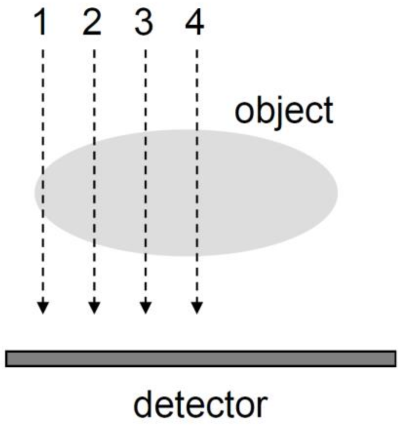


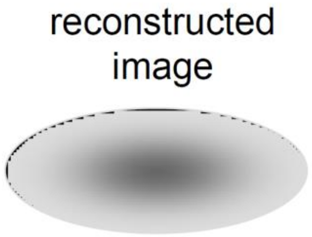
Fig. The slip-rings of a helical CT scanner.

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





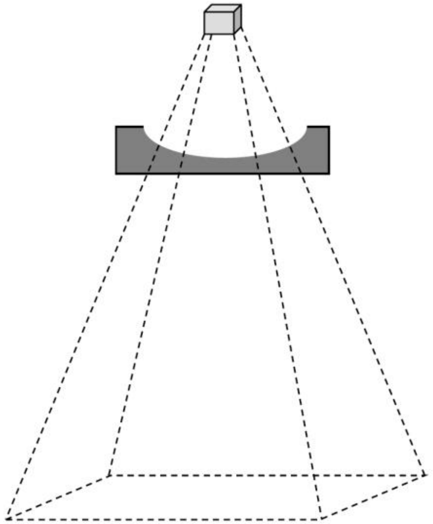


Fig. (left) Four parallel X-ray beams pass through an elliptical object with spatially uniform attenuation coefficient. The effective energy of beam 4 increases as it passes through the object to a greater degree than for beams 3, 2 and 1 since it has to travel the furthest distance through the object. 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

$$\text{CT number} = \frac{\mu - \mu_{H_2O}}{\mu_{H_2O}} \times 1000$$

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

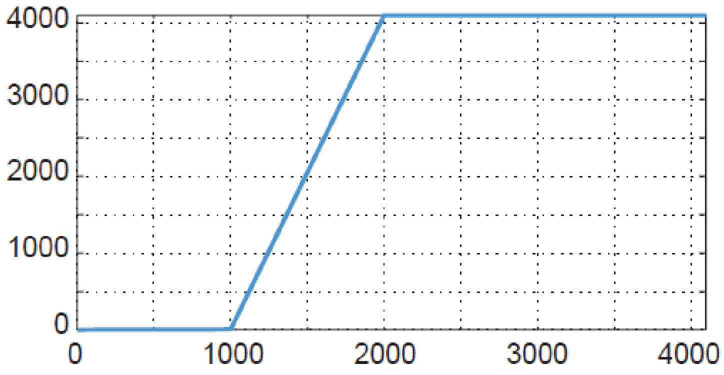
Window/level operation (窗口技术)

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

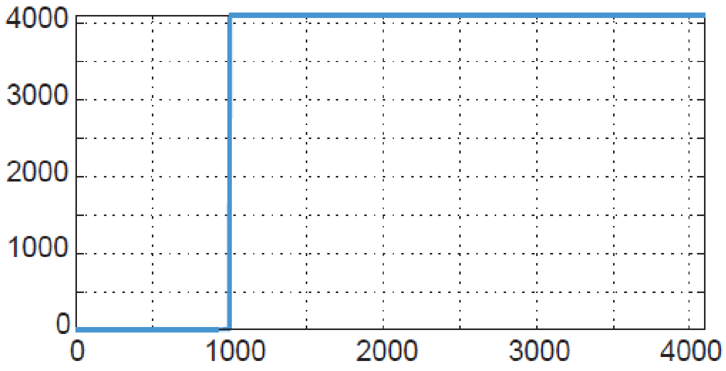
Where M: maximal available gray value

l : window level (窗位)

w : window width, (窗宽)



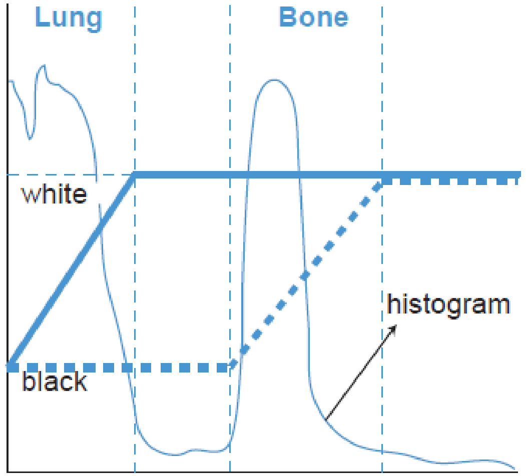
(a)



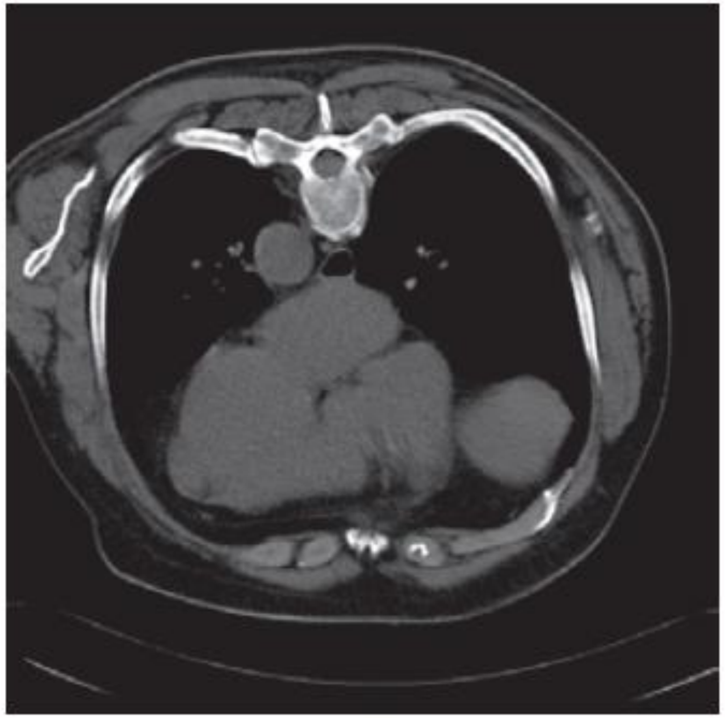
(b)

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

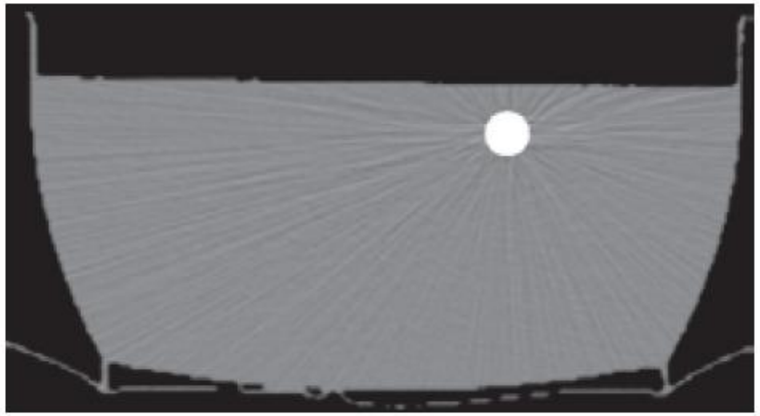


Fig. Reconstruction of a simulated water bowl with iron rod after noise was added to the simulated sinogram.

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

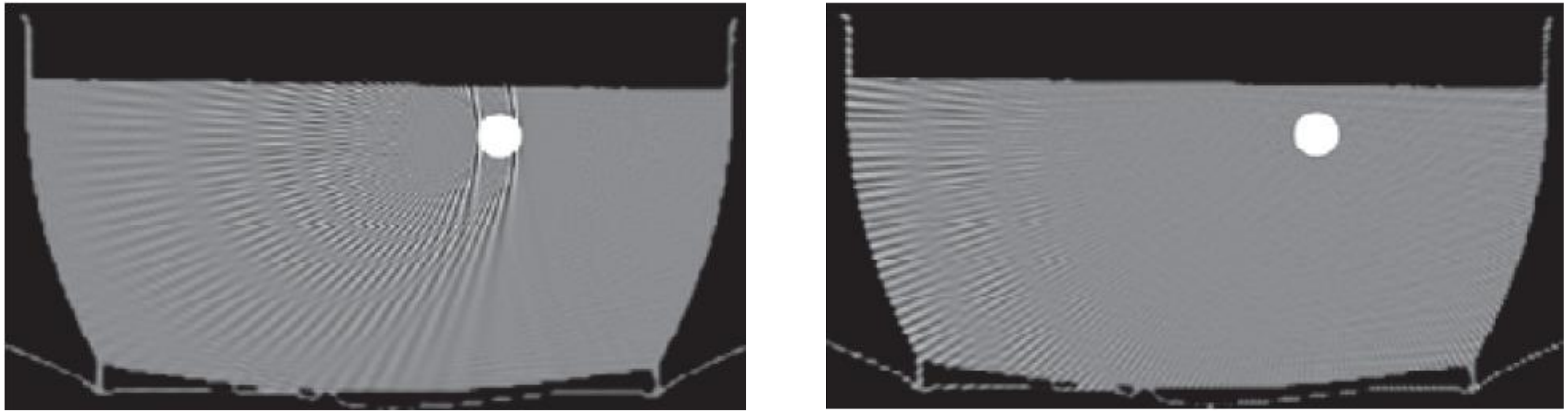


Fig. (Left) Aliasing artifacts occur when the number of detector samples is too small. (Right) Peripheral streaks occur when the number of views is too small.

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.

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

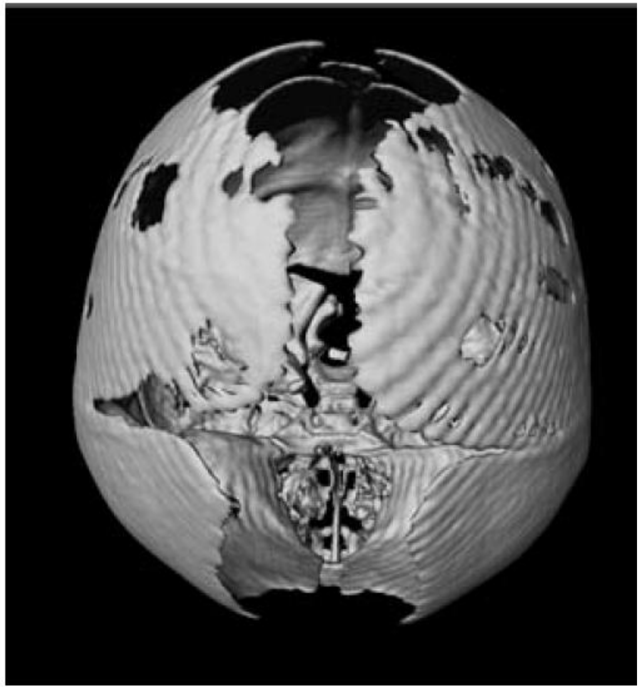


Fig. The stairstep artifact is visible in 3D images as a helical winding along inclined surfaces.

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

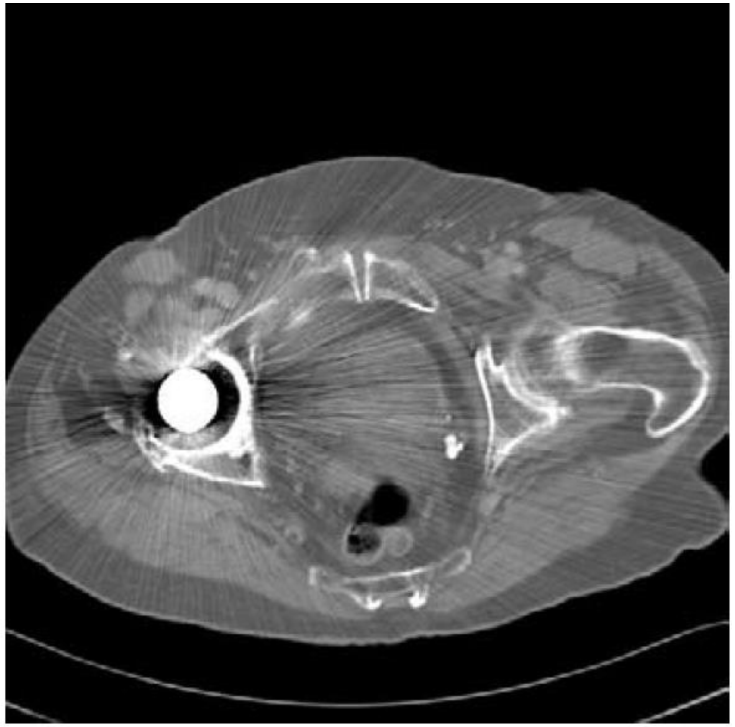


Fig. CT scan of a patient with a prosthetic hip implant, obtained with a multi-slice CT scanner. (left) Topogram, that is, an image of the projections $p_\theta(r)$ for a particular angle θ and varying depth z. This image looks like a radiograph. It is typically used as an overview image to define the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

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Digital X-ray Tomosynthesis

A hybrid of planar radiography and CT

- X-ray tube moved in a vertical path
- Tens of projection images acquired during the vertical motion of X-ray source
- Small focal spot (~0.6mm)
- Short exposure pulses of X-ray
- Lower radiation dose than CT
- Higher image information content than radiography
- More sophisticated form of backprojection and iterative algorithms are used for reconstruction

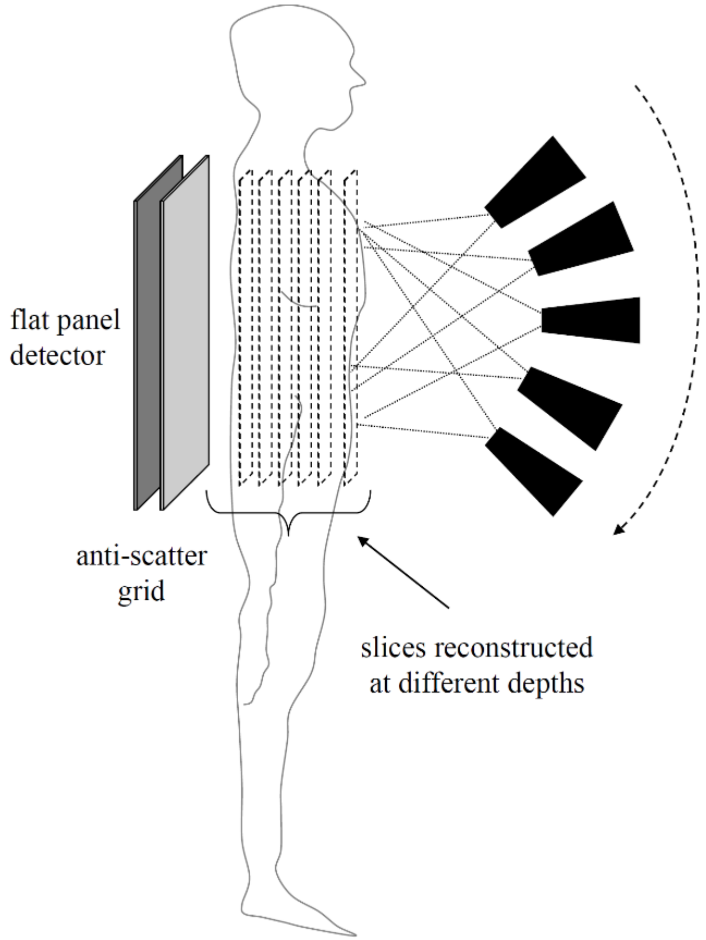


Fig. The basic technique of X-ray tomosynthesis, in which an X-ray source is rotated through a relatively small angle, with planar images being formed at each angle: the digital detector remains fixed for each scan. Image reconstruction allows slices at different depths to be formed.

General-purpose scanner

- Multiple detector rows (multi-slice CT)

  A typical 16cm of total volume will be suitable for

  - Axial scan mode
  - A cardiac scan in one single rotation

- Tilted gantry for imaging oblique slices

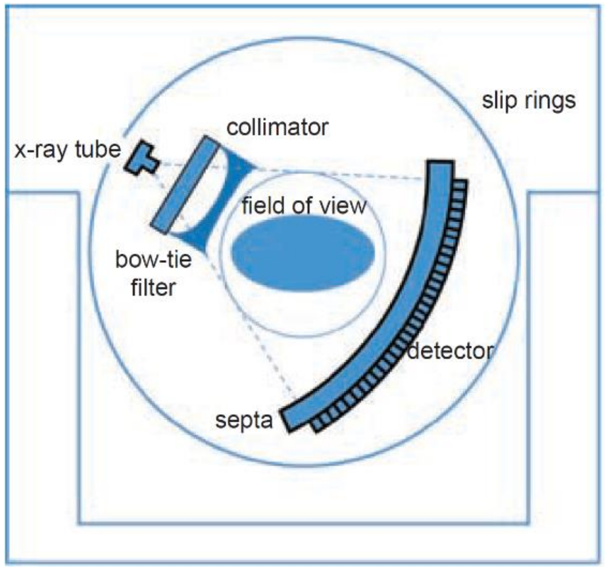


Fig. The basic internal geometry of a multi-slice helical CT scanner.

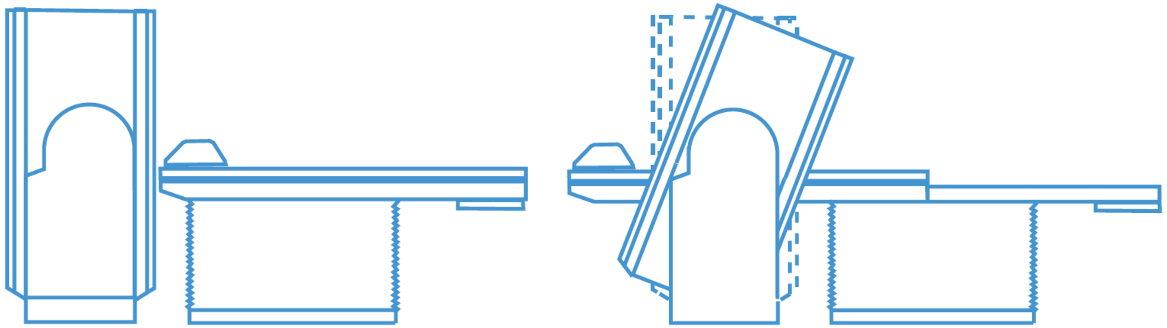


Fig. Schematic views of a helical CT scanner showing gantry tilt and table translation.

Dedicated CT scanners

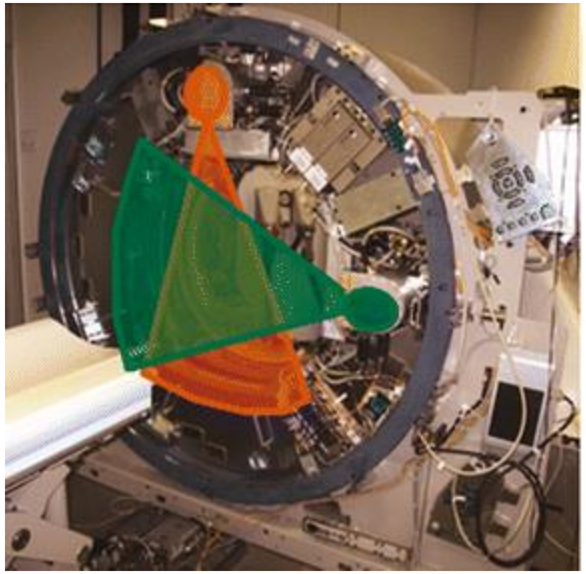
- Smaller and cheaper than general-purpose CT
- Circular cone-beam scanning
- Flat panel detectors (FPD) for high resolution images
- Acquiring volumetric data in a single orbit of the X-ray tube
- Limited field of view
- Not critical scan times – acquisition time of seconds or tens of seconds

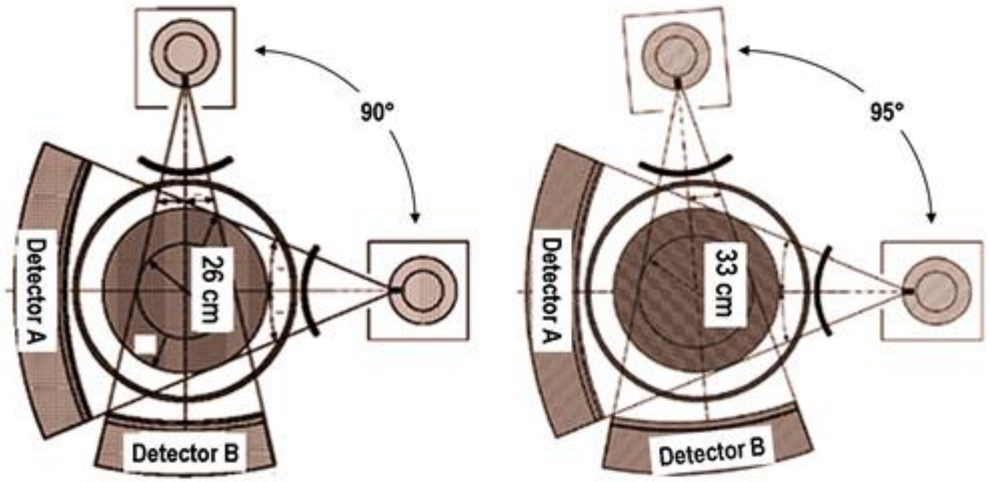
Dedicated CT scanners

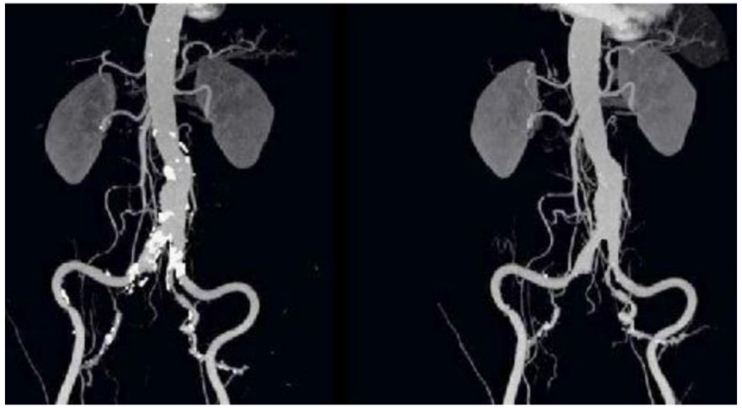
- **Oral and maxillofacial CT**
- **Interventional CT**
  - C-arm for fluoroscopy and angiography
  - Mobile scanner for spine and orthopedic surgery : O-arm
  - Portable CT for intraoperative imaging of the maxillofacial region
- **Breast CT**

Dual-source and dual-energy CT

- **Dual-source CT (DSCT)**
  - To achieve higher temporal resolution (twice of single source CT);
  - The second source covers two-thirds FOV of the primary source;
  - Important for cardiac imaging
- **Dual-energy CT**
  - Two different kVp (140kev and 80kev)







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Head and neck

Imaging objects: brain, maxillofacial structures, inner ear, soft tissues of the neck, etc.

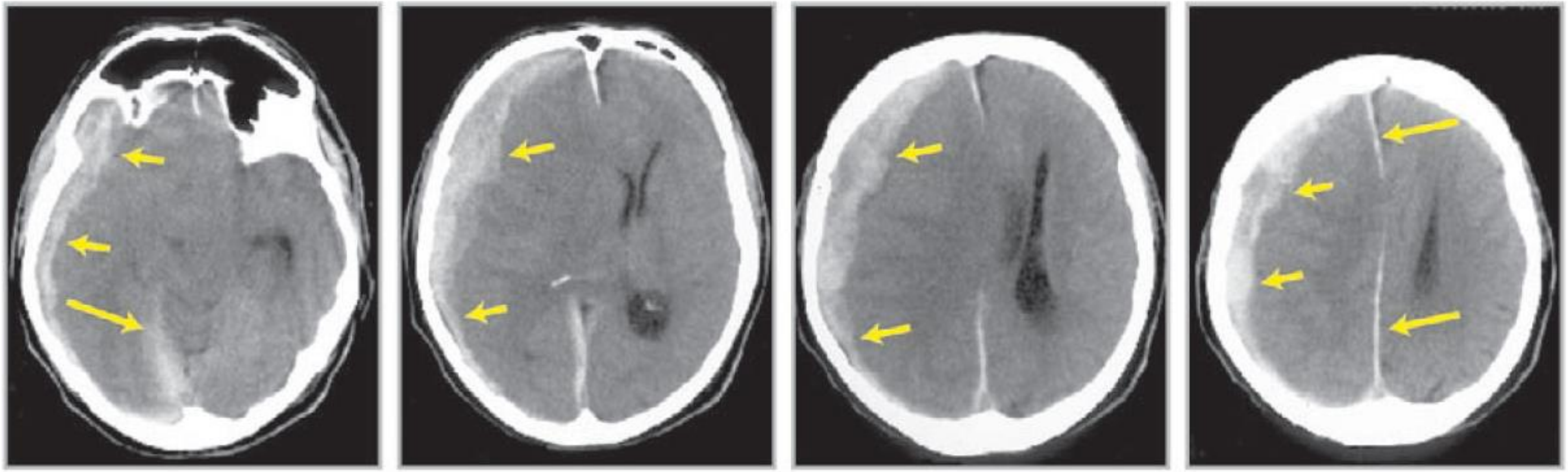
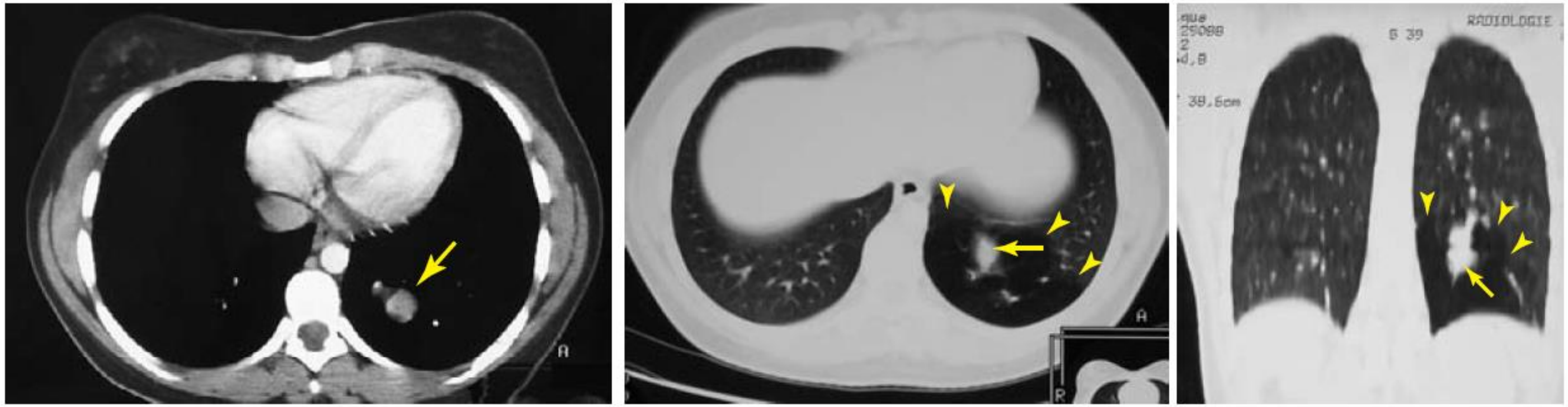


Figure 3.37 Subsequent CT slices through the brain show a subdural hemorrhage as a hyperdense region along the inner skull wall (short arrows). This blood collection causes an increased pressure on the brain structures with an important displacement of the midsagittal line (long arrows). (Courtesy of Professor G. Wilms, Department of Radiology.)

Thorax (胸腔)

Imaging objects: lungs, chest wall and mediastinum, heart and great vessels, etc.

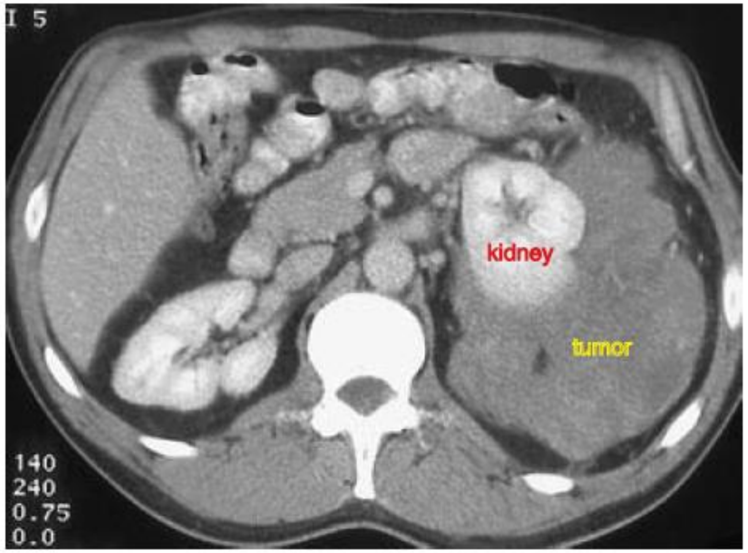


(a) (b) (c)

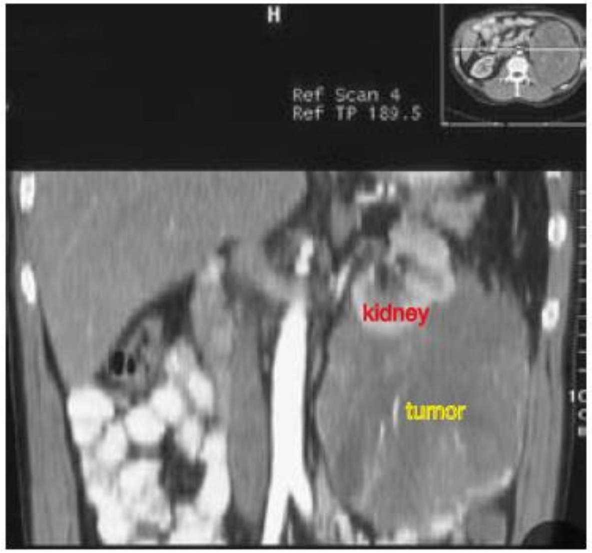
Figure 3.38 CT of the chest. **(a)** Mediastinal and **(b)** lung window/level settings, and **(c)** coronal resliced image. The images show a congenital malformation of the lung located in the left lower lobe. Notice the two components of the lesion: a dense multilobular opacity (arrow) surrounded by an area of decreased lung attenuation (arrow heads). (Courtesy of Professor J. Verschakelen, Department of Radiology.)

Urogenital tract (泌尿生殖器官)

Imaging objects: kidneys, adrenals, urinary bladder, prostate, retroperitoneal cavity, etc.



(a)

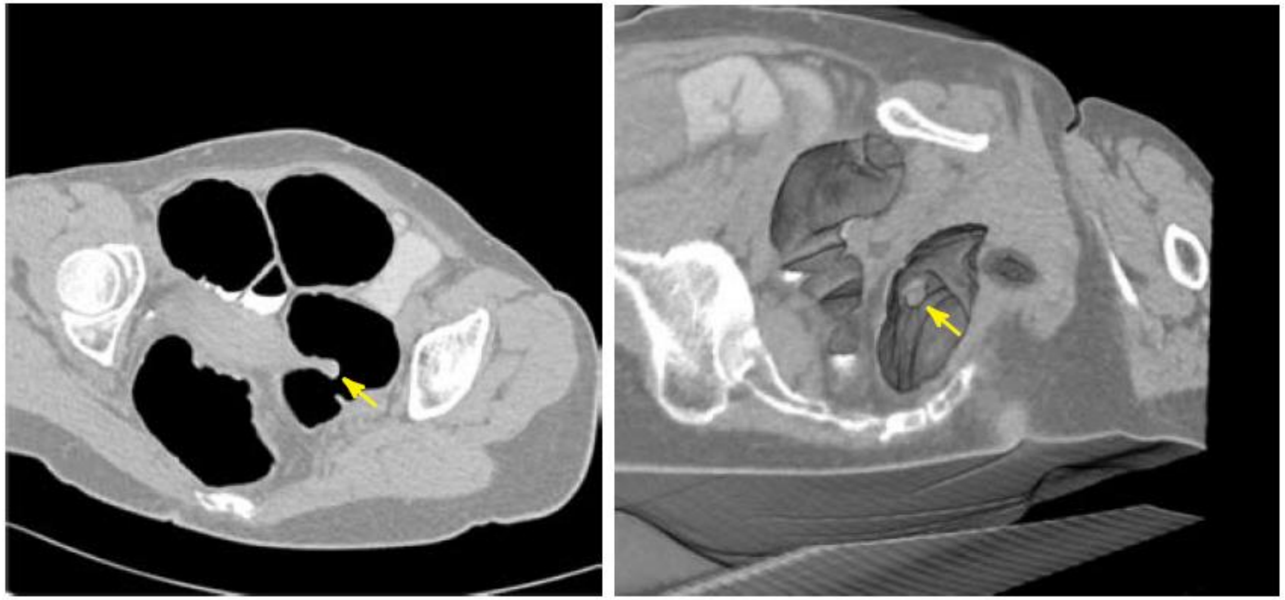


(b)

Figure 3.39 **(a)** Axial CT slice through the kidney showing a perirenal liposarcoma in the nephrographic phase after intravenous injection of contrast medium. **(b)** Reformatted coronal CT slice at the level of the aorta of the same patient. (Courtesy of Professor R. Oyen, Department of Radiology.)

Abdomen (腹部)

Imaging objects: gastrointestinal tract, liver, pancreas, peritoneal cavity, spleen, etc.

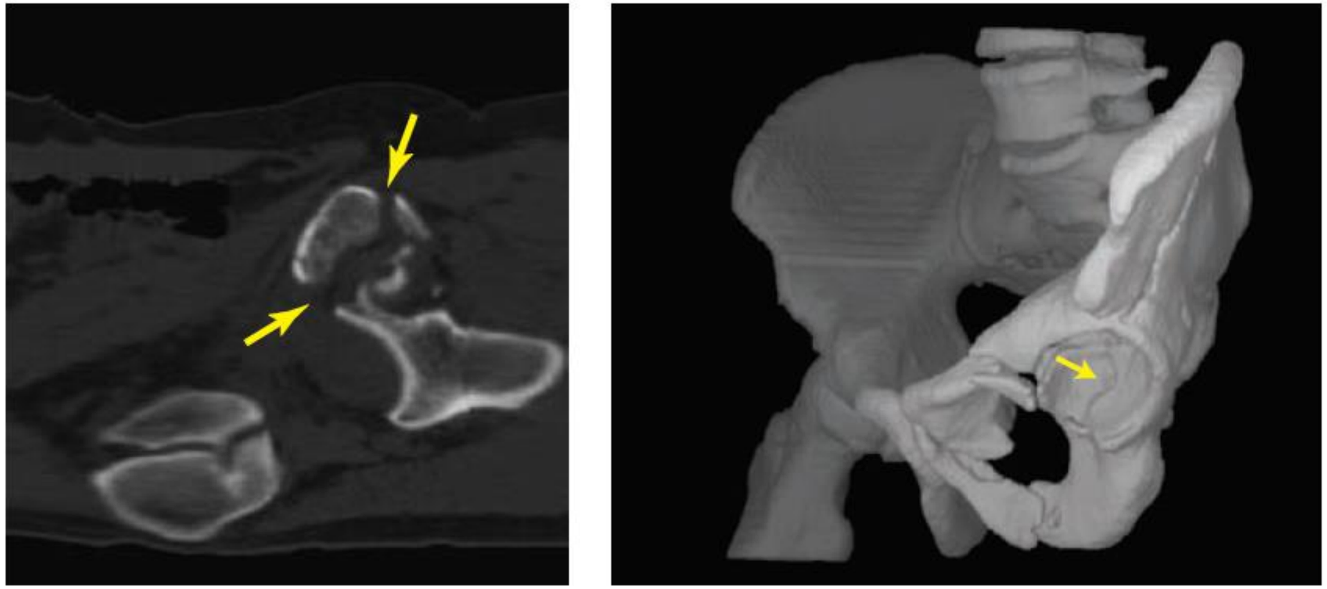


(a) (b)

Figure 3.40 **(a)** A CT slice through the colon shows a polyp (arrow). **(b)** A virtual colonoscopy program creates a depth view of the colon with polyp (arrow) and allows the clinician to navigate automatically along the inner wall. (Courtesy of Dr. M. Thomeer, Department of Radiology, and G. Kiss, Lab. Medical Image Computing.) 3D visualization is discussed further in Chapter 8.

Musculoskeleton system (骨骼)

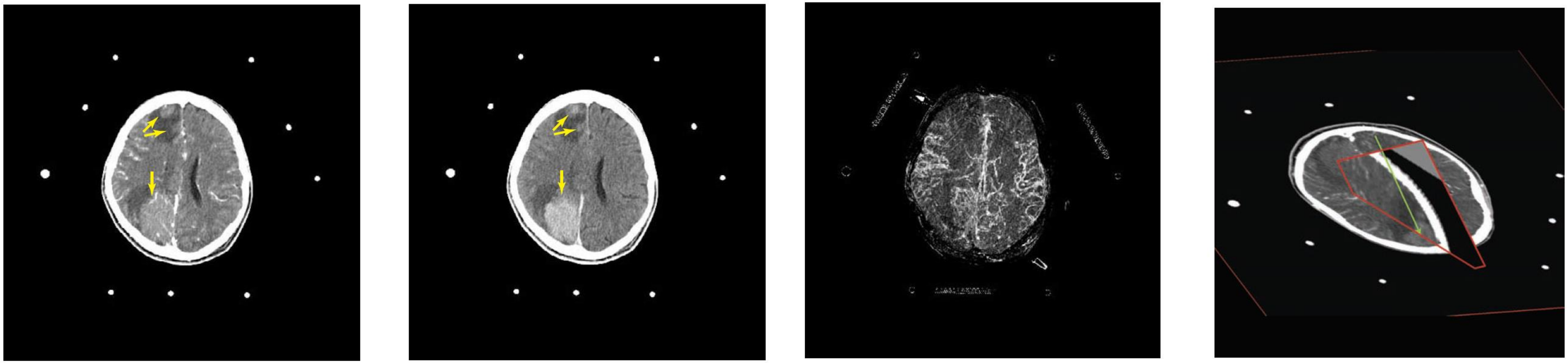
Imaging objects: bone fractures, calcium studies, soft tissue tumors, muscle tissue, etc.



(a) (b)

Figure 3.41 **(a)** On a sagittal reformatted CT image, an anteroposterior course of an acetabular fracture is visible. **(b)** A 3D view on the acetabular surface more clearly localizes the transtectal course of the fracture extending into the posterior column. (Courtesy of Professor M. H. Smet, Department of Radiology, and Professor J. Van Cleynenbreugel, Lab. Medical Image Computing.)

CT angiography (CTA)



(a) (b) (c) (d)

Figure 3.42 CT images through the brain used for neurosurgical planning. **(a)** CT slice immediately after contrast injection. The arrows show brain lesions surrounded by oedema. The nine bright spots around the patient are markers used for surgical planning. (More details are presented in Chapter 8.) **(b)** Late postcontrast image. After 10 minutes the tumoral lesions have absorbed the contrast and light up in the image. **(c)** By subtracting the CT images before and immediately after contrast injection, the cerebral blood vessels are visualized. In this image, the whole vessel tree is shown by a maximum intensity projection (MIP), explained in Chapter 4, p. 87. **(d)** All these images are used subsequently to calculate a safe trajectory (long arrow) through the blood vessels and toward one of the lesions in order to take a biopsy of the tumoral tissue. (Courtesy of Professor B. Nuttin, Department of Neurosurgery.)