Image Acquisition Systems

- Goals and Terminology
- Conventional Radiography
- Axial Tomography
- Computer Axial Tomography (CAT)
- Magnetic Resonance Imaging (MRI)
- PET, SPECT
- Ultrasound
- Microscopy Imaging
Image Acquisition Systems

Goal:

*To capture and record localized information about the physical and/or functional properties of tissues or cells.*

- Faithfulness and Efficiency of imaging is crucial
- Continual advances in imaging technology
- Routine clinical capabilities in 3D acquisition and 4D (fast scanning in 3D)
- 3D volume acquisition leverages the importance of 3D biomedical visualization and analysis techniques
- A wealth of 3D multimodal image information - leads to an integrated synergistic paradigm for improved diagnosis/treatment.
Image Acquisition Fundamentals: Image Formation

- Some form of energy is measured after passage through and interaction with a region of the body.
- Mathematical estimates are computed and images produced (of 2D/3D distributions of energy interactions with body tissues)
- Typically, simultaneous measurements are made of different regions of the body.
- Types of energy interactions: attenuation, absorption, magnetic resonance, etc.
Image Acquisition Fundamentals: Spatial Resolution

- Images are discrete - a pixel or voxel measures a specific sized region of the body.
- Dimensions determined by “space resolving power” of the acquisition system.
- Also a function of image processing/reconstruction
- Limits of the spatial resolution are the smallest object dimensions
- Isotropic vs. non-isotropic
Image Acquisition Fundamentals: Contrast Resolution

- Individual structures recognized by localized differences in signal strength
- Visibility depends on “contrast” against surrounding structures
- **Contrast resolution**: ability to detect differences in intensities between two structures - depends on physical properties of imaged structure
- Specified as a percent largest signal difference
Image Acquisition Fundamentals
Temporal Resolution

- Has 2 definitions: “aperture time” and “frame rate”

- **Aperture Time:**
  - Time taken to capture the signal information to form a single image
  - Critical to the temporal resolving power of the imaging system
  - Key to eliminating motion artifact.

- **Frame Rate:**
  - Smallest interval of time taken between successive images
  - Does not include reconstruction time, but the time required to reset and acquire signal information for a new image.
  - Critical to acquiring 4D volumes, may require “gating” of physiological events (cardiac cycle).
Conventional Radiography: Signal Acquisition

- X-Ray beam passed through body, differentially absorbed and scattered by structures.
- Absorption depends on x-ray beam energy and density and atomic composition of structures.
- Image projected onto radiographic film or stored digitally.
Conventional Radiography: Signal Acquisition

- Digital radiographic techniques used in “fluoroscopy” for procedures such as digital subtraction angiography (DSA) biplane cardiac imaging
- **C-arm imaging systems** permit multiple projections from different angles of view, resulting in 3D location and reconstruction (arterial tree reconstruction in the heart).
Conventional Radiography: Image Characteristics

- Recorded parameter is X-ray absorption, based on x-ray attenuation due to variances in electron density.
- 2D image (2D projection of a 3D structure).
- Spatial resolution: $2K \times 2K$ to $4K \times 4K$.
- Contrast Resolution: 1% of full range.
- Temporal Resolution: 10ms (exposure time).
- 12 bit density values (stored in 16 bits).
Conventional Radiography: Example

Figure 2.1 Diagram of conventional projection X-ray radiograph technique.
Conventional Radiography: Difficulties

Superposition Problem

- Two beams of equal energy may have passed through entirely different materials.

- Attenuation “adds up” - distribution of structures (electron density) in the path is lost.
Conventional Axial Tomography

- X-Ray source and photographic film moved in opposite directions
- All points in the focal plane project onto same points on the film, while those outside of the focal plane are projected to other points
Conventional Axial Tomography: Example

- Example: **Trachea region clearly visualized, but still some superposition remains** (spinal vertebrae superimposed on the trachea)
X-Ray Computed Tomography (CT)

- Minimize scatter by a highly collimated beam
- Eliminate superposition by scanning around transaxial plane.
- X-rays through the slice can detect intensity differences of less than 0.1%
- Individual attenuation coefficients are determined to within 0.5% accuracy using numerical reconstruction techniques
- 3D reconstruction by “stacking” 3D slices
X-Ray Computed Tomography (CT)
X-Ray Computed Tomography (CT)

Figure 2.3  *Diagram of computed transaxial tomography technique.*
X-Ray CT: Signal Acquisition

Goal: Determination of 2D or 3D distribution of x-ray densities (attenuation) of the imaged structure by mathematically reconstructing the desired distribution of the x-ray transmission measurements.
Conventional CT

- **Single x-ray tube** that rotates the full $360^\circ$, recording projections at fine angular increments (0.5-1 degree)

- Measurements processed, images formed by **mathematical reconstruction** techniques (filtered back projection/Fourier reconstruction)

- X-ray point source **collimated to a single slice**, forming a **fan beam geometry**

- **Detectors**: set of curvilinear solid state elements

- **Slice thickness**: determined by collimation of beam

- Table moved axially to acquire adjacent slices

- Scan time: 1-2 sec. per slice; faster acquisitions - **vary slice thickness adaptively** to area of interest.
Conventional CT

Figure 2.4 Diagram of X-ray CT system with rotating source and detector.
Spiral CT

- True volume imaging of the body
- Acquisition traces out a “spiral” trajectory, by continuous beam-detector motion and table movement.
- Recording on “non-coplanar” body sections
Spiral CT

- Larger amount of body area scanned in a shorter amount of time
- Reconstruction problem more interesting (complex) - has led to new algorithms
- Speed of table and beam-detector movements determine “pitch” of the spiral and the final spatial and temporal resolution of the images.
- More flexible reconstruction as slice thickness can be varied during reconstruction by suitably sampling the projections (isotropic voxels)
- Spiral CT: X-ray CT imaging system of choice
Multi-Detector CT

- Parallel array of detectors (beam targets) allows multiple adjacent projections to be acquired simultaneously
- Faster scans: multiple slices are acquired simultaneously
- **Table movement:** faster for quicker scans, slower for higher quality images
- High resolution, isotropic voxel resolution acquisitions
Multi-Detector CT

Figure 2.6 Diagram of geometry for multidetector CT scanning. Operation is similar to spiral CT scanning, except multiple parallel detector arrays record multiple fan beams simultaneously.
Electron-Beam CT

- Used in **functional applications**, electron-beam x-ray CT (EBCT) are high speed scanners, no moving parts.
- Single curved anode (180 degree curvature), with multiple tungsten targets.
- Focused electron beam (similar to CRTs), sweeps across targets to obtain multiple projections, collimated to produce 4-8 sections.
- Scan speed 50-100ms - high temporal resolution can image physiological events: beating heart, blood flow.
Electron-Beam CT

Figure 2.7 Diagram (top) and photograph (bottom) of electron beam X-ray computed tomography (EBCT) system for high speed 3-D imaging.
“Tomography” - refers to “graphical cuts” (slices) through a 3D object

Modeled as a “stack of planes”; basis of most forms of 3D biomedical imaging

Goal: Form 2D cross-sectional images free of “blurring” from structures not in the plane of interest, and termed “tomograms”

“Computed Tomography”, a well established technique - computer implementation of an appropriate inversion formula.

Image reconstruction algorithms implement mathematical formulations to estimate 3D distributions of x-ray attenuation coefficients, from multiple 2D projections
Image Formation/Reconstruction: Projection Geometry

- **Fan beam geometry**: Single point source outside the reconstruction plane, multiple projections are recorded simultaneously.

- Reconstruction may initially organize into “parallel data” (rebinning), but results in aliasing artifacts.

- Typically, reconstruction performed directly on original data.

- Fan beam versions of reconstruction algorithms derived for both Fourier inversion and Radon inversion formulas.
Image Formation/Reconstruction: Projection Geometry

- Spiral CT geometry makes reconstruction algorithms more complex; true projection data lie at an angle to the scanning axis.

- The linear relationship between scanning axis and projection angle can be modeled to use more accurate spiral interpolation mechanisms.

- In multi-detector CTs, full 360 degree linear interpolation is used; additional projection information about the same part of the body is exploited to improve slice selection sensitivity (more isotropic voxels).
CT Numbers: Hounsfield Scale

Figure 2.8 Standard (Hounsfield) scale for X-ray CT numbers.
CT Numbers: Hounsfield Scale

- **Soft Tissue Values**: span a range that includes statistical deviations (measurement errors, actual differences between specimens)

- **CT Number**: Represents attenuation of a particular tissue type in relation to water for the same x-ray energy.

\[
CTNumber = k(\mu - \mu_w)/\mu_w
\]

where \( \mu \) is the attenuation coefficient of the tissue, \( \mu_w \), for water

- **Typical Scale**: \( k \) is usually 50 or 100 and the scale ranges from -1000 to 1000 (represented as a 12 bit number)

\[
H = 1000(\mu/\mu_w - 1)
\]

\[
\mu/\mu_w = 1 + H/1000
\]
Image Characteristics

- Conventional X-ray CT imaging primarily used for structural (anatomical) imaging; contrast agents can be used for functional imaging
- 3D volumes formed as “stacks” of 2D slices
- Inplane spatial resolution 0.1-1mm, slice thickness 1-10mm
- **Number of slices**: 1-100, thickness varied across the volume for faster scans
- $512 \times 512 \times 1$ to $512 \times 512 \times 100$ voxels
- **Contrast Resolution**: 0.5% of full signal
- **Temporal Resolution**: 1-2 sec for 1 full scan (1 slice)
- **Hounsfield Scale**: -1000 to 1000, stored as a 16 bit integer
Vastly improved speed and spatial resolution scans

Can restructure volumes at different scales (by using different slice thicknesses)

**Acquisition speed:** 60 cm in 60 seconds

With sufficient projection information, sub millimeter thickness slices can be generated (*volumes of several hundred slices*)

**Isotropic volumes** (0.1-1mm in each dimension)

**Contrast resolution:** 0.5% of full signal.

**Temporal resolution:** very high.
Image Characteristics: Electron Beam CT

- 2D or 3D (volume) acquisition, 3D(2D+time) - 50ms per slice or 4D - multiple adjacent sections imaged at each time point
- Time varying scans are also acquired with cardiac gating
- Spatial Resolution: $0.5mm^2$, slice thickness of 5-10mm (not good enough for high res 3D Visualization)
- 512x512x1 to 512x512x???
- Contrast Resolution: 1% of full signal
- Temporal Resolution: Same as conventional CT