Fundamentals of Single and Multiple Row Detector Computed Tomography

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Outline

- Single row detector helical CT
- Multiple row detector helical CT
  - Four section/rotation scanners
  - Scanners with >4 sections/rotation
- X-ray tube issues
- Relationship between pitch, dose, noise and section thickness

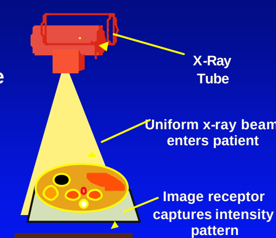
Introduction

- A recent survey* of internists rates CT among top 5 major medical innovations over the past 30 years
- Two major evolutionary leaps occurred during last decade, *spiral or helical CT* in early 90's and *multiple-row detector CT* late 90s to present
- CT has evolved considerably since its invention in 1972, the progression might be characterized as search toward the 3D radiograph

**Decisions in Imaging Economics, Nov 2001*

Conventional X-ray Imaging

Non-uniform beam exits opposite surface with intensity pattern due to differential attenuation of rays along different paths through patient



2D Images of 3D Anatomy from Single Projection

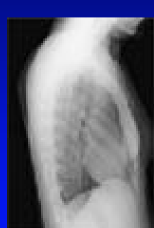


Image due to differences in x-ray attenuation along different paths through the patient

The Problem

- Resolution >5 lp/mm
- Acquisition time <<1 s (stops physiologic motion)

But in 2D images of 3D anatomy

- Tissues are superimposed
- Poor contrast resolution due to high scatter acceptance by image receptor

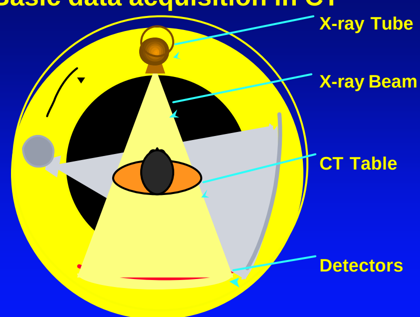
Ultimate Goal: 3D Radiography

- Resolution as good as conventional radiography in all planes
- High contrast sensitivity (no scatter)
- Fast acquisition times to stop physiologic motion
- *Can CT get us there?*

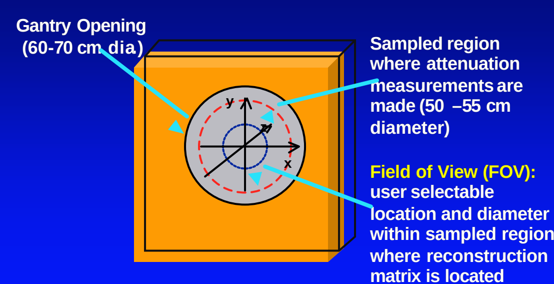
Computed Tomography

- Method for acquiring and reconstructing an image of a thin cross-section of an object
- Based on measurements of x-ray attenuation through the section plane using many different projections

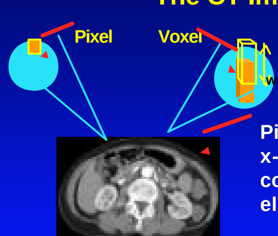
Basic data acquisition in CT



CT Gantry



The CT Image



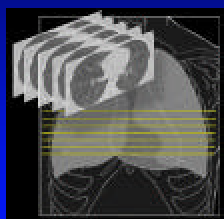
Pixel value is measure of x-ray attenuation in corresponding volume element (voxel)

- Depth dimension of voxel equal to section thickness (1-10 mm)

Limitations of Conventional CT

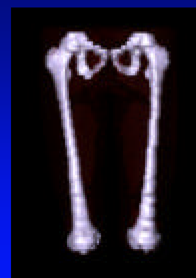
- Scan plane resolution is ~1-2 lp/mm
- Poor z-axis resolution
  - Section thickness ranges 1 to 10 mm
  - Volumes under-sampled with abutted slices
- *Inter-scan delay* due to stop-start action necessary for table translation and cable unwinding
- Section-to-section misregistration due to variation in patient respiratory motion

Progress toward true 3D imaging "Possible"



- "Step-like" contours
- Large temporal lag between sections
- Not useful with physiologic motion

True 3D not yet practical!

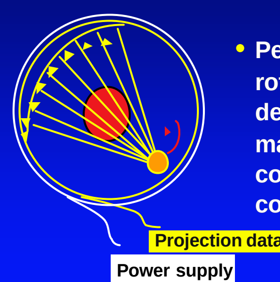


Surface rendition of early 3D reconstruction of lower limbs using 10 mm abutted sections

Technological Advances That Led To: Helical (Spiral) Acquisition

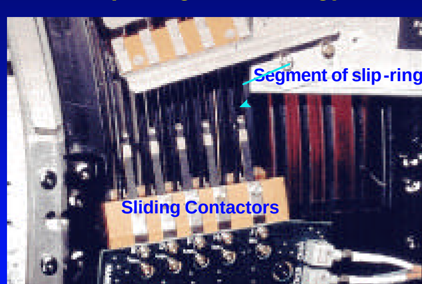
- Slip-Ring gantry
- High power x-ray tubes
- Interpolation algorithms

Slip-Ring Technology

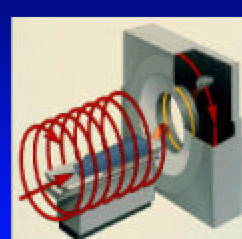


- Permits continuous rotation of tube and detectors while maintaining electrical contact with stationary components

Slip-Ring Technology



Helical/Spiral CT - Principles



- Patient is transported continuously through gantry while data are acquired continuously during several 360-deg rotations*

* Kalender WA, et.al. Radiology, 176(1):181-3, 1990

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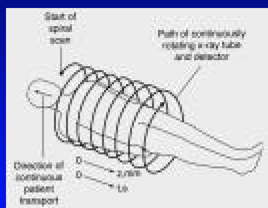
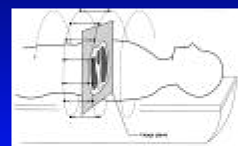
Helical Path of X-Ray Beam on Patient



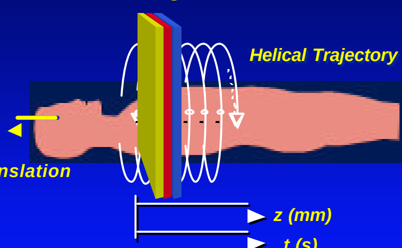
Technology Advances



- Interpolation algorithms
  - Projection data is no longer in a cross-sectional plane
  - Interpolation of projection data into plane of interest prior to conventional filtered back-projection*

* Kalender WA, et.al. Radiology, 176(1):181-3, 1990

Helical Single-Section Mode



Interpolation using samples from single row detector ring

Helical Pitch

$$\text{Pitch} = \frac{\text{Table increment per rotation (mm)}}{\text{Beam collimation (mm)}}$$

- Typical Pitch Ratio - 0.5, 1.0, 1.5, 2.0
- Pitch <1 implies overlapping and higher patient dose
- Pitch >1 implies extended imaging and reduced patient dose

Capabilities of Single Row Detector CT (SDCT)

- Large tissue volumes scanned in short times
- Inter-scan delay eliminated
- Arbitrary section position within scanned volume permits over-sampling without increased dose
- Z axis resolution improved by over-sampling
  - Up to ~ 2 lp/cm (best case), usually 0.5 to 1.0 lp/cm

Limitations of SDCT

- Large volume scan in short duration is limited
- Near isotropic resolution only over small volume
- Poor utilization of X-ray tube

- Multiple row detector CT (MDCT) offers substantial improvement in volume coverage, scan speed with efficient use of x -ray tube

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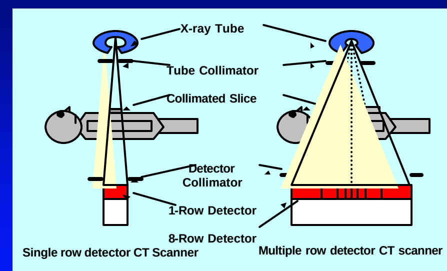
Multiple Row Detector Helical CT (MDCT)

- Single row of detectors replaced with multiple rows

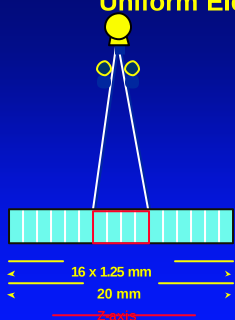
Single multi-element module

SDCT versus MDCT



**Mahesh M, RadioGraphics, 22: 949-962, 2002*

Uniform Element Arrays

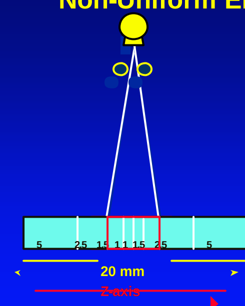


Possible section widths

2 x 0.63 mm
4 x 1.25 mm
4 x 2.5 mm
4 x 3.75 mm
4 x 5 mm
2 x 7.5 mm
2 x 10 mm

Lightspeed, GE Medical Systems

Non-Uniform Element Arrays

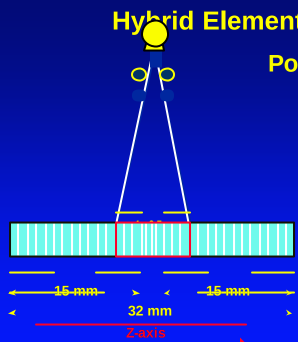


Possible section widths

2 x 0.5 mm
4 x 1 mm
4 x 2.5 mm
4 x 5 mm
2 x 8 mm
2 X 10 mm

Volume Zoom, Siemens Medical Systems

Hybrid Element Arrays

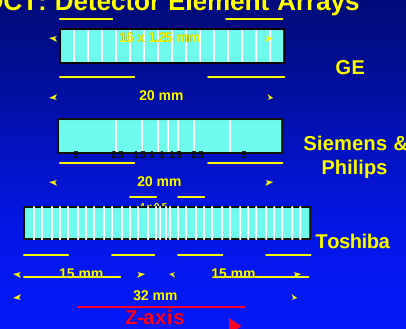


Possible section widths

4 x 0.5 mm
4 x 1 mm
4 x 2 mm
4 x 3 mm
4 x 5 mm
4 x 8 mm
2 x 10 mm

Acquilion, Toshiba Medical Systems

MDCT: Detector Element Arrays



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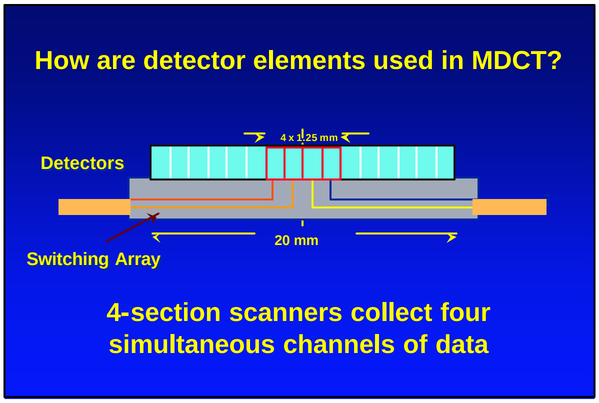

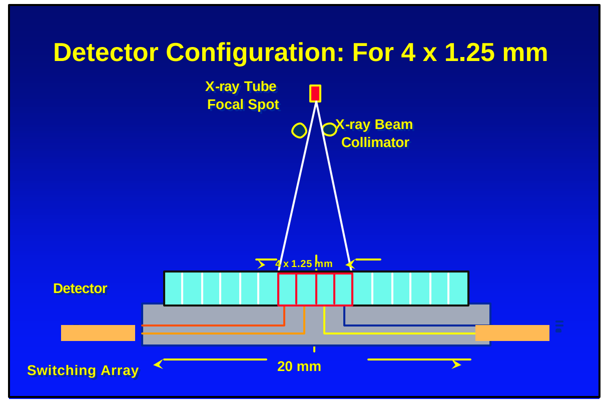

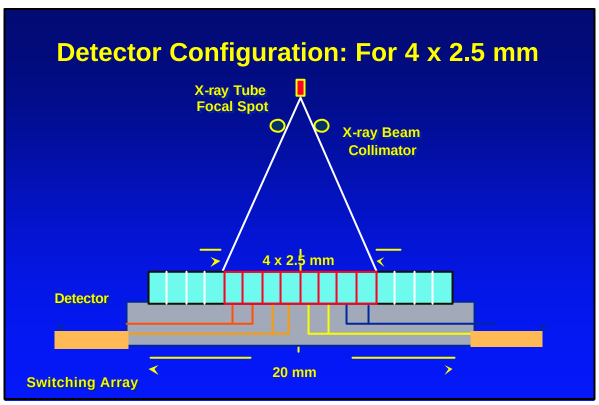

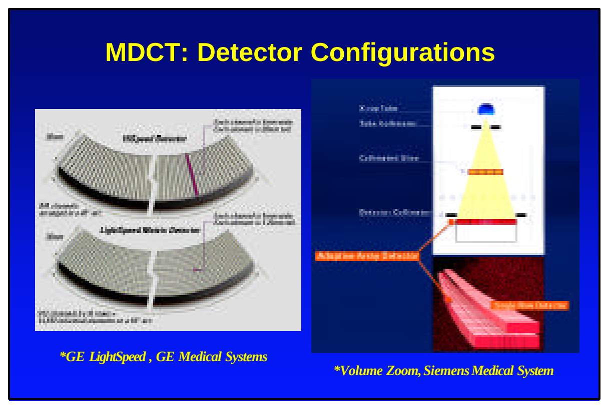

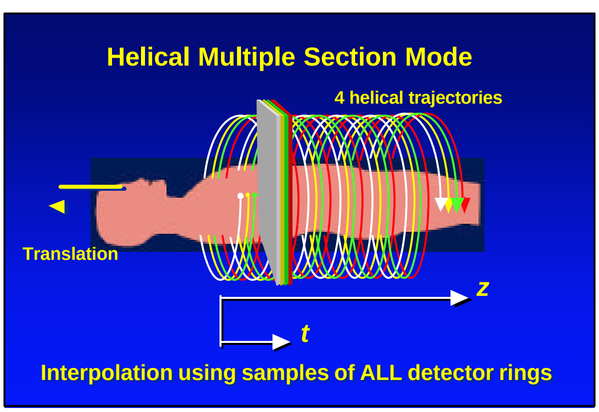

The Detector's Evolution…

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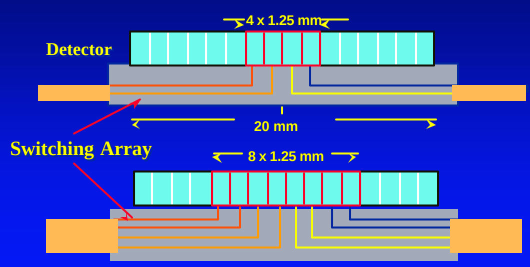
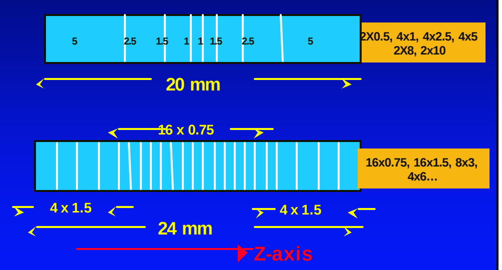
DAS channels: Four versus Eight



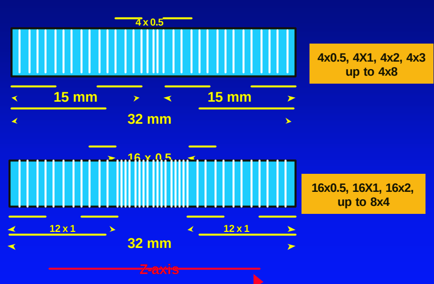
GE Medical Systems

Detector Evolution: 4 vs 16 sections per rotation



Siemens & Philips Medical Systems

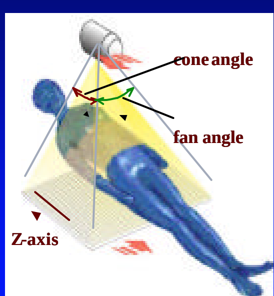
Detector Evolution: 4 vs. 16 sections per rotation



Toshiba Medical Systems

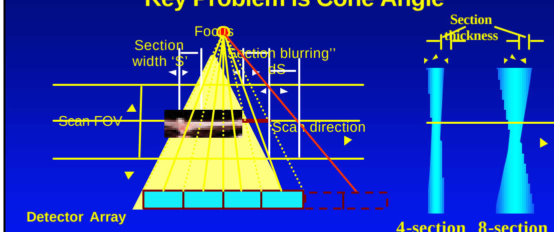
MDCT Episode II: Attack of the Cones

Cone Beam Geometry



- In MDCT, widening beam aperture in z-direction increases cone angle, that results in significant cone beam artifacts

Image Reconstruction: Key Problem is Cone Angle



- Up to 4 sections dS = S, cone angle may be neglected
- What about more than 4 sections?

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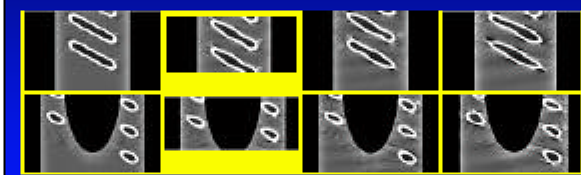
Key Problem: Cone Angle

- What happens, if the cone angle of the rays is neglected ?

4*1mm, pitch 1.5 (6) 12 mm/sec	8*1mm, pitch 1.5 (12) 24 mm/sec	12*1mm, pitch 1.5 (18) 36 mm/sec	16*1mm, pitch 1.5 (24) 48 mm/sec

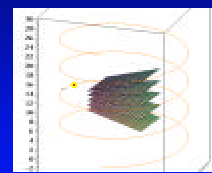


- Image results for > 4 sections are clinically unacceptable !

Courtesy Siemens Medical Systems

Cone Beam Geometry: Alternate Reconstruction Algorithms

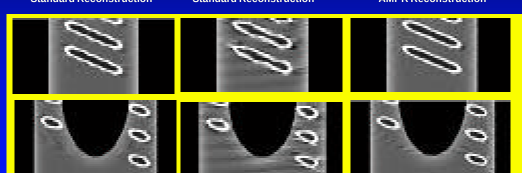
- Advanced Single Slice Rebinning (ASSR)
- Adaptive Multiple Plane Reconstruction (AMPR)
- Pi, Pi-Slant and 3-Pi methods
- Helical Feldkamp with weighting function (HFK)



Kohler T, et al., Medical Physics, 29 (1): 51-64, 2002

Cone Beam Reconstruction (e.g. Adaptive Multiple Plane Reconstruction)

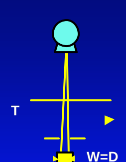
4*1mm, pitch 1.5 (6) 12 mm/sec Standard Reconstruction	16*1mm, pitch 1.0 (16) 32 mm/sec Standard Reconstruction	16*1mm, pitch 1.0 (16) 32 mm/sec AMPR Reconstruction



Courtesy Siemens Medical Systems

Helical Pitch - Reality vs. Myth Definition, Confusion…

Pitch redefined for MDCT

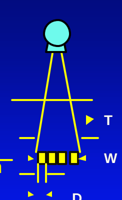


Single Row Detector Array

$$\text{Beam Pitch} = \frac{T}{W}$$

$$\text{Detector Pitch} = \frac{T}{D}$$

$$\text{Beam Pitch} = \frac{\text{Detector Pitch}}{N}$$



Multiple Row Detector Array

T - Table travel (mm)/rotation
W - Beam width (mm)

D - Single DAS channel width (mm)
N - Number of active DAS channels

Beam Pitch vs. Detector Pitch

Table Speed (mm/rotn)	Detector combi	Detector Pitch	Beam Pitch
3.75	4 x 1.25	3	0.75
7.5	4 x 1.25	6	1.50
7.5	4 x 3	2.5	0.625
13.5	4 x 3	4.5	1.125
16.5	4 x 3	5.5	1.375

Data for four-section MDCT

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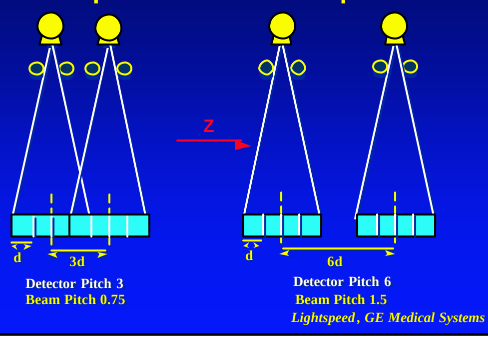
Example of Beam Pitch Options



Beam Pitch

- Beam Pitch >1 implies extended imaging and reduced patient dose with lower axial resolution
- Beam Pitch <1 implies overlapping and higher patient dose with higher axial resolution

Beam Pitch vs. Volume Coverage

- Increase in pitch implies faster acquisition and larger volume coverage
- Lower pitch implies slower table speed with overlapping of tissue (for P<1) and smaller scanned volume

Dose in Helical CT varies as:

$$\text{Dose}\ \mu\ \frac{1}{\text{Beam Pitch}}\ (\text{mAs/rotation})$$

Beam Pitch vs. Dose

- Varying pitch results in increase or decrease of radiation dose to patient
- However in some MDCT scanner, image noise is maintained constant by varying tube current (“effective mAs”), resulting in patient dose independent of pitch*

**Mahesh M, et.al., AJR, 177: 1273-1275, 2001*

High Power X-ray Tubes

X-ray Tubes

- In helical CT, Z-axis resolution and scan volume place huge demands on tube
- Several technical advances have been made to achieve power levels and deal with problems of heat generation, storage and dissipation

X-ray tubes used for Spiral CT

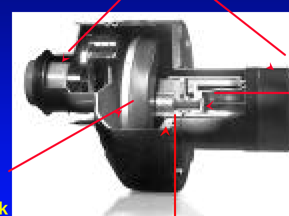
- Larger anode disks allow higher tube currents
- Anodes of graphite based body with tungsten-rhenium or tungsten-zircon-molybdenum* layer deposited by sintering or chemical or physical vapor process

** Ammann E, et al., BJR, 70, S1 -S9, 1997*

X-ray tubes used for spiral CT

- Metal envelopes with ceramic insulators provide higher heat storage capacity
- Spiral groove bearings improve heat dissipation requiring shorter cooling periods and therefore allow continuous rotation with minimal wear

X-ray tube used in Spiral CT



Courtesy Philips Medical Systems

Modern CT X-Ray Tubes

- Heat storage capacity exceeds >3-8 MHU
- No longer the limitations for studies demanding higher speed and larger volume coverage

Noise

$$\text{Noise} \propto \frac{1}{\sqrt{\text{no. of photons}}}$$

Tube current
Scan time
Section width

- Double the tube current, reduces noise by $\sqrt{2}$
- Halve the section width, increases noise by $\sqrt{2}$

Noise vs. Pitch

- For SDCT, noise is independent of pitch for constant mAs and section width
- However on most MDCT scanners, system software automatically adjust scan mA per protocol to obtain comparable image noise as user alters acquisition parameters

Effective Section Thickness

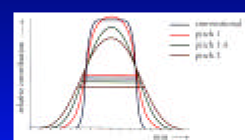
Section and Beam Collimation

- **SDCT:** Both are same, influences z-axis coverage per gantry rotation
- **MDCT:** Section thickness* is total beam collimation divided by number of active detector channels
  - e.g., 10 mm / 4 channels = 4 x 2.5 mm

**defined at center of rotation*

Section Thickness

- True thickness of the reconstructed image, measured as full width at half maximum (FWHM) of slice sensitivity profile
- Same as beam collimation in conventional scanning but different in spiral scanning



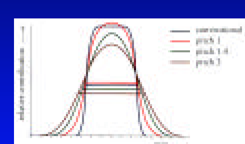
Slice Sensitivity Profiles: conventional and spiral acquisition

Effective Section Thickness

- Measure of slice sensitivity profile at FWHM
- Affected by beam collimation, pitch and interpolation algorithm
- In SDCT user selects section thickness, but true width of reconstructed section is influenced by pitch and interpolation algorithm (180° vs. 360°)
- In MDCT user selects beam collimation in combination with desired section width which is affected by pitch, interpolation algorithm & Z-filter

Pitch vs. Effective Section Thickness

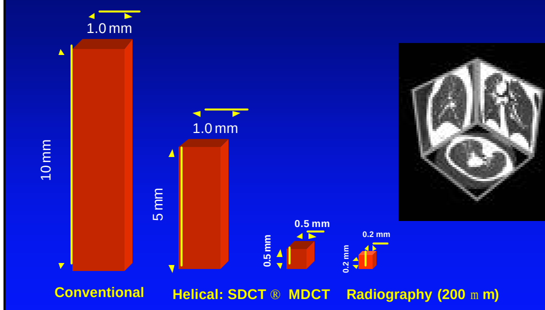
- Increasing pitch broadens effective section thickness
- Structures outside nominal section thickness will contribute to image



MDCT Advantages

- Compared to SDCT
  - Acquisition of same region in shorter scan time or larger region in same scan time
  - Thinner slices yielding higher z-axis resolution
- Increased coverage per rotation
  - Better tube utilization
  - Greater coverage per breath hold
  - Better use of contrast agents
- Approaching Isotropic Resolution!

Evolution of Isotropic Voxel

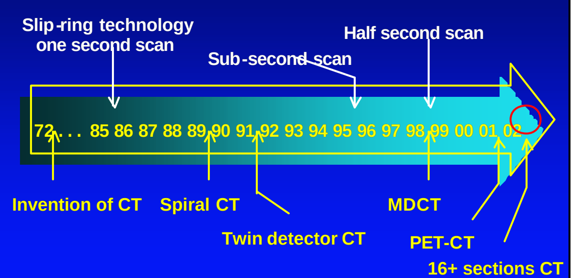


Speed of Volume Acquisition

Region	Distance (cm)	Section Thickness (mm)	Total scan time (sec) SDCT[†]	MDCT[‡]
Head	20	8	16.7	2.1
Neck	15	5	20.0	2.5
Chest	30	8	25.0	3.1
Abdomen	20	8	16.7	2.1
Pelvis	20	8	16.7	2.1
		Total	95.1	11.9

[†] 1 sec scan, pitch 1.5
[‡] 0.5 sec scan, pitch ~ 1.5 for 4-section MDCT

CT Timeline



Future Directions

- Partial rotation scan times ~150 ms possible!
- Cone beam reconstruction algorithms for 16, 40 and 64 row detectors are available
- Extended z-axis coverage to cover most organs in one or two gantry rotations should be possible with large area detectors or flat panel detectors

Conclusions

- CT technology has evolved to level where large 3D volumes can be imaged with:
  - isotropic resolution
  - acquisitions independent of most physiologic motion
- 3D imaging of 3D anatomy - the 3D radiograph - is becoming a reality!