# Introduction to Computed Tomography

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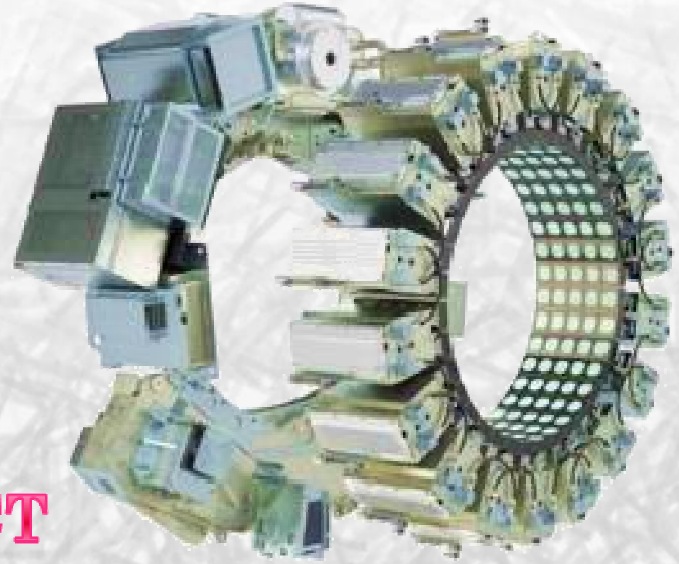
**Institute For Medical Physics (IFMP) Workshop**
**"PET Principles, PET use in hospital, and ongoing developments"**
**Ohrid, Macedonia; 6-8 September 2015**

We are at this medical physics workshop devoted to PET developments and applications, …

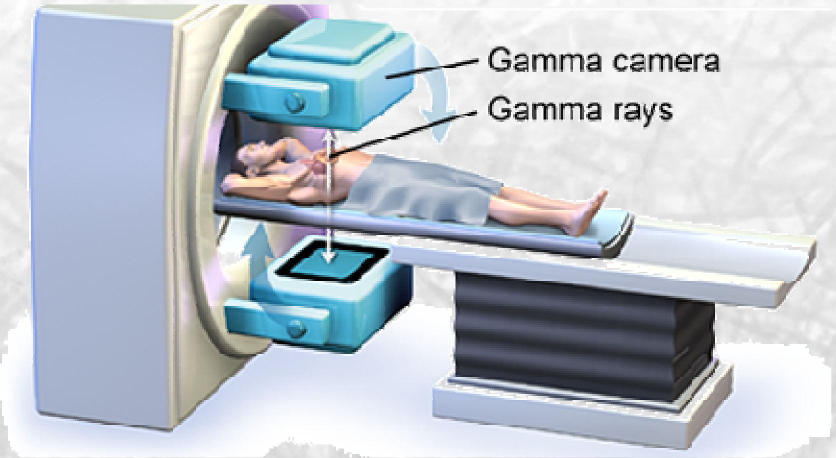
…so why are we talking about CT?

Look at a modern clinical scanner, and you see PET + CT



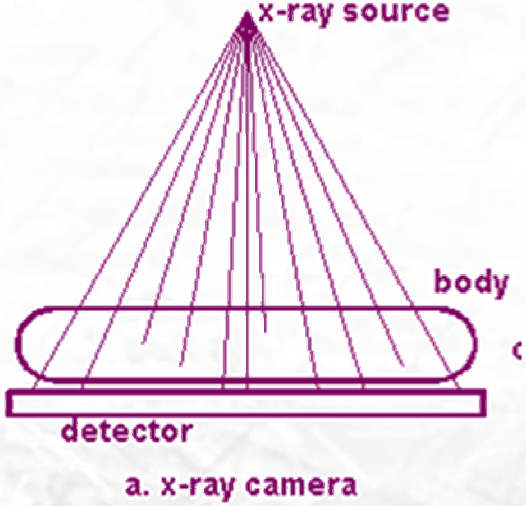
# X-ray versus Nuclear Medicine

CT is a røntgen / x-ray technique
→radiation from outside


Compared to SPECT or PET
→nuclear medicine
→the patient is the source

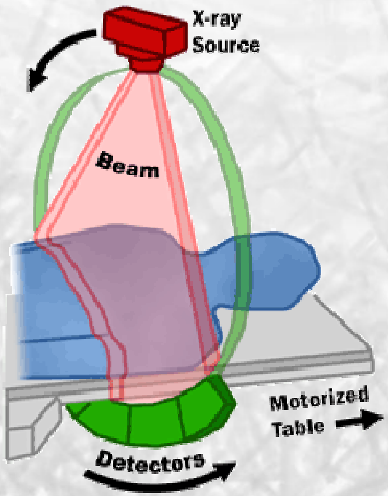
# From x-ray to CT




Traditional x-ray → overlapping information from different depths in the body

Patient = 3D volume
X-ray = picture on a 2D surface

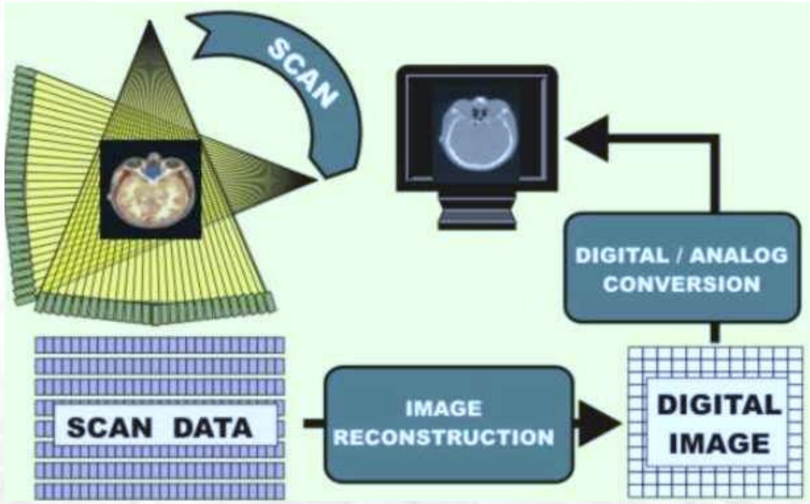
Overlapping information from different depths
→ bad image contrast




Solution:

- Let the x-ray tube rotate
- Make measurements at different angles
- Mathematically reconstruct slice images
- A thin slice of patient ≈ a 2D plane
- No overlapping of information from different depths → improved image contrast

# CT Image Formation




3 steps of CT image formation:

- Scanning
- Reconstruction
- Digital-to-analog conversion

Scanning: produces data, no image

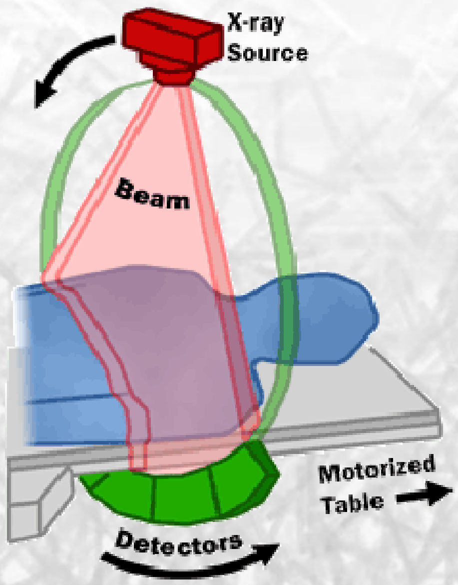
Reconstruction: processes the data, forms a digital image

Digital-to-analog conversion: produces a visible analog image in grey scale

# CT Scanning

Scanning: produces data, no image

- During scanning, a beam of x-rays is scanned around the body
- The beam is fan-shaped




The amount of radiation that penetrates the body along each ray through the body is measured by detectors opposite the body

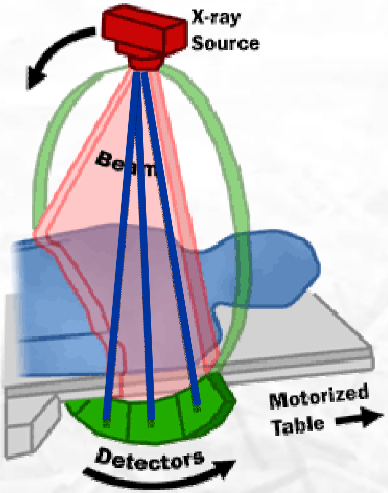
Computed Tomography

tomo = slice

An image is made of a thin cross-sectional slice of the body, slice by slice

# CT Image "View" & "Ray"

View: the projection of the fan-shaped beam from one x-ray tube focal spot position




Many views are projected from around the body

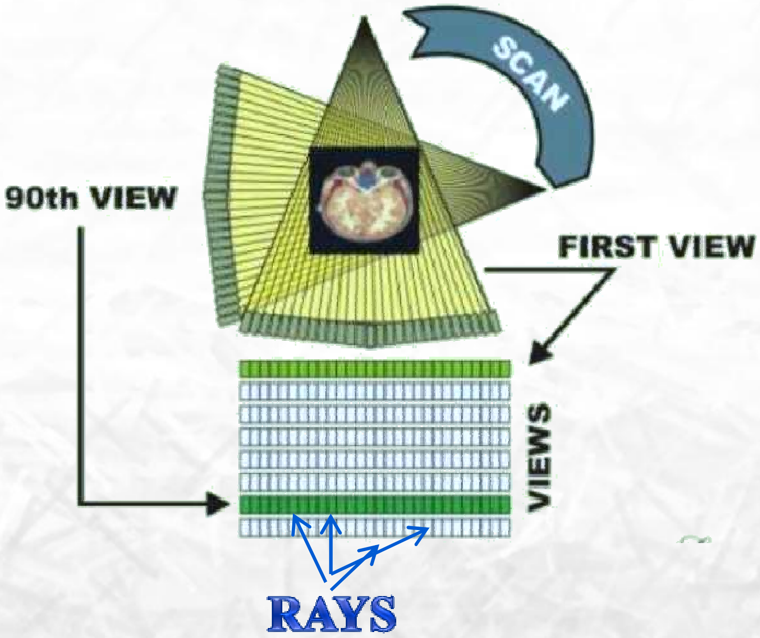
Projecting around the body accumulates data to be reconstructed into an image

Ray: the path of a portion of the x-ray beam from one specific focal spot position to a specific detector position

The ray measures the total x-ray attenuation along it's path
The detector records x-ray attenutaion

one View = many Rays

# The CT Scan

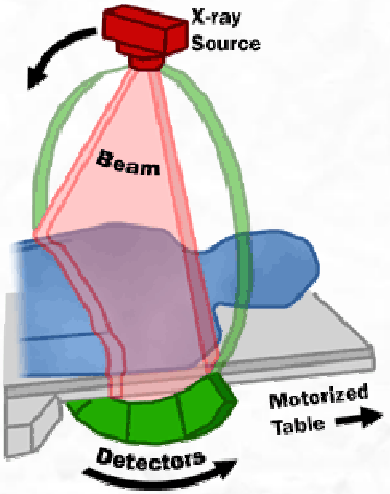



A complete scan is made by rotating the tube completely around the body

→projecting many views

Each view = one profile = one line of data

In principle, one scan produces data for one image slice



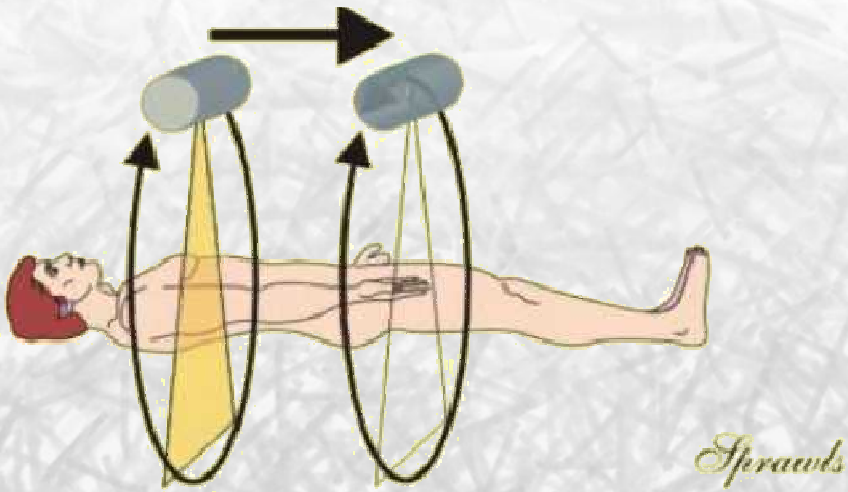

# X-ray tube motion

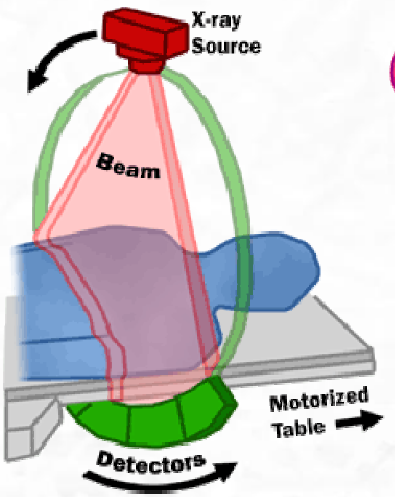
CT: an image is made of a thin cross-sectional slice of the body, slice by slice

## How do we do it?

(1) Rotation
→scan the beam around the body

(2) Translation
→move the beam along the length of the body
→move the body through the beam as it is rotating






# CT Scanner Designs

**Generation I:** 1 røntgen tube, 1 detector, everything rotates

**Generation II:** 1 røntgen tube, a small number of detectors measure coincidentally in a narrow fan beam, everything rotates

**Generation III:** 1 røntgen tube, up to 1000 individual detectors, everything rotates

→ multiclice CT scanners are Generation III

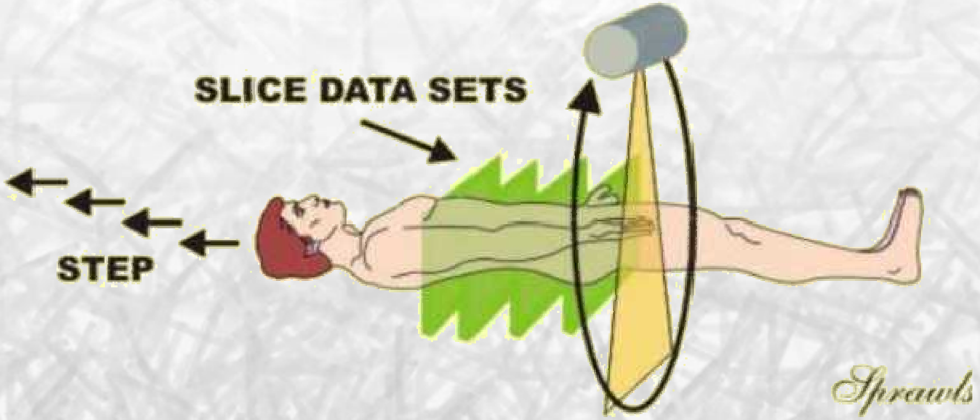
**Generation IV:** 1 røntgen tube, up to 5000 detectors mounted in a ring around the patient, only the røntgen tube rotates

→ suffers from scatter; many detector elements = expensive

# Step & Shoot

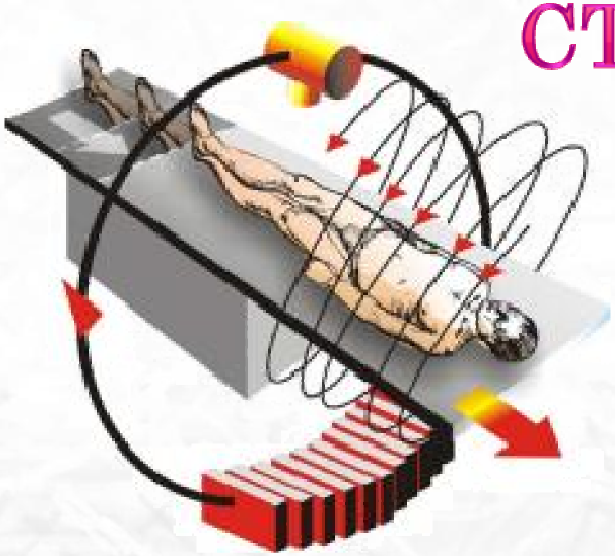
Generation I-IV: scan and step

One complete scan around the body is made
The body is moved to the next slice position
One complete scan around the body is made
The body is moved…




Limitation: the data set is fixed to a specific slice
→Slice thickness, position, orientation are fixed during scanning

# CT Scanner Designs



Generation I-IV: increase the number of detectors, but the patient must hold the breath when scanning the breast

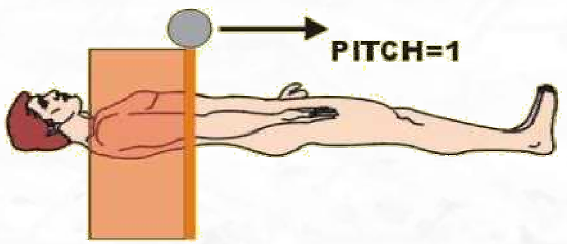
Generation V: Spiral tomography

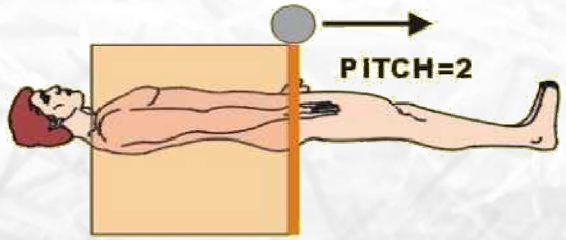
To examine a larger volume in a short time, use spiral tomography →volume scanning

Patient table slowly moves at the same time the røntgen tube rotates

→røntgen radiation makes a spiral track around the patient

# Spiral Tomography



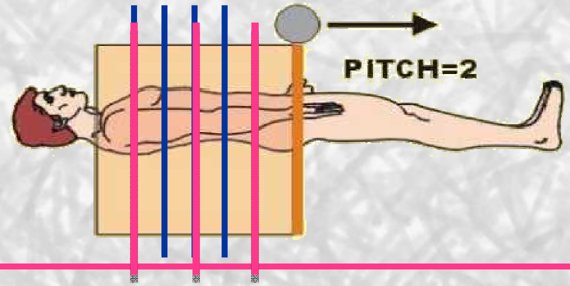




Spiral scanning produces a continuous data set over a volume of patient

The spiral data set is not broken into slices

Remember: step & shoot acquisition produces data that is fixed to specific slices

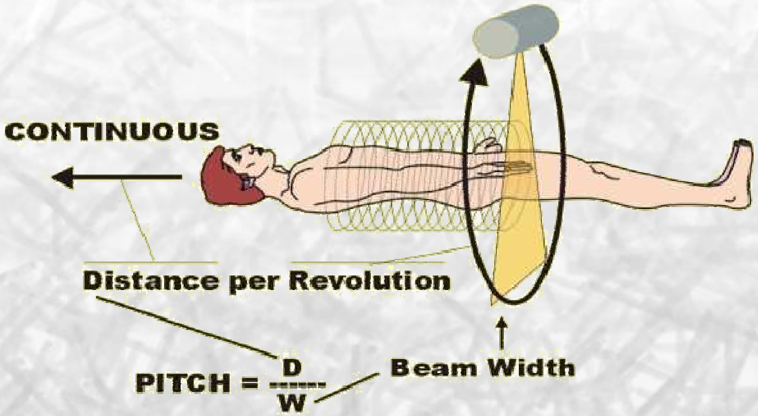
The volume data set from spiral scanning can be sliced as desired during image reconstruction



# Spiral Tomography & Pitch

Patient table is moved continuously as the x-ray beam is scanned around the body

Pitch = the distance the body is moved during one beam rotation
→expressed as multiples of the x-ray beam width



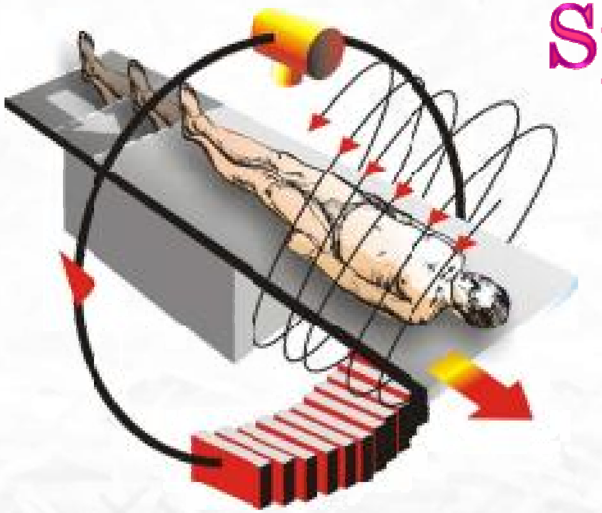

**Example:**

During one rotation, the body is moved 10mm
Beam width = 5mm
Pitch = ?
→pitch = 2

# Spiral Tomography & Pitch

↑ Pitch → x-ray beam is spread over more of the body
→"x-ray beam moves faster along the patient"

↑ Pitch → ↓ Time to cover the same volume
Radiation less concentrated
Dose reduced
Less detail in the data
Reduced image quality

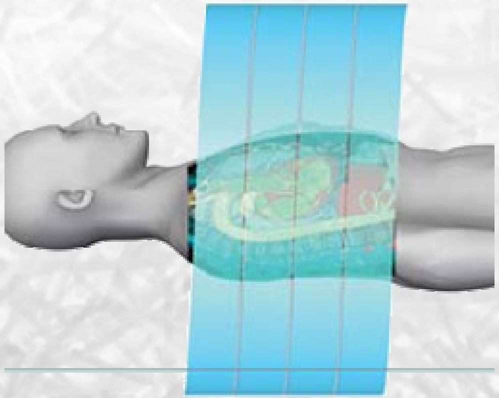


# Spiral Tomography

The volume data set can be sliced as desired during reconstruction
→Thickness, position, orientation of image slices can be adjusted

Can create images of overlapping slices

Repeat reconstruction to produce images with different spatial characteristics



Volume data set → 3D images

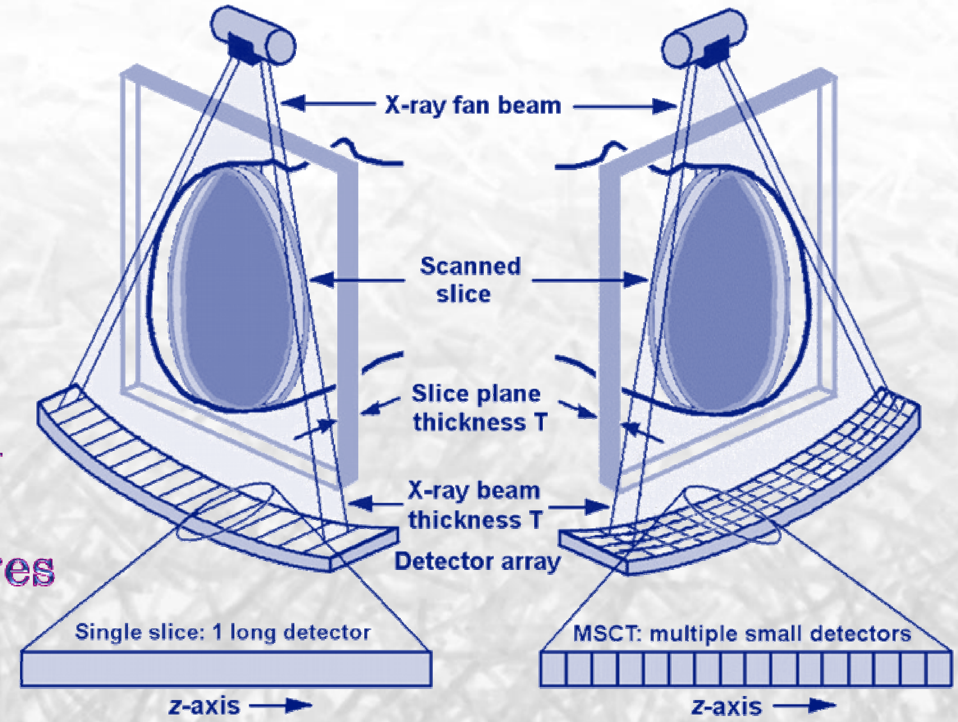
3D images of good quality require good detail along the patient axis → scan with thin beams and low pitch

# CT Detector Array

CT detectors span and intercept one view
CT scanners can have a single row of detectors or multiple rows

## Multiple Detector Rows:

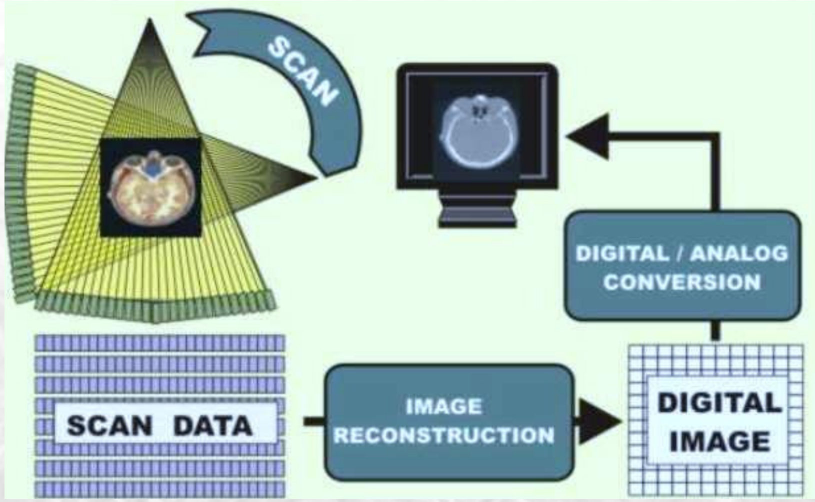
- Faster scanning of a section
- Multiple fan beams scan simultaneously
- Significant for large section/thin beams
- Can produce thin, high-detail slice images
- Can produce 3D volume images



# CT Image Formation

3 steps of CT image formation:

- Scanning: produces data
- Reconstruction: processes data, forms digital image
- Digital-to-analog conversion



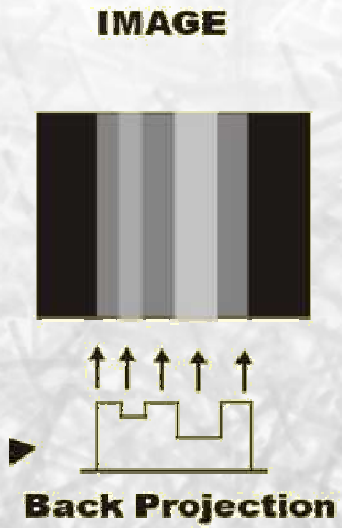

Scan data is processed into a digital image that is a matrix of pixels

Image reconstruction via iterative reconstruction or filtered back projection

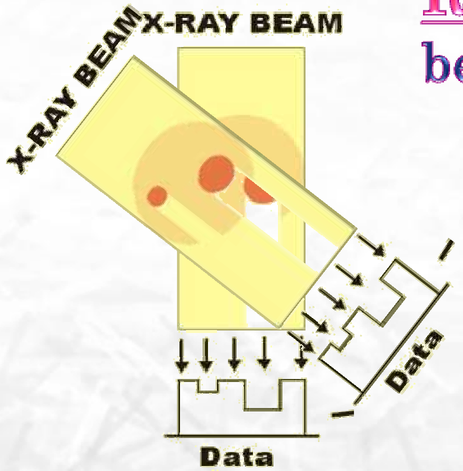
# CT Data Reconstruction: FBP


One scan through a slice with 2 objects
→The data is a profile of the x-ray attenuation by the objects

Back Projection:
Draw an image by projecting the profile onto an image surface
The information from the scan profile only allows the drawing of streaks or shadows across the image area



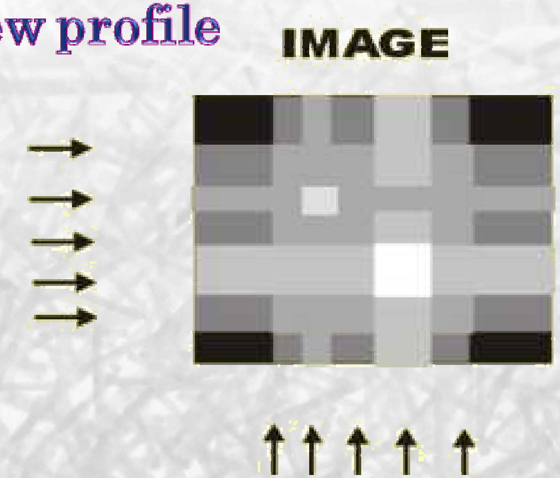
# CT Data Reconstruction: FBP




Recall: "View" = the projection of the fan-shaped beam from one x-ray tube focal spot position

Rotate the x-ray beam and obtain another view profile

Back project this profile onto the image area along with the previous view profile



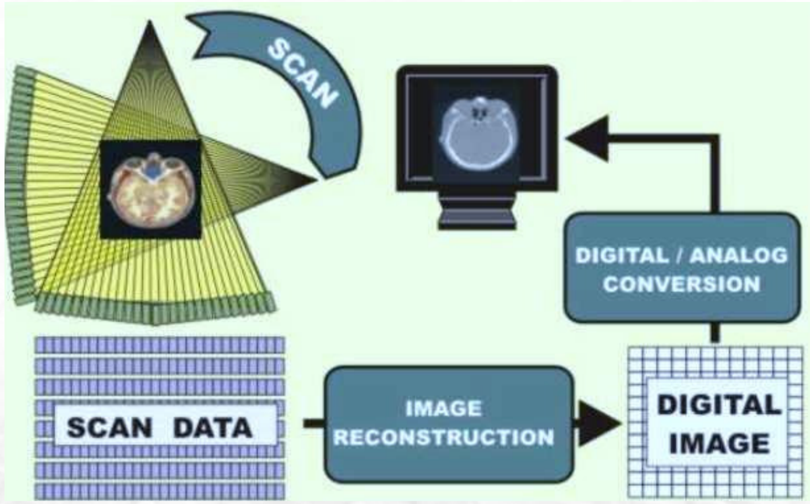

More views → higher quality images

Several hundred views create clinical CT images

# CT Data Reconstruction

Scan data is processed into a digital image that is a matrix of pixels

Image reconstruction includes assigning a CT number to each pixel




The amount of x-ray attenuation in a tissue voxel is described by the "CT Number" of the image pixel

$$CT = 1000 \cdot \frac{\mu - \mu_{water}}{\mu_{water}}$$

# CT Number & Hounsfield Units

The amount of x-ray attenuation in a voxel is described by the "CT Number"

$$CT = 1000 \cdot \frac{\mu - \mu_{water}}{\mu_{water}}$$

Unit: Hounsfield Units

CT Numbers are calculated from x-ray linear attenuation coefficient values for each tissue voxel

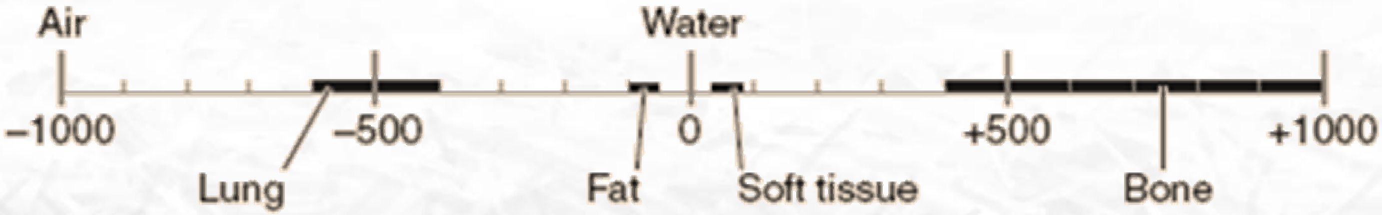
Attenuation coefficient is calculated by the reconstruction process

X-ray attenuation depends on:

- density and atomic number of the materials
- energy of the x-ray beam

# CT Number & Hounsfield Units

CT Number scale: -1000 → attenuation of air
0 → attenuation of water (by definition)




No upper limit of the scale!

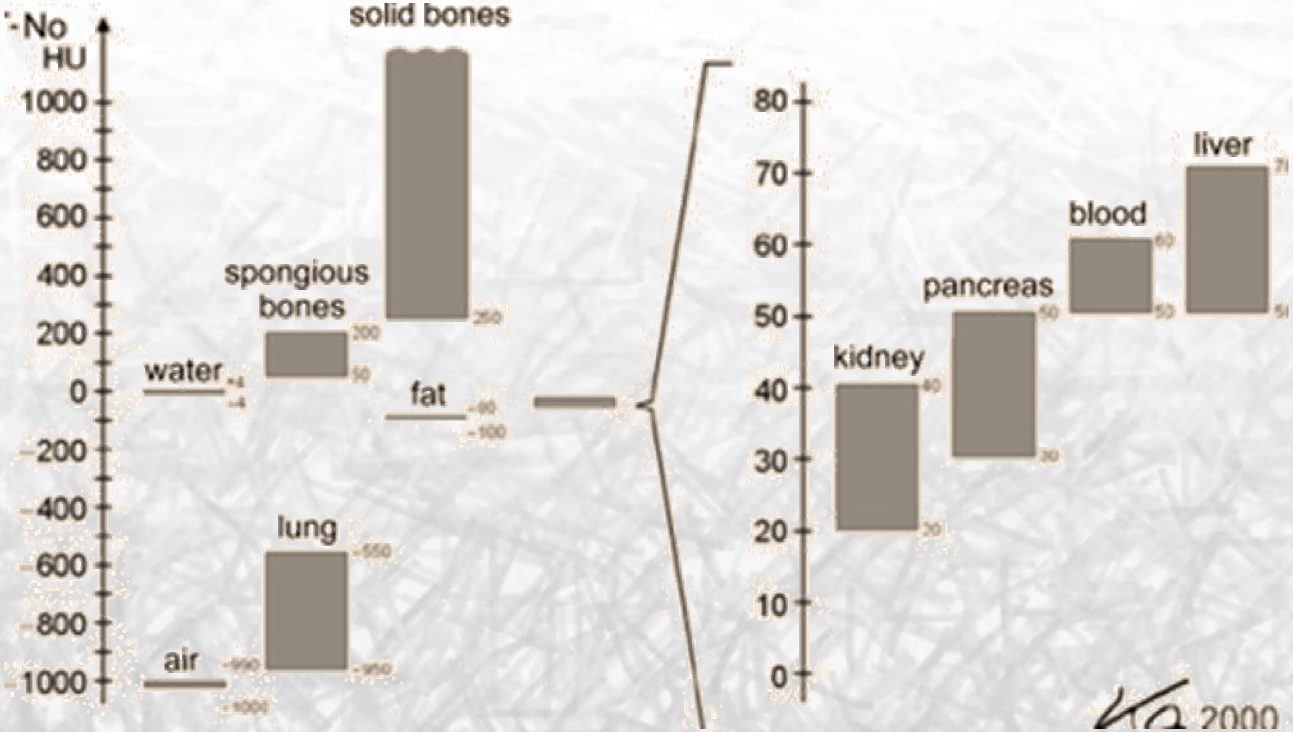
Range of CT Numbers varies between scanners and available bits/pixel

Tissues with density (attenuation) > water → + CT Numbers
Tissues less dense than water → negative CT Numbers

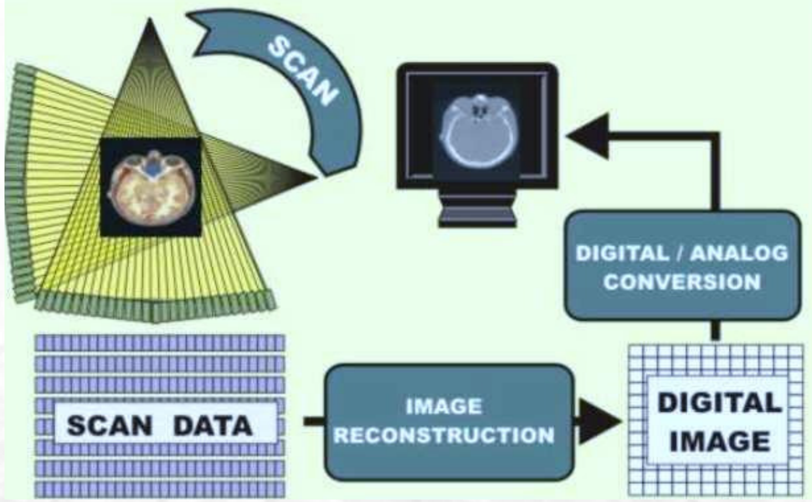
# CT Number & Hounsfield Units

CT Number scale: -1000 → attenuation of air
0 → attenuation of water (by definition)

No "typical" values for soft tissues

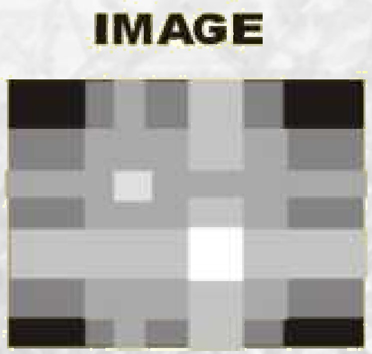


# CT Image Formation




<u>3 steps of CT image formation:</u>

- Scanning: produces data
- Reconstruction: processes data, forms digital image
- Digital-to-analog conversion: produces an analog image in grey scale




After reconstruction, the CT image is an image of densities of the tissues

# Digital to Analog Conversion

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2 | -2 | -3 | 0 | -6 | -6 | 1 | 0 |
| 4 | 1 | 2 | 5 | -1 | 1 | 5 | 3 |
| 2 | -1 | 0 | 5 | 0 | 0 | 2 | 1 |
| -1 | -1 | -2 | 0 | 0 | 1 | 0 | 0 |
| 1 | 1 | -2 | -1 | 1 | -1 | -4 | -2 |
| -2 | 2 | -1 | 0 | 1 | -1 | -3 | 0 |
| 6 | -3 | 2 | 1 | -4 | 3 | 1 | 4 |
| 3 | 4 | 2 | -4 | -3 | -1 | -2 | -5 |

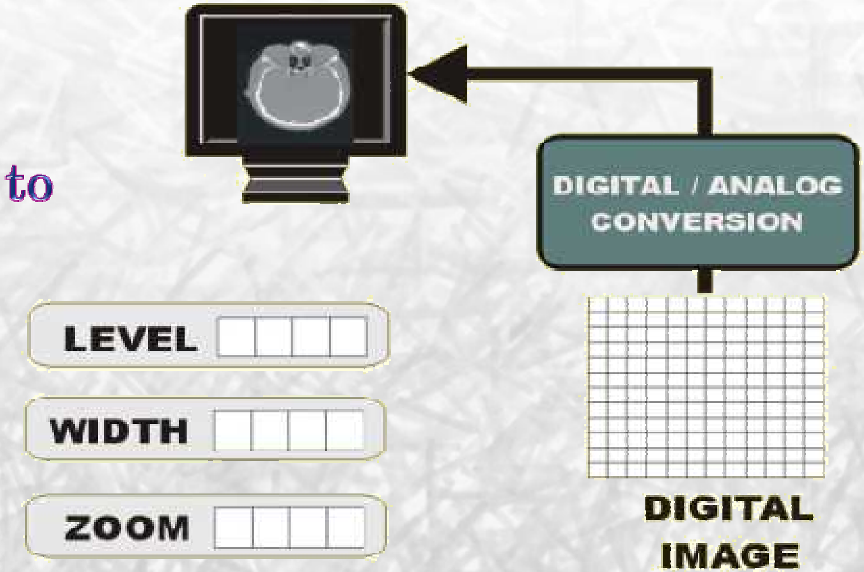
CT image is a matrix of pixels

Each pixel has a CT Number

Conversion creates a visible image on a grey scale

Factors that control digital to analog conversion:

- Windowing
  - Level
  - Width
- Zooming



# Window: Width & Level

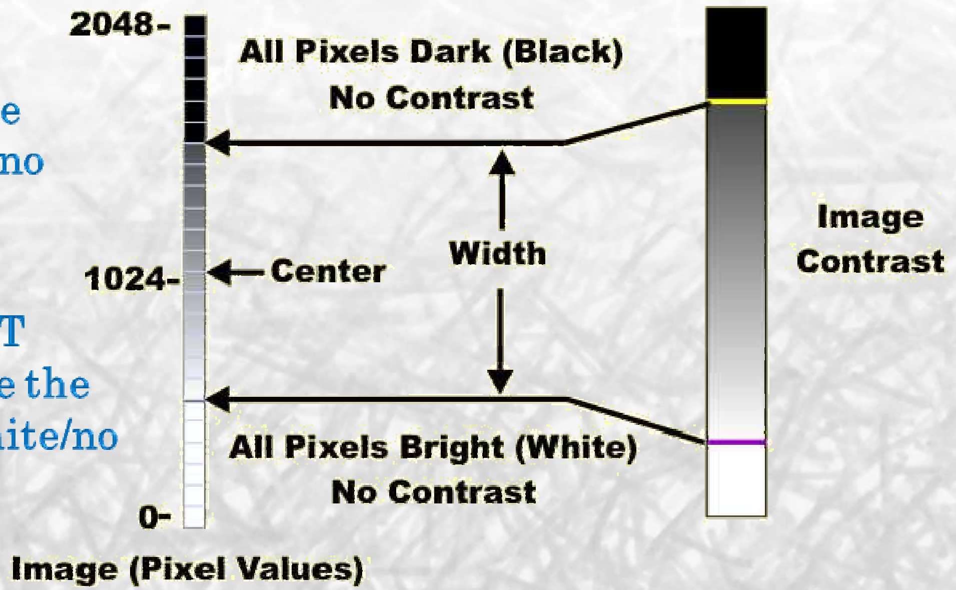
Window: a portion of the CT scale that is viewed
→ range of CT Numbers that will be displayed with different shades of grey

Window Width → narrow increases image contrast

Window Level (Center) → lower brightens the image
raising darkens the image

Tissues with CT Numbers below the window are black/no contrast

Tissues with CT Numbers above the window are white/no contrast



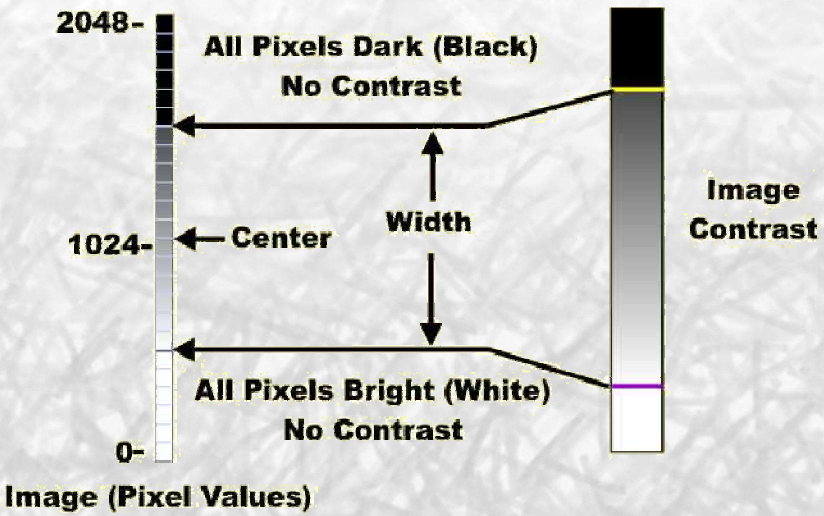

Tissues within the window have visible contrast

# Window: Width & Level

Window Width adjusts the range of CT numbers that will be displayed with contrast

Width controls image contrast

CT has high contrast sensitivity due to window width
→ a window can be set to display small differences in tissue densities




Tissues within the window have visible contrast

# Zooming

Zooming: selecting a small area within the total image to cover the full display

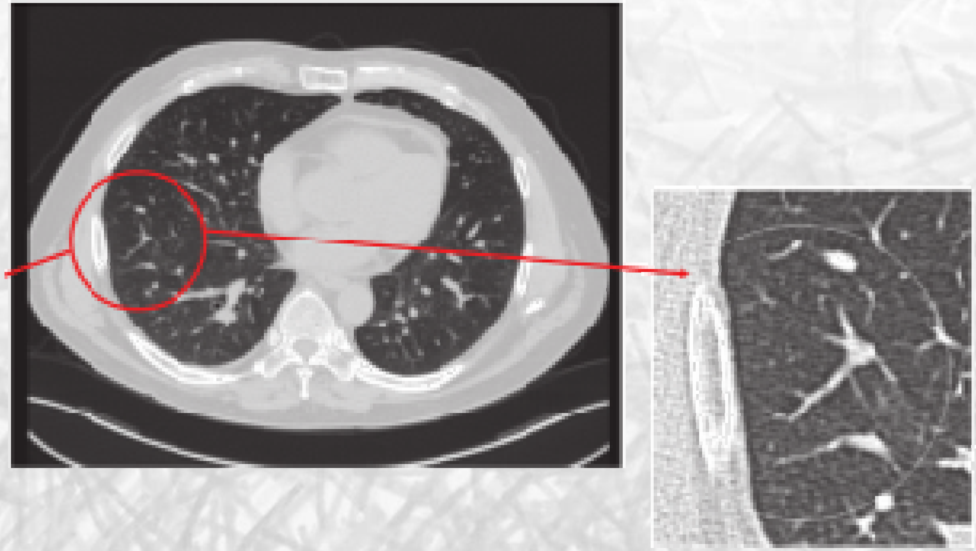
→the area of the digital image that is displayed

→ The enlarged reconstruction of a part of an image

→ Enlarges a small area

**OBS!**

Zooming is not changing the field of view



# Zooming

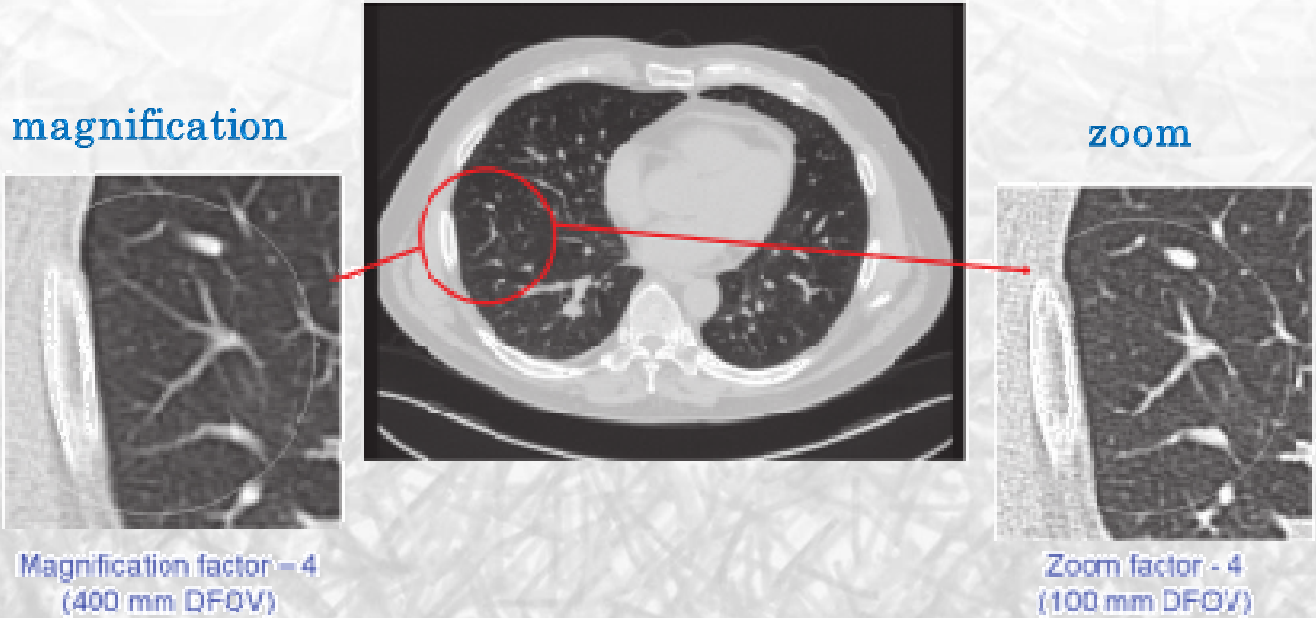
Zooming is not changing the field of view

+Advantage: spatial resolution loss is minimal

-Disadvantage: smaller field of view

Zooming factor: Scan FoV / Display FoV

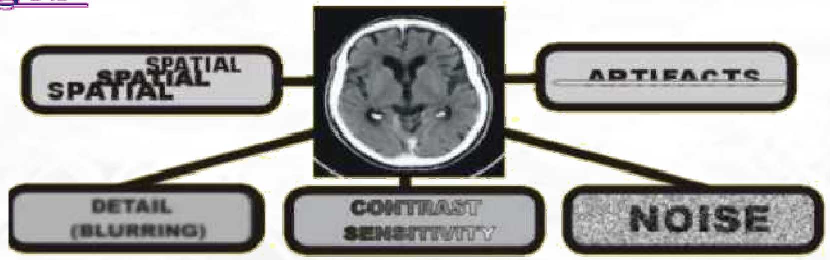
**MDCT Physics:** The Basics—Technology, Image Quality and Radiation Dose



# CT Image Quality

5 principle characteristics of CT images:

- Contrast sensitivity
- Detail / Blurring
- Visual noise
- Artefacts
- Spatial characteristics (views, FoV,…)




DEVELOPMENT and DESIGN

PERFORMANCE

OPERATION

Image quality is determined by a combination of factors:

- Development and design of the CT scanner
- General performance and maintenance of the equipment
- How the equipment is used

The greatest variation in image quality

# CT Image Quality

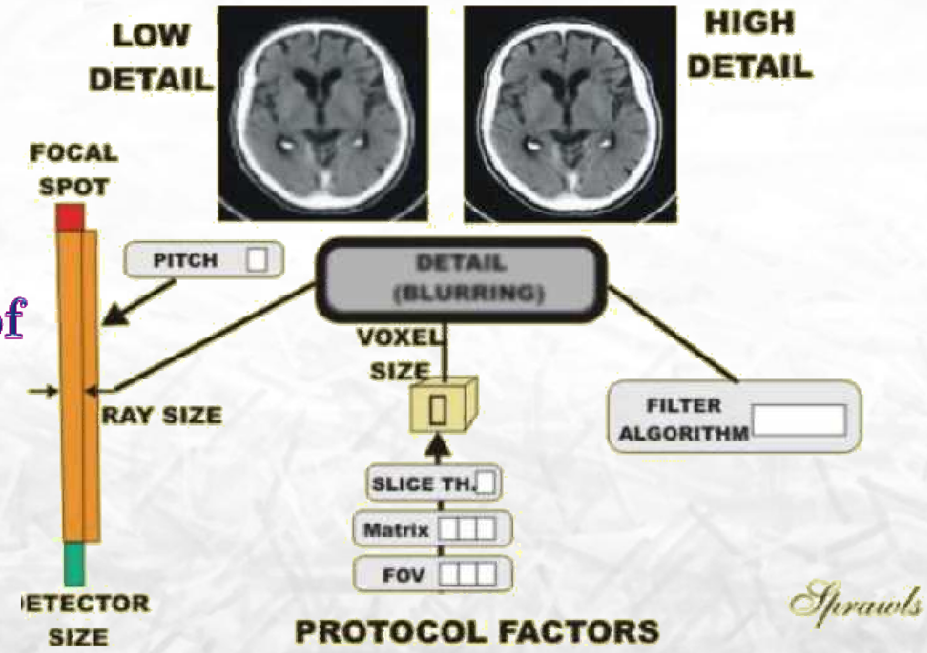
Image quality depends on the selection of protocol factors

Optimizing image quality:
Balancing image characteristics with radiation dose

Protocol values should optimize image quality characteristics *for specific clinical objectives*

# Blurring

Blurring affects image detail



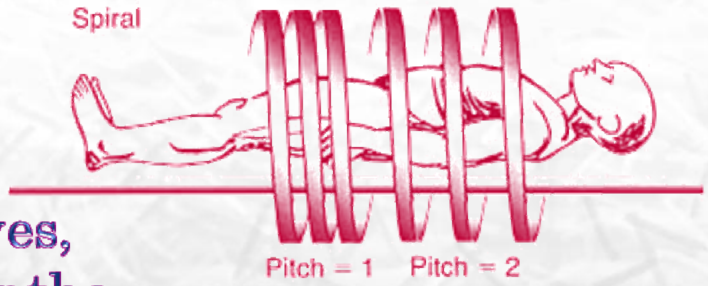

Occurs during scanning:
Focal spot size and detector dimensions determine the size of each ray in the beam
→ small rays, better detail
→ increasing pitch reduces detail in the direction of patient motion
All anatomical detail within each voxel is represented by one CT Number
→ small voxels, less blurring, better detail

Occurs during reconstruction:
filter algorithms used to reduce noise

# Blurring

Dimensions of each ray are determined by detector size

Impossible to have an x-ray beam width smaller than the detectors → detector size limits image detail




Spiral Tomography:

Pitch determines how fast the body moves, how much the x-ray beam is spread over the volume being scanned
Increasing pitch limits detail in the direction of motion
→increases effective beam width, increases blurring

Remember: image quality depends on specific clinical objectives
→the required detail limits the maximum pitch

# CT Image Noise

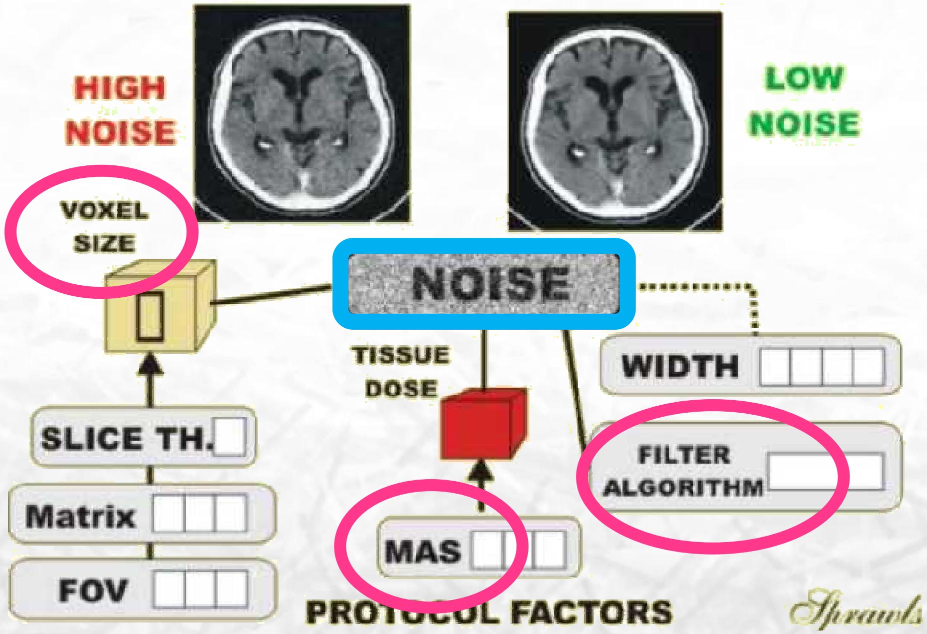
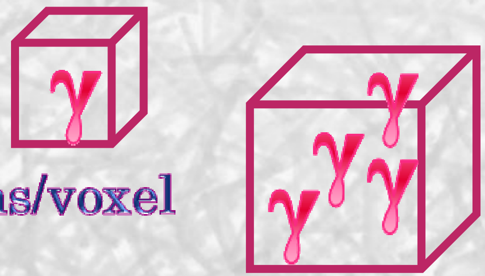



Image noise is affected by:

- Voxel size
- mAs
- Filter algorithms

↑ mAs → ↑ dose ↓ noise

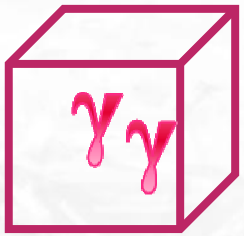
↓ Voxel size → ↑ Detail
Noise → fewer photons/voxel

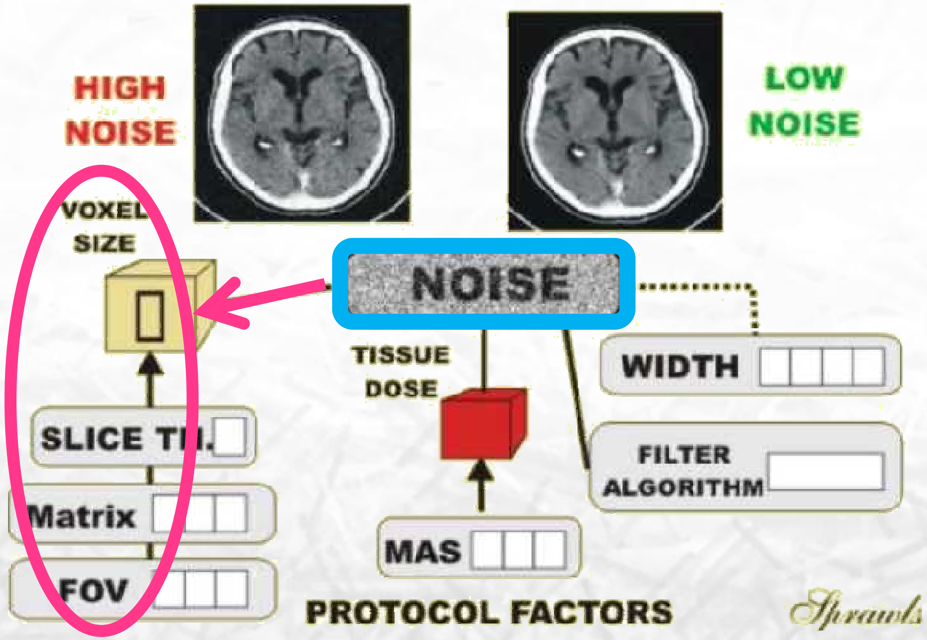


# CT Image Noise

Image noise is affected by:

- What's in the voxel




Recall:

CT Numbers depend on the measured tissue attenuation coefficients

Quantum noise is determined by the number of photons absorbed in each voxel

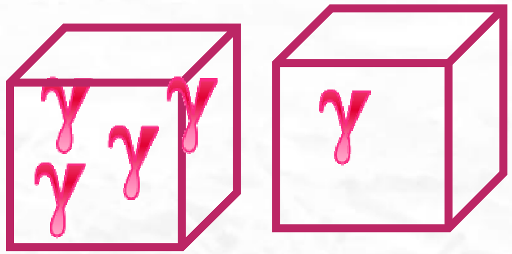
↓ Slice thickness → ↑ Detail
Dose for same Noise (smaller voxels)

Julie Haglund, haglundj@aol.com, augusti 2015

# CT Image Noise

Quantum noise is determined by the number of photons absorbed in each voxel

→ directly related to dose




↓ dose → ↑ noise

Noise is produced by the difference in number of photons from one voxel to another

↓ # photons
Exposure
Dose → ↑ Statistical variation in number of photons/voxel

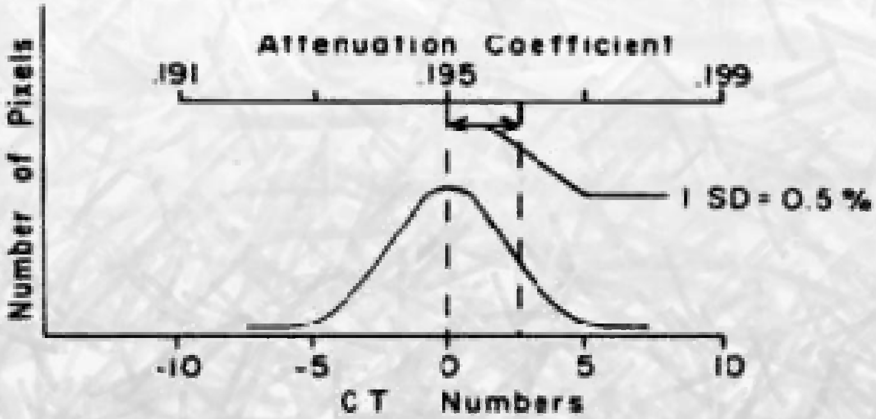
# CT Image Noise

Example: random distribution of CT Numbers for a region in water

What do we know about water?
CT Number = 0 (by definition)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2 | -2 | -3 | 0 | -6 | -6 | 1 | 0 |
| 4 | 1 | 2 | 5 | -1 | 1 | 5 | 3 |
| 2 | -1 | 0 | [illegible] | 0 | 0 | 2 | 1 |
| -1 | -1 | -2 | 0 | 0 | 1 | 0 | 0 |
| 1 | 1 | -2 | -1 | 1 | -1 | -4 | -2 |
| -2 | 2 | -1 | 0 | 1 | -1 | -3 | 0 |
| 6 | -3 | 2 | 1 | -4 | 3 | 1 | 4 |
| 3 | 4 | 2 | -4 | -3 | -1 | -2 | -5 |

All pixels do not have CT Number = 0!
Variation in CT Numbers = Noise




Amount of variation is calculated by the standard deviation = level of noise in CT images

# CT Image Noise

All CT scanners can calculate the standard deviation in a region of interest in an image

To measure noise in a CT image:

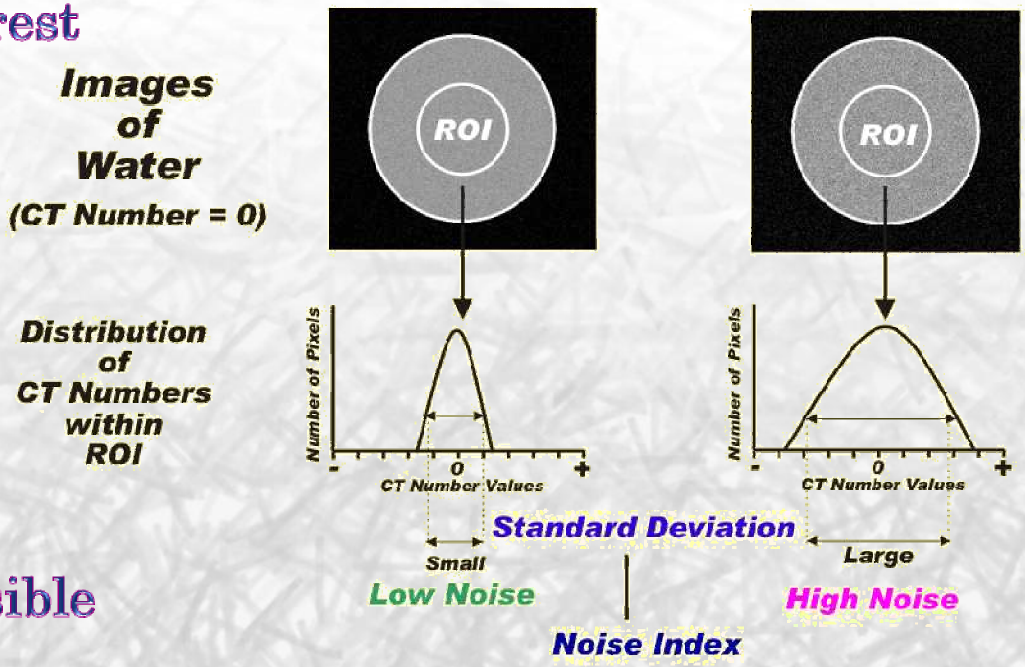
(1) Scan a water phantom

(2) Define a region of interest

(3) Calculate the standard deviation

Visual noise affects visibility of low-contrast structures

More noise → fewer low contrast objects are visible



# CT Image Noise

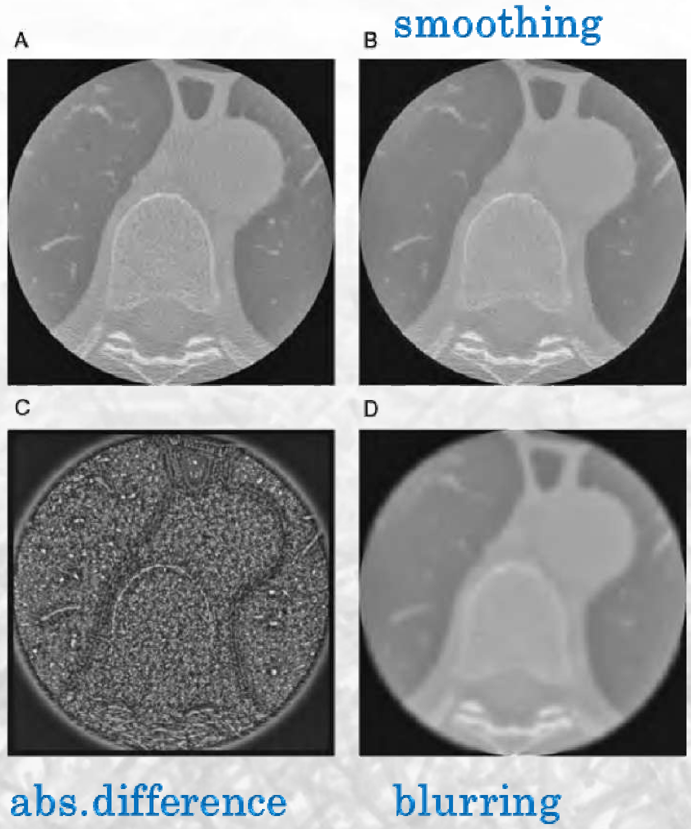
Recall that image reconstruction uses Filtered Back Projection

The "filter" can control noise

Smoothing filters reduce noise
→ increase blurring
→ decrease detail

Edge enhancing filter
→ visualize small details

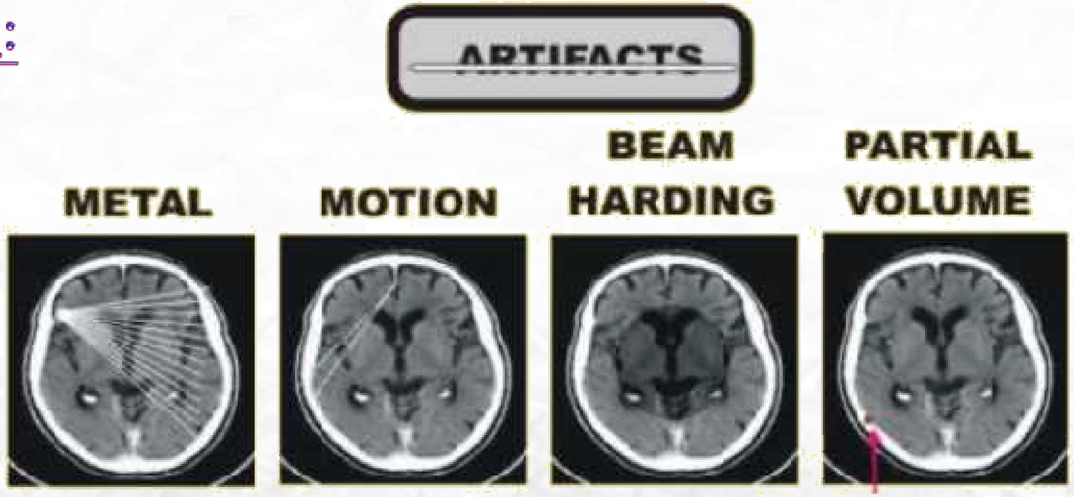
OBS! Noise is a form of image detail
Any filter that increases detail
increases noise!



# CT Image Artefacts

Image artefacts arise from:

- Metal
- Patient motion
- Incorrect CT Numbers
- Beam hardening
- Partial volume

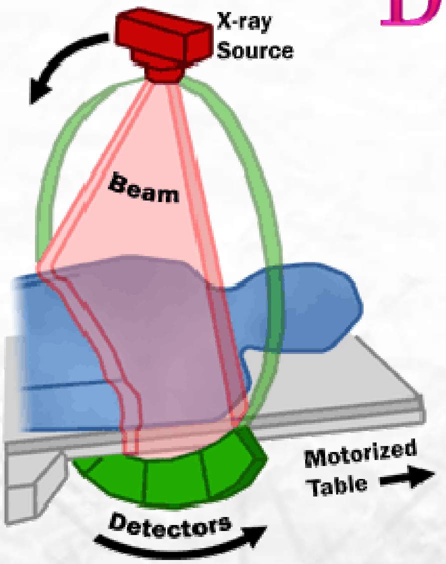



Beam hardening can be corrected during reconstruction

Partial volume: a voxel has 2 very different materials (different CT Numbers)
→the calculated CT Number is in-between and incorrect

**OBS! Partial volume effect has a different PET definition! **

# From the mechanical to the clinical: Dose Concepts in CT

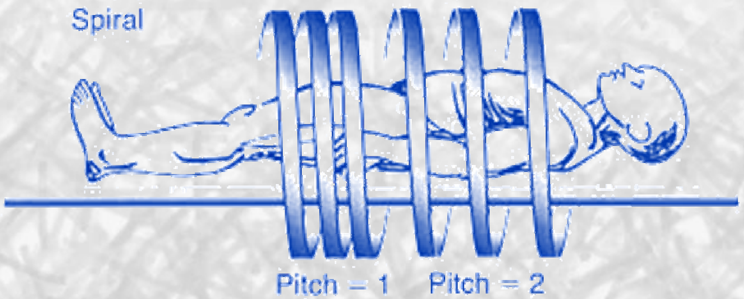



Dose = concentration of radiation energy absorbed in the tissue

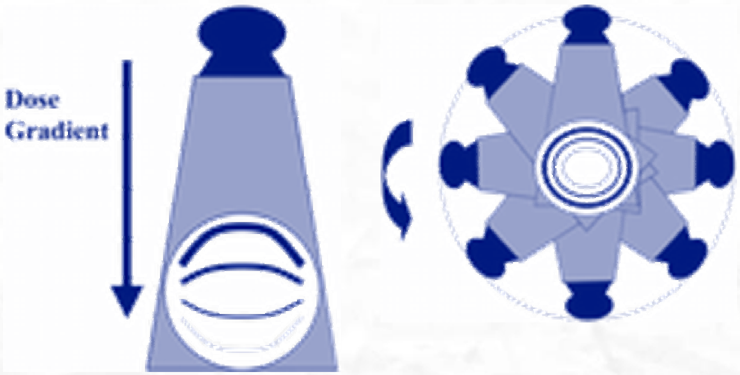
Goal: ALARA = produce acceptable image quality without unnecessary radiation exposure of the patient

Factors affecting CT radiation dose:

- Beam energy
- Tube current-time product
- Pitch
- Collimation
- Patient size



# Dose Concepts in CT




Entrance skin dose > exit skin dose

Radiation dose from CT shows variations within the scan plane and along the z-axis because of unique geometry and applications
→ CT specific dose concepts have been developed

**CTDI: Computed Tomography Dose Index**
The radiation dose, normalized to beam width, measured from 14 contiguous sections/slices

CTDI can be measured!
→ A dosimeter is inserted into a phantom
→ Dose is measured by scanning one slice

# Dose Concepts in CT

**CTDI: Computed Tomography Dose Index**

The radiation dose, normalized to beam width ... 4 contiguous sections/slices

**$CTDI_{100}$:**

A linear ...

io... ...ation of

a b...

**CTD...**

Repr... index the provides a weighted average of the center ... peripheral contributions to the dose within the scan plane

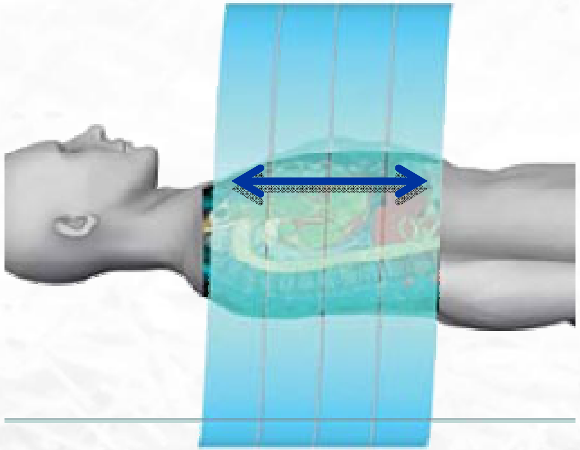
**$CTDI_{vol} = CTDI_{w}/pitch$:**

Takes into account helical pitch or axial scan spacing

**Remember: CTDI definitions are an index of radiation dose due to CT scanning, but not an accurate estimate of individual patient dose! (The phantom is homogeneous.)**

# Dose Concepts in CT

The total radiation energy deposited in the patient depends on the volume scanned



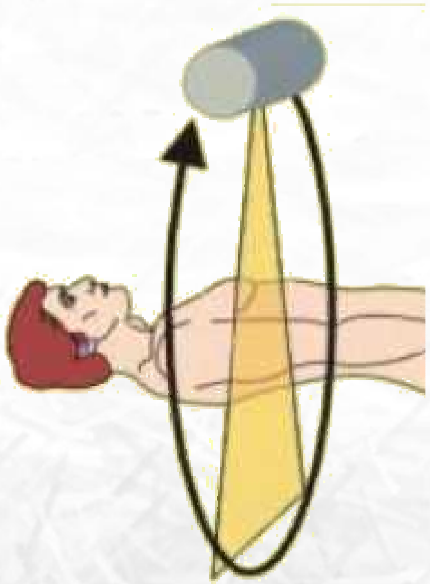
Total radiation delivered is proportional to the volume of tissue scanned

## DLP: Dose Length Product

$$DLP = CTDI_{vol} * \text{scan length}$$

Scan length [cm]
DLP [mGy*cm]

# Dose Management



**Factors affecting CT radiation dose:**

- Beam energy
- Tube current-time product
- Pitch
- Collimation
- Patient size

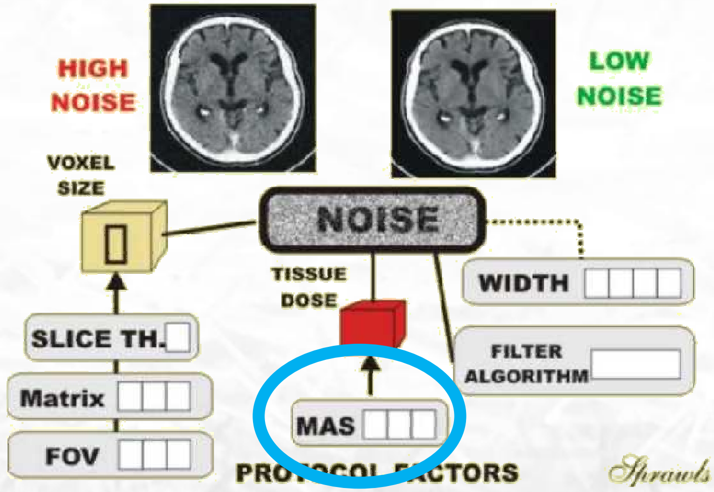
↓ Beam energy (kVpeak) → ↑ $CTDI_w$

Julie Haglund, haglundj@aol.com, augusti 2015

# Dose Management

**Factors affecting CT radiation dose:**

- Beam energy
- Tube current-time product
- Pitch
- Collimation
- Patient size



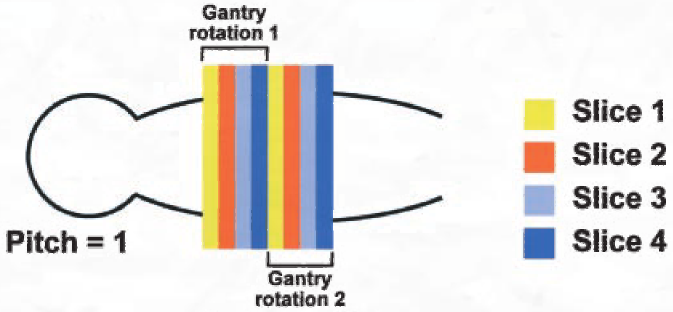

**Adjust parameters to maintain ALARA!**

↓ Slice thickness → ↑ Detail
↑ Dose for same Noise (smaller voxels)

↑ mAs → ↓ Dose for same Noise

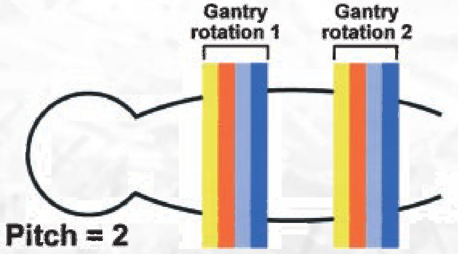
Julie Haglund, haglundj@aol.com, augusti 2015

# Dose Management



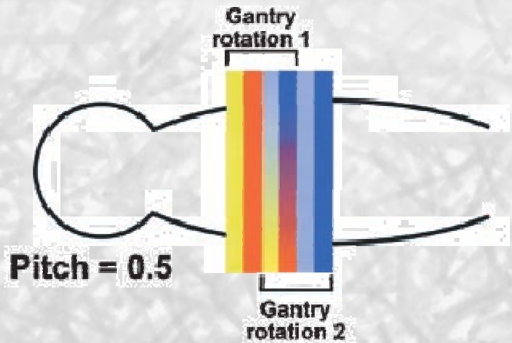

**Factors affecting CT radiation dose:**

- Beam energy
- Tube current-time product
- Pitch
- Collimation
- Patient size




↑ pitch → ↓ Dose, Scan time (faster scanning), Reduce image detail

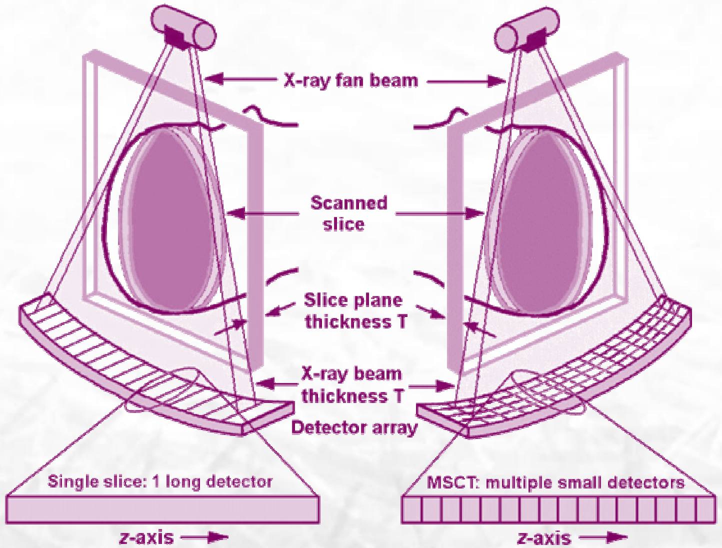
↑ Blurring



# Dose Management

Factors affecting CT radiation dose:

- Beam energy
- Tube current-time product
- Pitch
- Collimation
- Patient size




Single detector scanners:
CTDI decrease with increased collimation (small effect)

Multiple detector scanners:
CTDI decrease with  wider beam (significant effect)

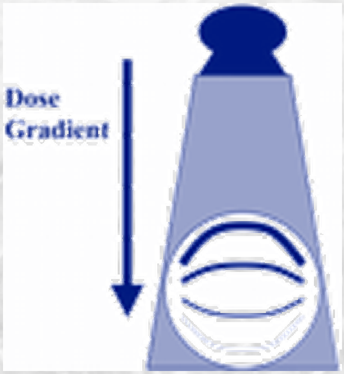
# Dose Management


Factors affecting CT radiation dose:

- Beam energy
- Tube current-time product
- Pitch
- Collimation
- Patient size

When measuring CTDI with phantoms:
Body phantom > Head phantom
→ smaller objects absorb higher dose

For smaller patients:
Exit radiation has been attenuated by less tissue
→ More uniform dose distribution




Entrance skin dose > exit skin dose

# Dose Management

CTDI, DLP,… What's useful or meaningful to a patient?

Effective Dose: takes into account where the dose is absorbed (tissue) and attempts to reflect the equivalent whole-body dose

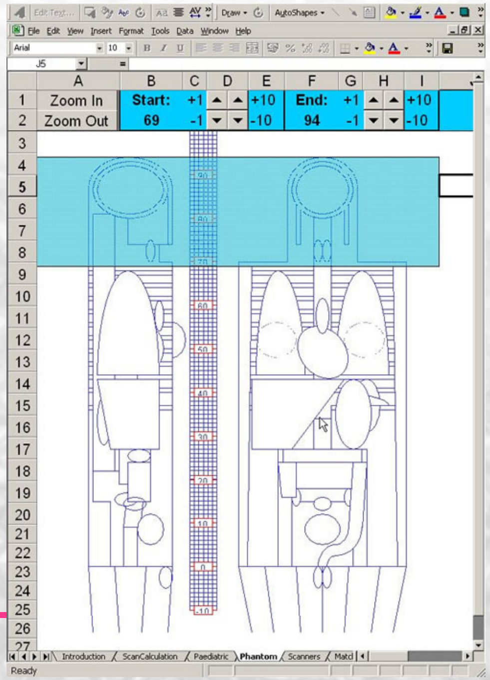
→ A weighted average of organ doses

→ Direct measurement not possible

Estimating effective dose from CT is difficult!

→ Accurate estimation of dose to individual organs…?

→ Unique patient characteristics/densities



Methods do exist:

- CT Dose computer program
- CT Expo
- ImPACT dose calculator


# Now the coffee break...

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