CT physics:

what you should know when buying a CT scanner…
but may be afraid to ask

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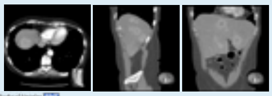
CT scanning

- 1980s
- CT TAP
  - 70 x 10 mm slices
  - 8 min scan time
  - 20 min reconstruction
  - 14 mSv

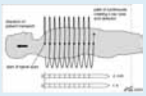
CT scanning

- 2010
- CT TAP
  - 700 x 1 mm slices
  - 8 sec scan time
  - 20 sec reconstruction
  - 18 mSv



Technical advances: spiral CT

- introduced in 1989
- continuous gantry rotation
  - slip rings
- continuous translation
- selectable image plane
  - overlapping images
  - scan plane and recon plane decoupled



Technical advances: MDCT

- widely introduced in 1998
- 2D detector
  - up to 320 detector rows
- multiple slices per rotation
  - e.g. 4, 16, 64, 128, 256, 320
- different slices per rotation
  - thin and thick slices
  - beam width and slice thickness decoupled

Impact on CT imaging

1980s	2010	technical advances	clinical impact
70 x 10 mm slices axial images	700 x 1 mm slices MPRs	2D detector > 16 x 1 mm slices per rotation 3D reconstruction	3D image display techniques available better spatial and contrast resolution
8 min scan time	8 sec scan time	spiral scanning faster rotation time high power x-ray tubes improved scintillators	better contrast utilisation better temporal resolution dynamic imaging
20 min recon	20 sec recon	more powerful computers more complex recon	higher patient throughput
14 mSv	18 mSv	thinner slices tube current modulation	50 % of medical radiation

Outline

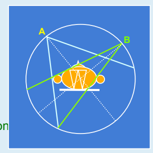
- review of technical developments
  - 1998 onwards
- imaging capabilities of 16- and 64-DCT
- latest imaging techniques
  - do we need them?

Recent technical developments in CT imaging

- dual source CT
- advances in imaging components
- tube current modulation
- 3D image reconstruction

Dual source CT

- Siemens Definition Flash
- 2 imaging chains mounted at 94°
  - 50 cm FOV on A mode
  - 33 cm FOV on B mode
- faster acquisition of projection data set
  - enhanced temporal resolution
  - faster coverage
- doubled x-ray flux



Imaging components: gantry

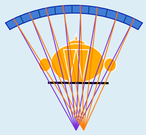
- rotation times
  - 0.3 – 1 s for helical scanning
  - up to 3 s for axial scanning
- gantry tilt
  - ± 30º for axial scanning
  - not available on some scanners
- bore size options
  - 70 cm standard bore
  - big bore
    - for bariatric patients, radiotherapy simulation
    - bigger room needed
    - longer geometry requires higher exposure parameters

Imaging components: X-ray generator and tube

- x-ray generator
  - high power rating
    - 60-100 kW, 2 x100 kW
  - 3 or 4 kVp points
    - 80, 100, 120 and 140 kVp typical
  - user selectable tube current
    - maximum 500 – 800 mA, kVp dependent
- x-ray tube
  - excellent heat dissipation
  - FF for high spatial resolution, BF for high power
  - focus selection algorithm
  - flying focal spot

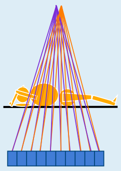
Imaging components: x-ray tubes

- xy flying focal spot
  - focal spot moved electromagnetically
    - in scan plane
  - interleaved 1D projections
    - spatial sampling in scan plane doubled
  - now generally adopted



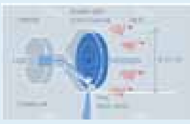
Imaging components: x-ray tube

- z flying focal spot
  - focal spot moved electromagnetically
    - along z-axis
  - interleaved 2D projections
    - spatial sampling along z-axis doubled
  - adopted by some manufacturers



Imaging components: Straton Z x-ray tube

- rotating tube envelope
  - about spindle
- rotating anode
  - part of envelope
  - cooled directly
- single filament
- beam steering system
  - focal spot position
  - focal spot size



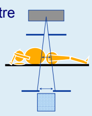
from Siemens Definition brochure

Imaging components: filtration

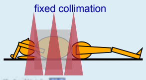
- flat filters
  - used by some manufacturers
  - reduce beam hardening
- shaped or bowtie filters
  - compensate for patient cross-section
  - reduced dynamic range of signal at detector
  - 1 – 3 depending on manufacturer

Imaging components: pre-patient collimation

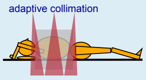
- nominal collimation defined at isocentre
  - slits or movable jaws define width of fan
- adaptive collimation in spiral mode
  - trims start and end of irradiated volume
  - % dose saving depends on scan range
  - setting of scan range more important



fixed collimation

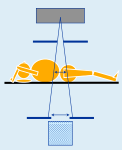


adaptive collimation



Imaging components: post-patient collimation

- post-patient collimation
  - generally not used in MSCT
- comb collimator for high resolution imaging
  - reduces effective size of detector element in scan plane



Imaging components: scatter rejection

- air gap
  - intrinsic feature of gantry design
  - less effective in MSCT
- anti-scatter grid
  - 1D grid standard in MSCT
  - 2D grid used by at least one manufacturer
- empirical scatter correction
  - adopted by most manufacturers for MSCT
  - details proprietary

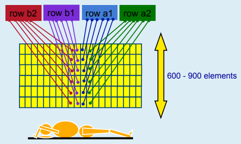
Detector technology: 2D arrays for MDCT

- typically 600 – 900 elements in scan plane
- 8 – 320 detector rows along axis of rotation
- scintillator detectors
  - ceramic (e.g. YGdO, Gd_2O_2S or LuTAG "Gemstone") + photodiode
  - high DQE with low electronic noise
  - signal proportional to energy absorbed
  - low afterglow
  - linear response over wide dynamic range
    - 1 to 1,000,000
  - stable over scanning period

Detector technology: DAS sampling

- along the z-axis:
  - same or fewer DAS channel rows than detector rows
    - 4 – 320 DAS channel rows
    - each DAS channel row may interrogate one or several detector rows
    - whole detector may not be interrogated
- along the detector row:
  - each detector element interrogated by 1 DAS channel
- 1 kHz typical sampling rate
  - depends on rotation time
    - fewer samples for fast scans if sampling rate stays the same

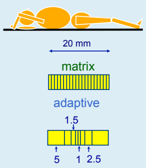
Detector technology: DAS sampling



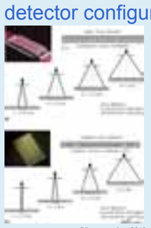
DAS arrangement for a 4DCT scanner

Detector technology: 4-DCT detector configurations

- matrix or adaptive detector arrays
  - 16 rows: 16 x 1.25 mm elements
  - 8 rows: 2 x (1, 1.5, 2.5, 5) mm elements
- 4 DAS channels

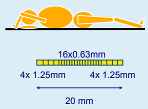


Detector technology: 4-DCT detector configurations



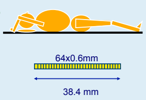
Detector technology: 16-DCT detector configurations

- mixed matrix detector arrays
- e.g. 24 detector rows
  - 16 x 0.63 + 8 x 1.25 mm elements
- 16 DAS channels
  - 16 x 0.63
  - 16 x 1.25
  - 8 x 2.5 etc



Detector technology: 64-DCT detector configurations

- matrix detector arrays
- 64 DAS channels
- 64 detector rows
  - Toshiba: same detector width, finer elements
  - GE: same element size, greater detector width
  - others: finer element size, greater detector width

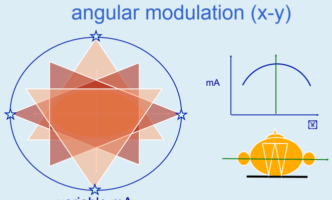


Tube current modulation

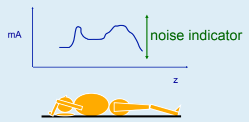
- tube current adjusted for
  - patient eccentricity
  - overall patient size
  - patient thickness along axis of rotation
- image noise may
  - stay constant
  - decrease for small patients

from Siemens Definition product brochure

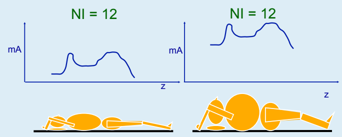
Tube current modulation: angular modulation (x-y)



Tube current modulation: z-axis modulation



Tube current modulation: patient size modulation

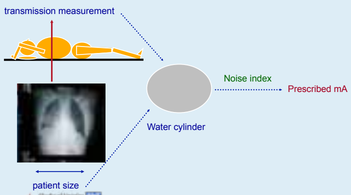


- noise indicator depends on
  - diagnostic task
  - slice thickness, etc

Tube current modulation: strategies

supplier	xy-modulation	z-modulation	patient size	noise indicator
GE	Smart mA (with Auto mA)	Auto mA	Auto mA	Noise Index
Siemens	CareDose CareDose 4D	CareDose 4D	CareDose 4D	quality reference mAs (70 - 80 kg)
Philips	D-Dom	Z-Dom	ACS DoseRight	mAs per slice (thickest body part)
Toshiba	SUREexposure	SUREexposure	SUREexposure	noise in virtual image

Tube current modulation: GE approach – Auto mA

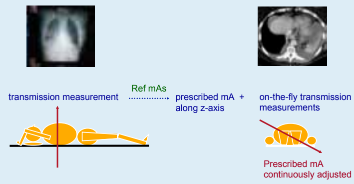


Tube current modulation: GE approach

phantom	mA (lat)	mA (AP)	image noise HU	$CTDI_{vol}$ mGy
head	43	43	14	1.7
shoulders	210	133	16	6.9
chest	384	334	16	14.5

- scan prescriptions for phantom family
  - NI = 11.57
- Auto mA + Smart mA

Tube current modulation: Siemens approach – CareDose 4D



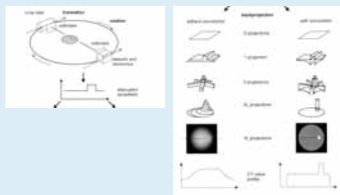
Tube current modulation: Siemens approach

from Siemens Definition product brochure

Image reconstruction

This topic contains low concentrations of mathematics that may provoke allergic reactions in some individuals

2D FBP in theory: parallel beam



2D FBP in practice

- fan beam projections
  - weighted / rebinned
- can modify kernel
  - to enhance / suppress spatial frequency content

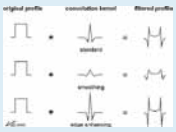
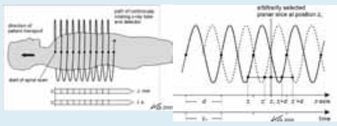
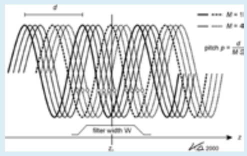


Image reconstruction: spiral scanning



- one x-ray projection in image plane
  - data interpolation required

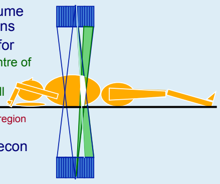
Spiral scanning: linear interpolation for MDCT



- filter and backproject synthesized projection set

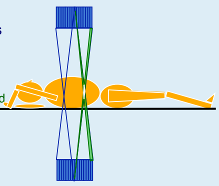
MDCT image reconstruction: when cone angle can be ignored

- in 2D FBP we assume co-planar projections
- assumption holds for
  - thin slices from centre of detector
  - thick slices from full detector
    - projection overlap region > patient
- 2D FBP used for recon up to 4-DCT



MDCT image reconstruction: when cone angle can't be ignored

- if full detector is used for thin slices
  - projection overlap region < patient
  - assumption fails
  - artefacts generated
- 3D recon needed for 16-DCT onwards

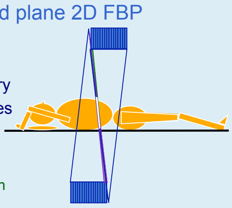


MDCT image reconstruction: solutions for cone beams

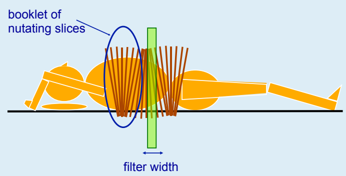
- tilted plane 2D FBP
- approximate 3D FBP
  - Feldkamp algorithm

Solutions for cone beams: tilted plane 2D FBP

- 16-DCT scanners
- spiral trajectory
- different names
  - AMPR (Siemens)
  - hyperplane reconstruction (GE)



Solutions for cone beams: tilted plane 2D FBP



Solutions for cone beams: Feldkamp algorithm

2D FBP (flat panel detector):

$$f(r,\varphi)=\int_0^{2\pi}\frac{D_{SO}^2}{U^2}\int_{-\infty}^{\infty}q(\rho'-\rho)R_\beta(\rho)\frac{D_{SO}}{\sqrt{D_{SO}^2+\rho^2}}\,d\rho\, d\beta$$

post-convolution weight; convolving kernel; projection; pre-convolution weight

Feldkamp (flat panel detector):

$$f(r,\varphi,\xi)=\int_0^{2\pi}\frac{D_{SO}^2}{U^2}\int_{-\infty}^{\infty}q(\rho'-\rho)R_\beta(\rho,\xi)\frac{D_{SO}}{\sqrt{D_{SO}^2+\rho^2+\xi^2}}\,d\rho\, d\beta$$

In essence: do a 2D-like FBP reconstruction using 3D cone-beam projections, approximately correcting for the tilt of the rays through pre-convolution weighting

Solutions for cone beams: FDK in practice

- rebinning of cone-beam projections
  - improves computational speed and image quality
- reconstruction without complete projection data
  - central 2π reconstruction region
  - peripheral (π – 2π) reconstruction regions
- changes to back-projection weighting
- helical focus trajectory

Solutions for cone beams: practical implementation

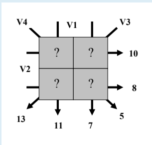
Manufacturer / Scanner	Scan type	Algorithm
< 30 mm MDCT: Toshiba & Philips	axial helical	modified FDK modified FDK
< 30 mm MDCT: GE & Siemens	axial helical	2D-FBP tilted plane 2D-FBP
>30 mm MDCT: most manufacturers	axial helical	modified FDK modified FDK

Image reconstruction: iterative methods

- algebraic reconstruction (ART)
- modern implementations

Iterative methods: ART

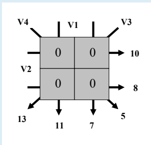
Simplest example in 2D:
4 pixels (top-left, top-right etc.) & 4 views (V1-V4)



Ray Projections

Iterative methods: ART

Initialise pixel values



Iterative methods: ART

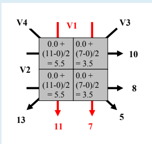
Next-Estimated-Pixel-Value

=

Previous-Estimated-Pixel-Value
+
(Measured-Ray-Sum – Previous-Estimated-Ray-Sum)
/Number-Pixels-in-Line

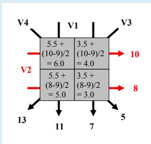
Iterative methods: ART

1st iteration



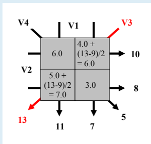
Iterative methods: ART

2nd iteration



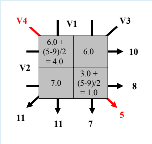
Iterative methods: ART

3rd iteration



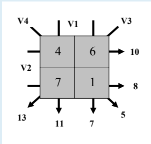
Iterative methods: ART

4th iteration



Iterative methods: ART

we have converged!



Iterative methods: modern implementation

- general idea generalises to 3D
  - more complicated!
- iterations reduced by initialising image with FBP image
  - volume reconstructed in less than a minute
- can work with incomplete data or non-uniform sampling
- different image texture and artefacts to FBP

Imaging capabilities of MDCT

- 16-DCT
- 64-DCT

Technical summary for 16-DCT scanners

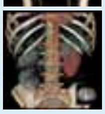
supplier	scanner model	slices per rotation x thinnest slice mm	z-coverage mm	mini-mum rot s
GE	LightSpeed 16	16 x 0.625	20 (16 x 0.625 + 8 x 1.25)	0.4
Siemens	Sensation 16	16 x 0.75 (spiral only)	24 (16 x 0.75 + 8 x 1.5)	0.42
Philips	Brilliance 16	16 x 0.75	24 (16 x 0.75 + 8 x 1.5)	0.5
Toshiba	Aquilion 16	16 x 0.5	32 (16 x 0.5 + 24 x 1.0)	0.5

What do they offer?

- axial and spiral scanning
- limited detector utilisation
  - 10 mm of detector available at sub-mm slices
- reasonably fast scanning
  - fast enough for limited CT angiography
  - not fast enough for cardiac CT
- 0.5 – 0.8 mm slices for 3D imaging
- patient dose optimisation features
  - early versions of tube current modulation

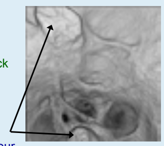
16-DCT scanning: CT angiography

- scan acquisition
  - contrast bolus
  - fast spiral scan
- image reconstruction
  - 0.5 - 1 mm image stack
- image display
  - CT thresholding
  - volume and surface rendering
  - MIPs



16-DCT scanning: CT endoscopy

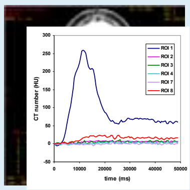
- scan acquisition
  - spiral scan
- image reconstruction
  - 0.5 – 2.5 mm image stack
- image display
  - CT thresholding
  - surface rendering
  - virtual navigator

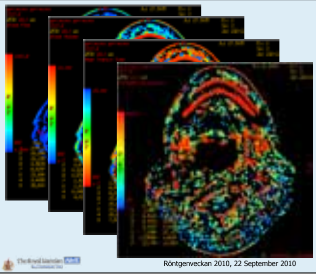


tumour

16-DCT scanning: CT perfusion

- scan acquisition
  - contrast bolus after scan start
  - cine mode
  - ~ 20 mm coverage
  - 60 s total exposure
- image reconstruction
  - 5 mm images every 0.5 s
- image analysis
  - input arterial function
  - ROIs
  - compartmental analysis
  - deconvolution analysis
  - perfusion maps





What more do we need?

- clinical requirements
  - better CT angiography
  - coronary CTA
  - functional imaging
    - multi-phase
    - whole organs
  - low dose paediatric imaging
- performance requirements
  - faster coverage
    - wider detector
    - faster rotation times
  - more thin slices per rotation
  - better temporal resolution
  - dose optimisation
  - 3D image display techniques

Technical summary for 64-DCT scanners

supplier	scanner model	slices per rotation x thinnest slice mm	z-coverage mm	mini-mum rot s
GE	LightSpeed VCT	64 x 0.625	40	0.35
Siemens	Definition AS+	(2 x 64) x 0.6	38.4	0.30
Philips	Brilliance 64	64 x 0.625	40	0.40
Toshiba	Aquilion 64	64 x 0.5	32	0.40

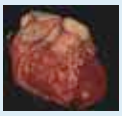
NB manufacturers with z-FFS double number of slices per rotation

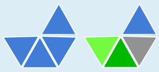
What do they offer?

- full detector utilisation at sub-mm slices
  - 40 mm instead of 10 mm
- faster scanning
  - 0.3 - 0.4 s instead of 0.4 - 0.5s
  - suitable for cardiac CT
- 0.5 – 0.6 mm slices for 3D imaging
  - general and cardiac CTA
- CT perfusion with increased coverage
  - 40 mm instead of 20 mm
  - shuttle mode for increased range at reduced temporal sampling
- patient dose optimisation features
  - mature versions of tube current modulation
  - adaptive collimation

Functional / coronary CTA

- contrast bolus
- slow spiral scan
- retrospective ECG-gating
- single or multi-segment recon
- images at
  - one or several cardiac phases
- patient dose 15-50 mSv





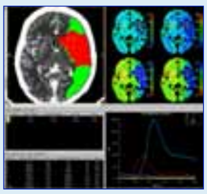
Coronary CTA

- step-and-shoot mode
  - contrast bolus
  - fast partial axial scan
  - prospective ECG-gating
    - heart frozen in selected phase
  - ~ 4 rotations
  - patient dose 1 – 5 mSv

CT brain perfusion: left cerebral infarction

Brain Perfusion with Summary Maps

- Summary maps showing infarcted area in red and penumbra area in green



Courtesy of UMC Utrecht, The Netherlands, and Philips

Latest imaging techniques

What more could we have?

- more slices per rotation
- dual energy imaging
- DS CT
- iterative reconstruction
- better dose management

Technical summary for top MDCT scanners

supplier	scanner model	detector design rows x element mm	slices per rotation x thinnest slice mm	z-coverage mm	minimum rot s
GE	Discovery 750 HD	64 x 0.625	64 x 0.625	40	0.40
Siemens	Definition Flash	64 x 0.6 x2	128 x 0.6	38.4	0.30
Philips	Brilliance iCT	128 x 0.625	256 x 0.625	80	0.30
Toshiba	Aquilion One	320 x 0.5	320 x 0.5	160	~0.35

NB manufacturers with z-FFS double number of slices per rotation

How do we get more slices?

- longer z-axis coverage

supplier	scanner model	no of rows x element size mm	z-coverage mm
Philips	Brilliance iCT	128 x 0.625	80
Toshiba	Aquilion One	320 x 0.5	160

- note native slice thickness 0.5-0.6 mm
  - consistent with focal spot sizes

How do we get more slices?

- z-axis flying focal spot

supplier	scanner model	scanner description	no detector rows	slices per rotation (axial)
Philips	Brilliance iCT	256-slice	128	≤ 128
Siemens	Definition series	128-slice	64	≤ 64

- number of slices does not increase
- object sampling doubled along z-axis
  - improved z-axis spatial resolution

Do we need more slices?

- faster scanning
  - better contrast utilisation
  - reduced contrast dose
- whole organ coverage in one rotation
  - brain, heart
- functional CT
  - stroke
  - tumour angiogenesis
- 4D CT
  - tumour motion

Diagnosis of stroke

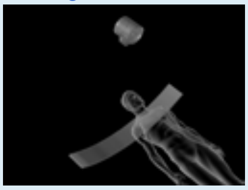
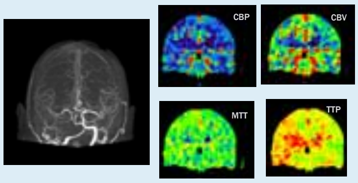


image courtesy of Toshiba Corp

CT brain perfusion: right ICA Occlusion

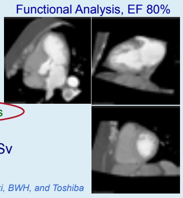


Courtesy of Dr Rogalla, Charite, and Toshiba Corp

Functional / coronary CTA

- contrast bolus
- fast cine scan
- retrospective ECG-gating
- images from
  - several cardiac phases
  - one cardiac phase
- patient dose 15-50 mSv

Functional Analysis, EF 80%



Courtesy of Dr Rybicki, BWH, and Toshiba

Coronary CTA

- step-and-shoot mode
  - contrast bolus
  - fast axial scan
  - prospective ECG-gating
    - heart frozen in selected phase
  - 1- 2 rotations
  - patient dose 1 – 5 mSv

Volume rendered heart showing an LAD with stent

Courtesy of Universität Ulm, Germany, and Philips

Potential problems with increased coverage

- increase in patient dose
  - wide x-ray beam collimations
    - harder to tailor scan range
    - larger axial overlap to satisfy FDK reconstruction
  - tube current modulation
    - coarse adjustment to patient attenuation
  - high local doses in functional CT
- degradation of image quality by scatter
  - physical or software scatter correction

Dual energy imaging

- concurrent acquisition at two energies
  - two imaging chains
  - HT switching
  - sequential scans

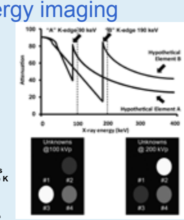


Illustration of dual-energy technique shows hypothetical elements A and B, which have K edges of 90 keV and 190 keV, respectively.

Coursey C A et al. Radiographics 2010;30:1037-1055

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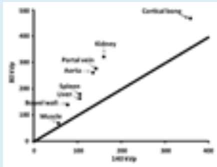
Dual energy imaging

Graph shows the attenuation values of eight tissues at 80 kVp and 140 kVp.



Coursey C A et al. Radiographics 2010;30:1037-1055

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Dual energy imaging

- tissue decomposition
  - proprietary base decomposition analysis
  - tissue maps instead of attenuation maps
    - bone, water, iodine

Water

Iodine

images courtesy of GE

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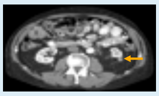
Do we need dual energy imaging?

- may increase radiologist' s confidence

Water density

Iodine density



DIAGNOSIS: BENIGN HEMORRHAGIC CYST

images courtesy of GE

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Potential problems with dual energy imaging

- increased radiation dose
  - implemented as an additional investigation
- loss in spatial and contrast resolution
  - implemented as routine clinical care
- uncertainties in tissue decomposition
  - polychromatic spectrum
- clinical validation in progress
- loss of clinical skill

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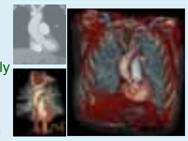
Do we need DS CT?

- improved temporal resolution
  - projection data set acquired more quickly
- fast scanning
  - Flash mode
    - high pitch acquisition
    - paediatric imaging
- dual energy imaging



breath hold optional

Courtesy of Institute of Medical Physics / Erlangen, Germany, and Siemens

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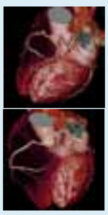
Coronary CTA

- Flash mode
  - dual source mode
  - contrast bolus
  - very fast spiral scan
    - pitch 3.2
  - prospective ECG-gating
    - heart frozen in selected phase
  - 1 rotation
  - patient dose ≤1 mSv



Courtesy of Institute of Medical Physics / Erlangen, Germany, and Siemens

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Potential problems of DS CT

- two imaging chains to maintain
- scatter
  - data contamination between imaging chains
- fast scanning also achievable with wider collimation at lower pitch

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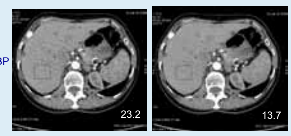
Iterative reconstruction

- widely implemented
- FBP logical starting point to iteration
- images can be mix of FBP and iterative recon

FBP



50% ASIR

images courtesy of GE

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Do we need iterative reconstruction?

- potential for lowering patient doses
  - FBP introduces noise to images
  - % dose reduction depends on protocol and minimum signal
- images less prone to FBP artefacts

Courtesy of Dr Sablayrolles, CCN, France and GE

Potential problems with iterative reconstruction

- image quality
  - different image texture
    - disorients radiologists
    - low contrast resolution
  - new artefacts
    - aliasing patterns and edge artefacts
    - choice of image grid
- long reconstruction times
  - about a minute
  - potential impact on clinical decisions

How do we get better dose management?

- scan protocol parameters
  - consider $CTDI_{vol}$, DLP
- tailoring protocol to clinical task
  - e.g. cardiac CT
- tube current modulation
  - manufacturer's implementation
  - users' understanding

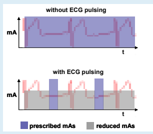
Tube current modulation: pitfalls

elliptical phantom 16 x 30 cm

SPR	AEC mode	mA (lat)	mA (AP)	$CTDI_{vol}$ mGy
90º then 0º	Auto mA	55		5.7
90º then 0º	Smart mA + Auto mA	55	47	5.3
0º then 90º	Auto mA	99		10.1
0º then 90º	Smart mA + Auto mA	99	52	7.7

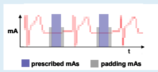
Which new features can lower doses?

- iterative reconstruction
- improved tube current modulation
  - ECG-gated tube current pulsing
- adaptive collimation in spiral scanning



Which new features can increase doses?

- more powerful tubes, DSCT
  - higher mAs values possible
- wide x-ray beam collimations
- dual energy imaging
- tube current modulation
  - tube current padding
    - in prospective ECG-gated acquisition
  - simultaneous activation of temporal and spatial modulation may be problematic



Summary

- Technical developments in CT scanning reviewed
- Imaging capabilities of 16- and 64-DCT scanners described
- Novel imaging techniques available with top-of-the range scanners discussed

Acknowledgements

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