the art* of ct

* the algebraic reconstruction technique for computed tomography

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agenda

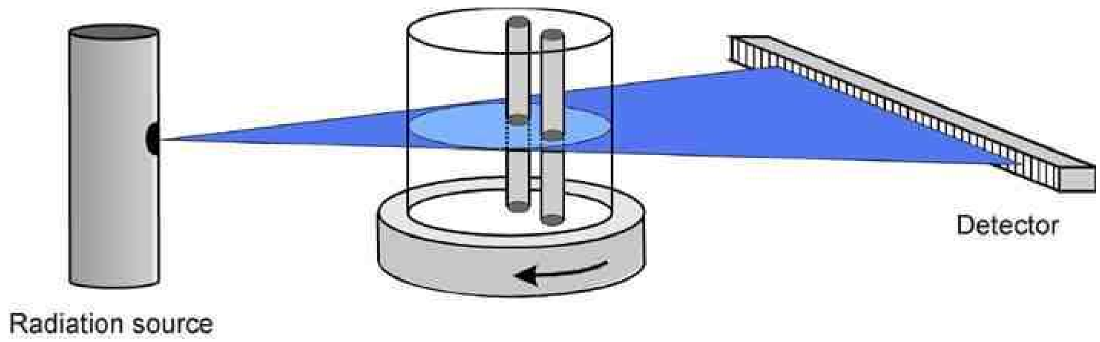
- CT basics
- overview of the current ct systems [the ct zoo]
- algebraic reconstruction technique [ART]

ct basics

computed tomography basics

- what is ct?
- how does ct function?
- what is measured?
- how is it measured?
- what happens with the measured data?
- how do the results look like?

computed tomography scan process



- scaning the object with x-rays => projections
- reconstructing the object: making an image out of projections

what is actually measured?

- attenuation: describing how much x-ray intensity is reduced by the material
- only morphological properties [anatomy] can be measured
  => no functional imaging

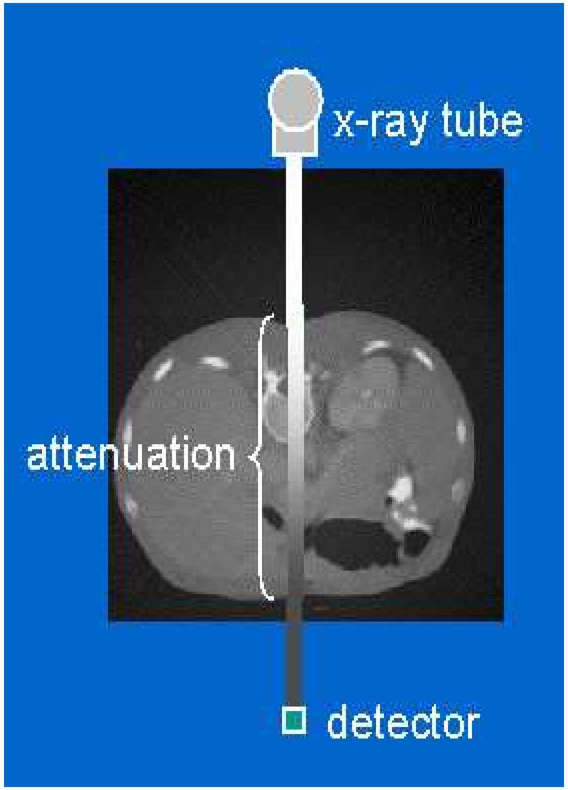
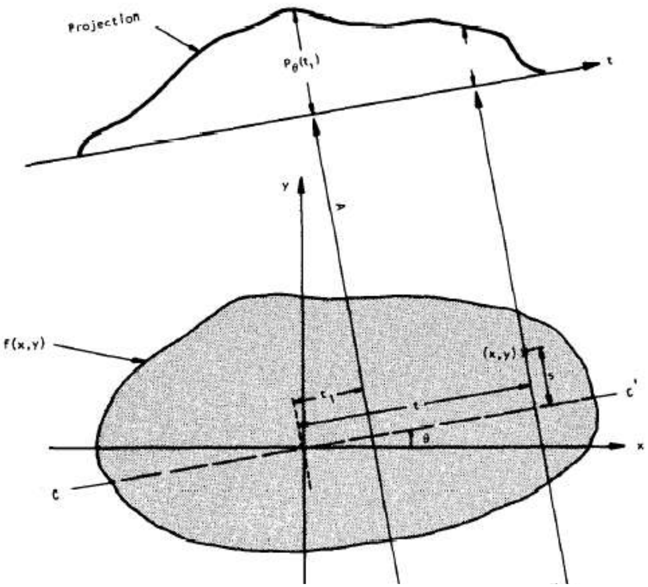
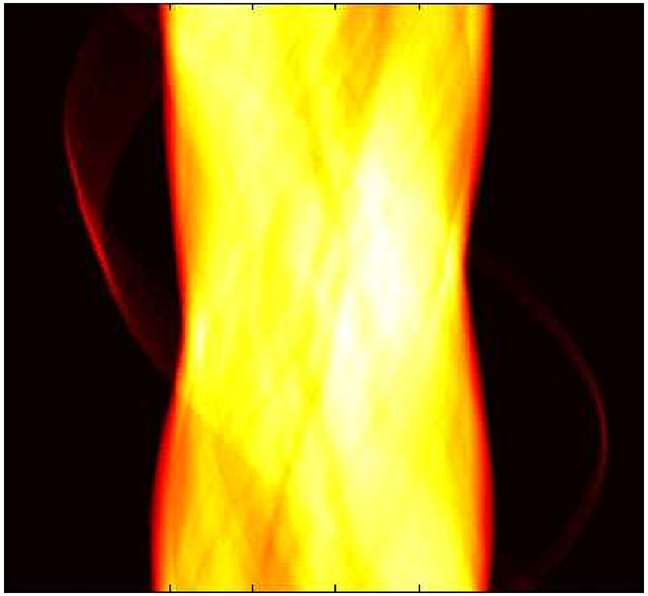


image source (for all the images with same characteristic blue background): http://www.impactscan.org

reconstruction: from projections...



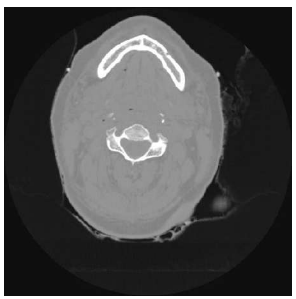
one projection



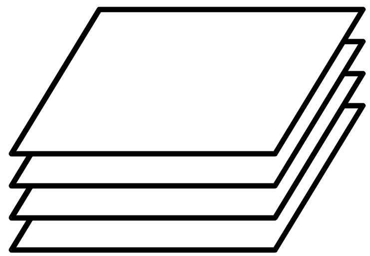
many projections
=
sinogram

image source: Kak and Slaney

... to images



individual slice



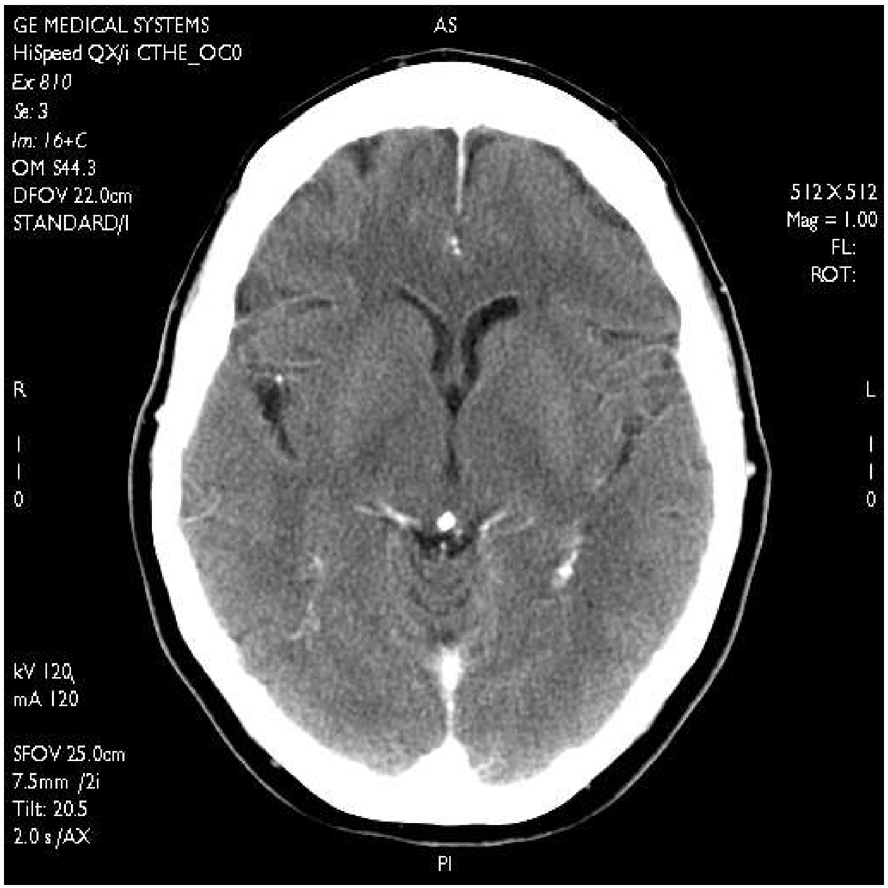
stack of slices

3D volume

reconstruction methods

- direct methods:
  - fourier reconstruction
  - filtered back-projection [FBP]
- iterative methods:
  - algebraic reconstruction technique [ART]

how do reconstructed images look like?



objectives

- small dose
  - as few projections as possible
  - low intensity
- fast data acquirement
  - scans of moving body parts: heart, lungs, angiography ...
  - 4D tomography
- fast image reconstruction
  - intra-operative use

overview of current ct systems

modern ct systems

image source: Siemens Press, GE Medical Systems

history

- 1971 Dr. Godfrey Newbold Hounsfield
- EMI Laboratories, England
- 1979 Nobel Prize in Medicine with Allan McLeod Cormack
- British Knighthood

image source: http://

history

- 1967:
    - first prototypes
    - data acquisition: several hours
    - reconstruction: several days
- 1971
    - brain images only
    - data acquisition: 5 min.
    - reconstruction: 20 min.
- 1974/1975
    - first clinical installations
- 1976
    - whole body scanners

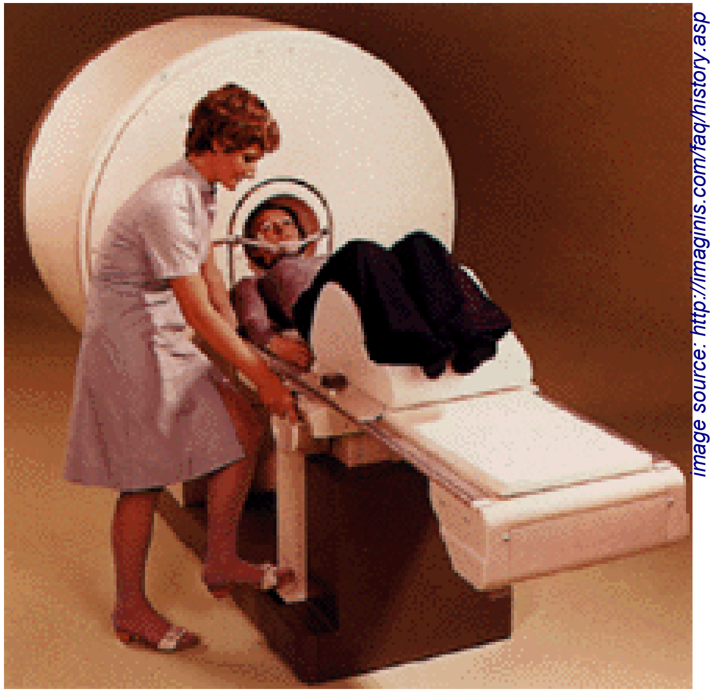
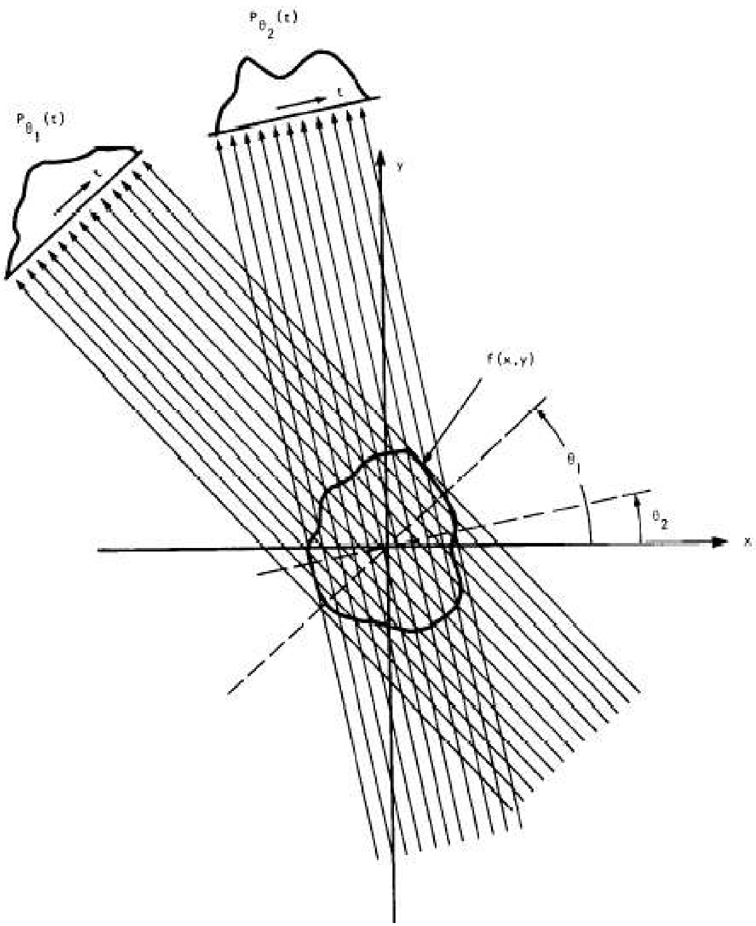


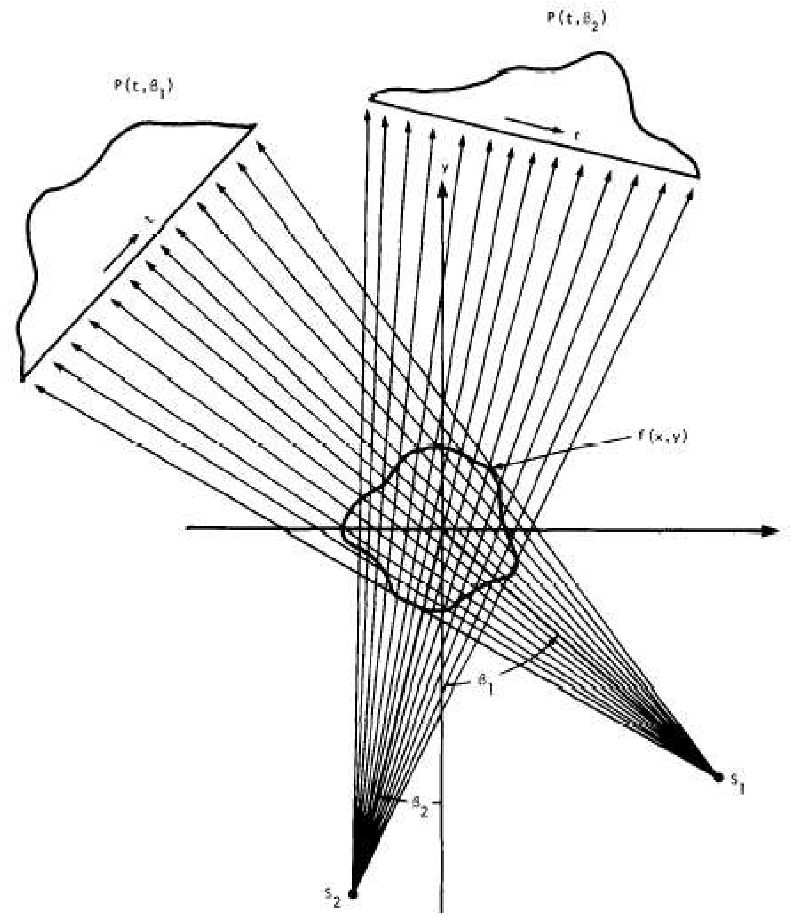
image source: http://imaginis.com/faq/history.asp

clinical head scanner 1974

data acquisition :: one slice per projection



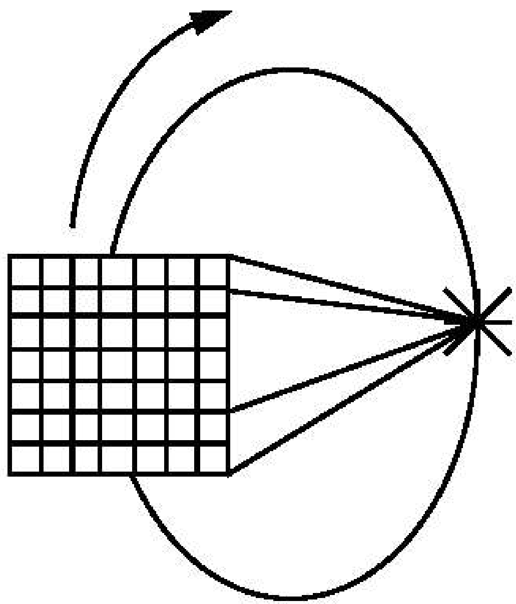
parallel beam

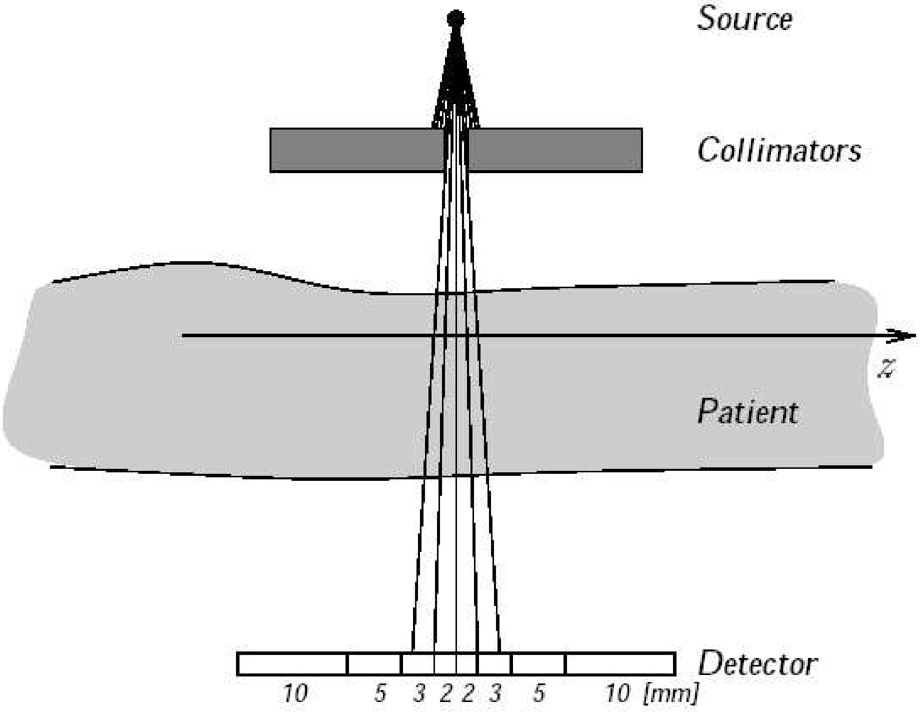


fan beam

image source: Kak and Slaney

data acquisition :: several slices per projection



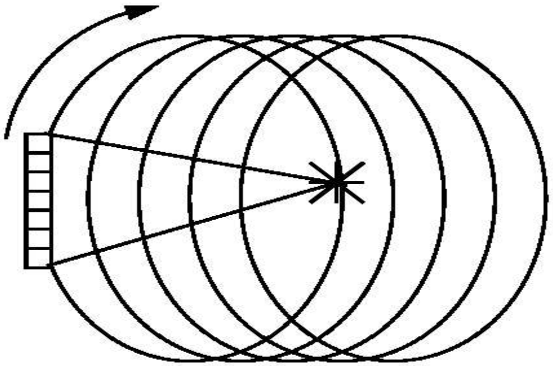


cone beam

image source: Mueller, Turbell

scan methods

- slice based ct



- helical ct [1989]

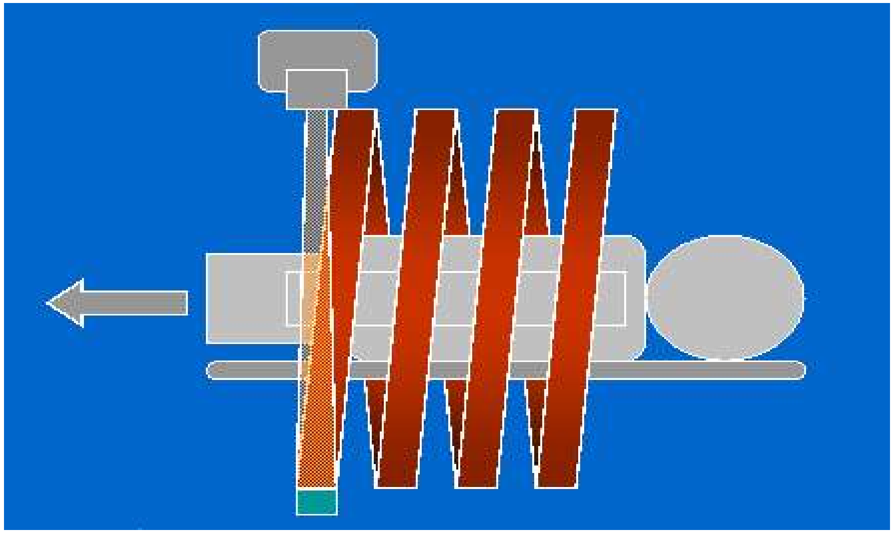
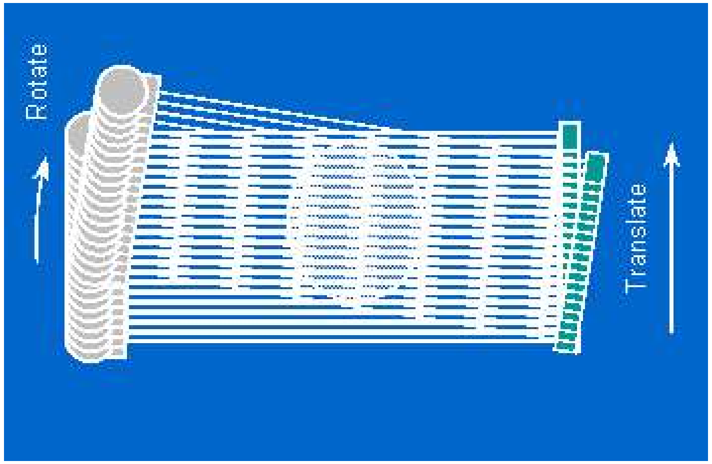


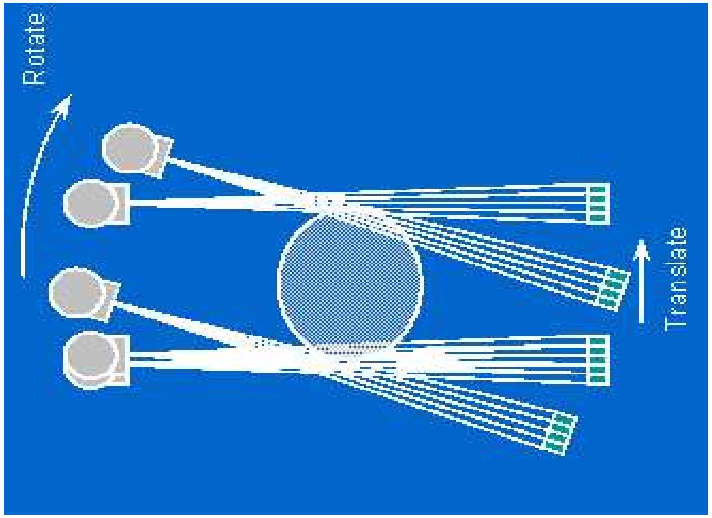
image source: Mueller

ct systems :: past

- 1th generation:
  - parallel-beam geometry
  - single highly collimated x-ray pencil beam and detector
  - scan time: 5 min.

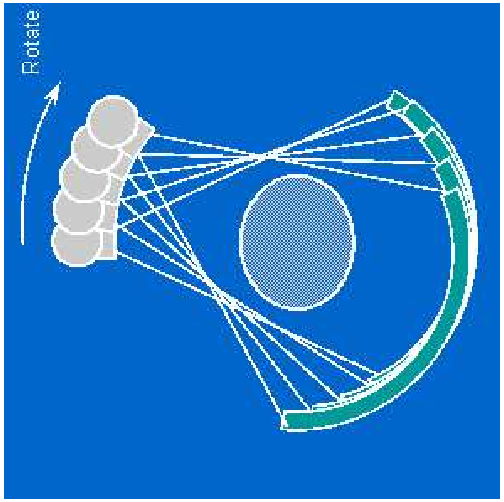


- 2nd generation:
  - narrow fan beam
  - linear detector array
  - scan time: 30 sec.

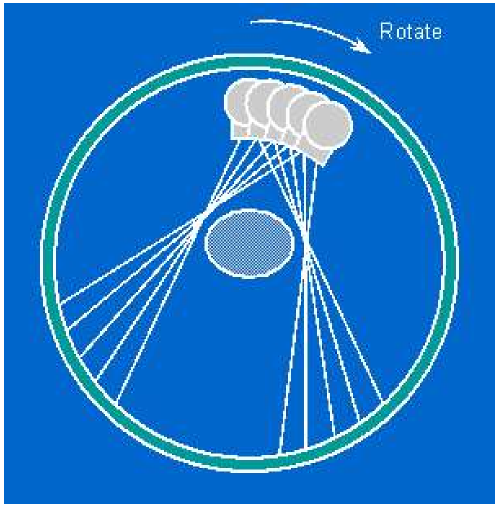


ct systems :: today

- 3rd generation:
  - since 1976
  - rotating fan/cone beam
  - rotating detectors
  - scan time: 1 sec.



- 4th generation:
  - rotating fan/cone beam
  - fixed detector
  - scan time: 1 sec.



ct systems :: today

- cine CT [5th generation]
  - stationary X-ray source and detector
  - no mechanical scaning motion
  - X-ray source: large semicircular anode
  - scan time: 50 ms

- slip ring technology [1985]
  - replacing cables for power and data transfer

ct systems :: today

- mobile C-arm / C-arc:
  - operating room, emergency dept., ...
  - scan time: 60° per second
  - drawbacks:
    - smaller field of view [30 cm]
    - focus on iso-center
    - less stability

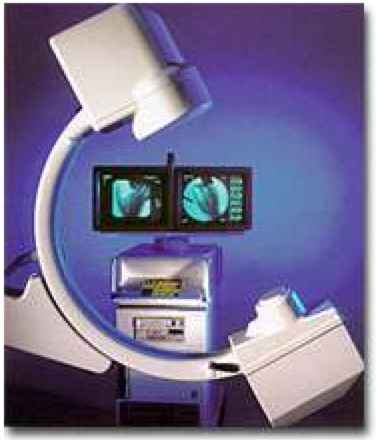


image source: Siemens Press, GE Medical Systems

current systems

- example: SOMATOM Sensation 64, SIEMENS

- 4th generation cone beam scanner
- gentry rotation: 0.37 sec
- 64 slices per rotation
- down to 0.3mm slice distance
- resolution: 0.4 mm
- field of view: 82 cm

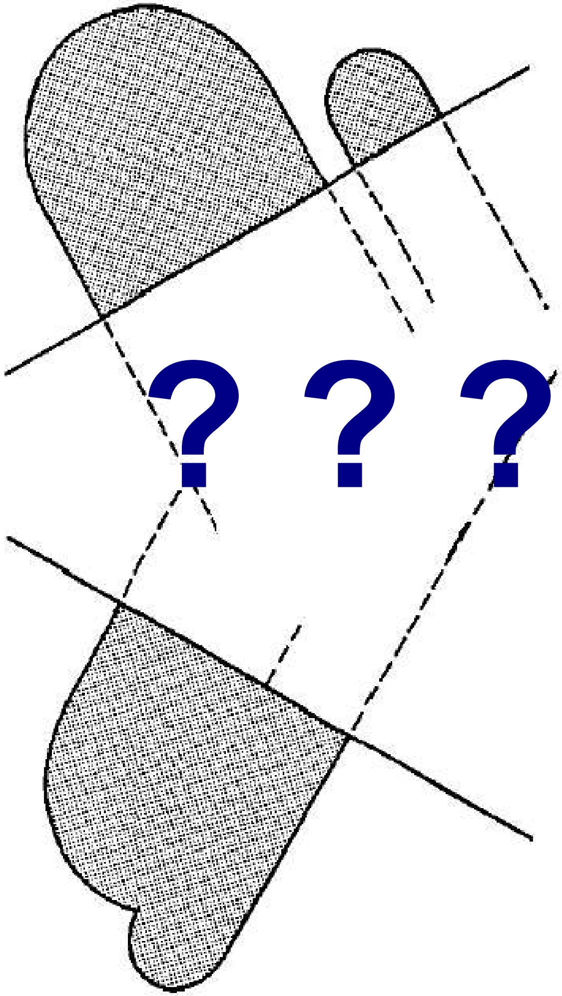
- reconstruction time: ~ 5 frames per second*
  *valid for another comparable system

image source: Siemens press picture

algebraic reconstruction technique

art :: the problem

- given:
  set of projections of the image
- goal:
  reconstruct the original image



art :: the idea

- make initial guess
- check how well it corresponds to the measured data [back-projection]
- calculate the difference between the result and real measurement
- correct the values
- repeat until results satisfying

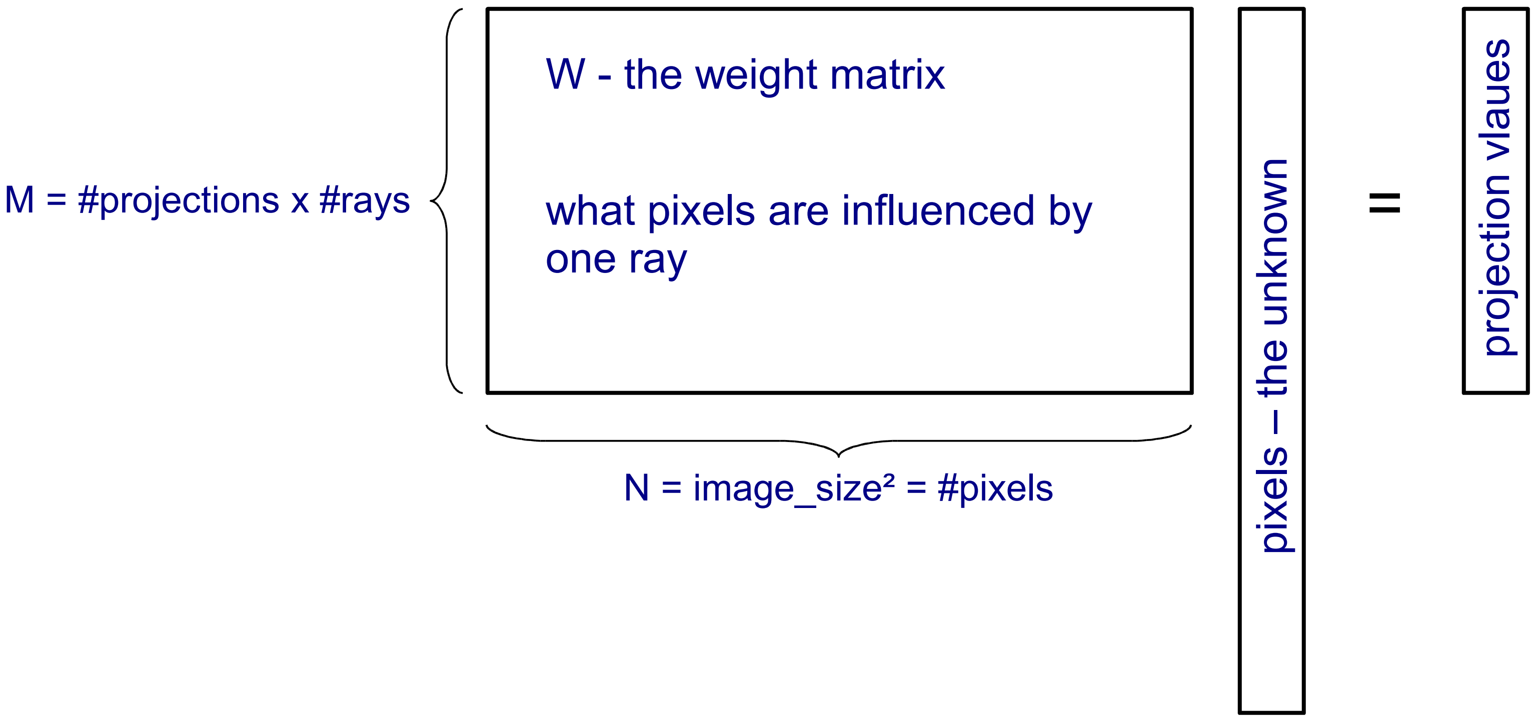
art :: simple example

3	12	3
3	12	3
3	12	12

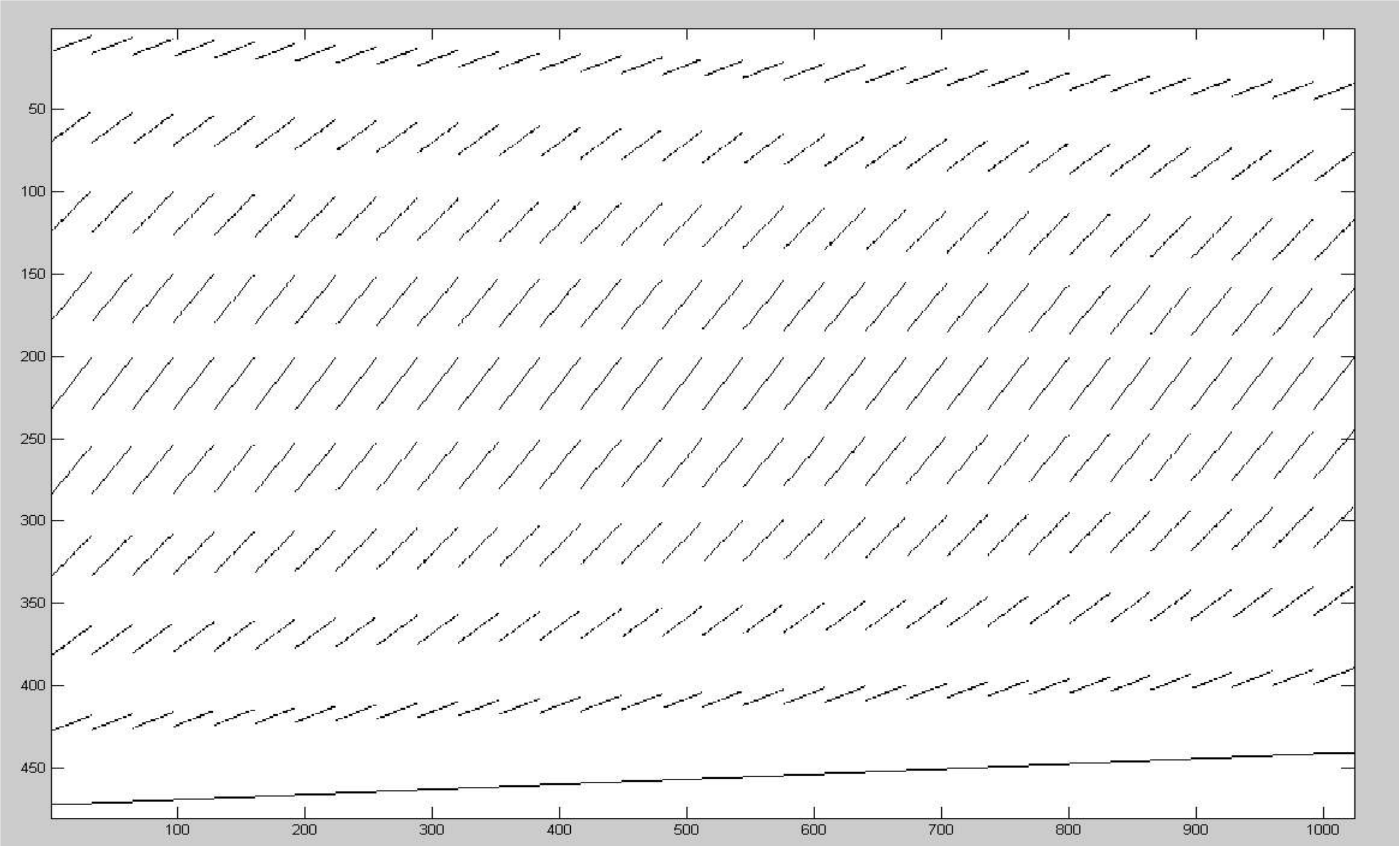
- make initial guess
- while convergence not reached // iterations
  - for each projection
    - for each ray
      - compute back-projection
      - compute difference to measured projection
      - distribute difference
    - end for
  - end for
- end while

the equation system

$$W \cdot f = p$$



details :: weight matrix structure



one iteration step :: the kaczmarz method

- update for one single ray projection k:
  - for a pixel j=1:N do:

the difference

$$f_j^{(i)} = f_j^{(i-1)} + \lambda \cdot \frac{p_k - \vec{w}_k \vec{f}^{i-1}}{\sum_{l=1}^{N} W_{kl}^2} \cdot W_{kj}$$

new pixel value

old pixel value

relaxation parameter

normalizing the difference

weighting the correction

a different view at the method

- one iterative step can be seen as a projection of the current solution on a corresponding hyperplane

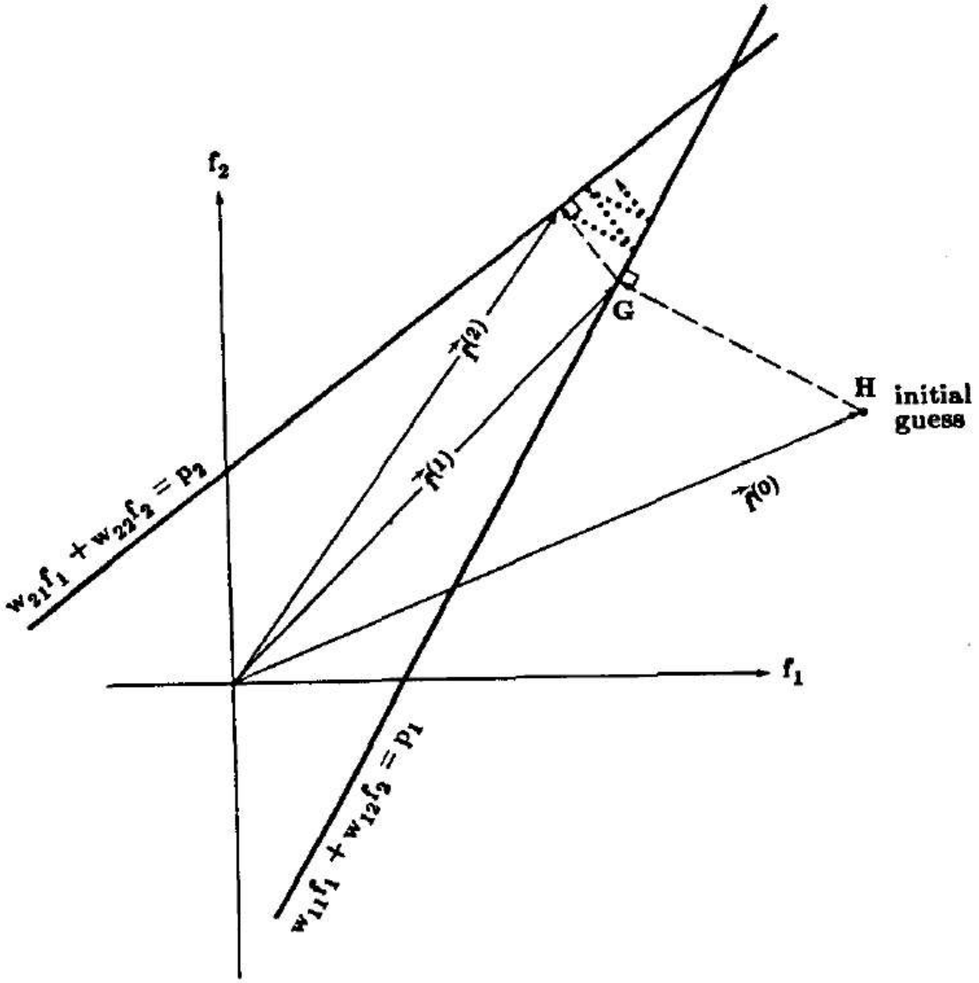


image source: http://imaginis.com/faq/history.asp

solution :: existence and uniqueness

- the equation system can be :
  - underdetermined [M < N]
  - overdetermined [M > N]
  - inconsistent through noise

- it can be shown that:
  - if unique solution given,
    the kaczmarz method converges towards it
  - if solution not unique,
    the kaczmarz method yields the result colsest to the initial guess

tuning options

- reducing noise:
  - relaxation parameter [lambda]
  - simultaneous steps
  - heuristics [hamming window]

- improving convergence:
  - order of equations: orthogonality
  - heuristics - using a priori information
    [hamming window, initial guess, using borders for values]

alternatives

- SIRT
  - no ray-by-ray iterations, simoultanous steps instead
  - result: better quality & slower convergence

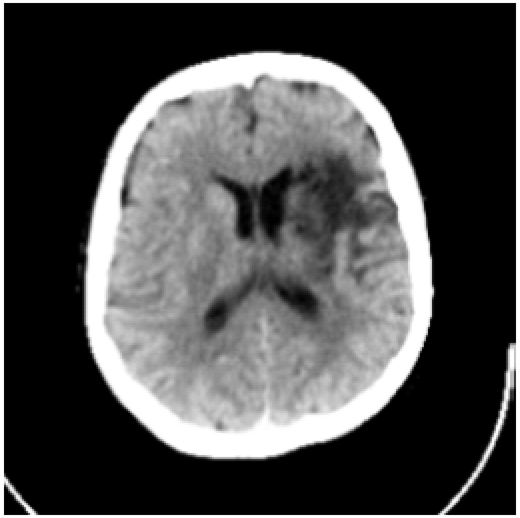
- SART
  - reducing errors in ray integral approximation by replacing pixels by bilinear elements
  - simoultaneous iteration steps [as in SIRT]
  - heuristic use: Hamming window
  - result: better quality & faster convergence
  - gives reasonable images in one iteration

a little demo

- parallel beam scan
- almost perfect weight matrix [sart-like results for art]
  => nalmost no errors in back-projections
  => this art-version corresponds to real sart
- art and sirt simuation
- tests for source size [truncation], number of projections, number of iterations, lambda variation, run times
- tests for use of hamming window, initial guess, a priori information
- comparison with matlab in-build FBP reconstruction

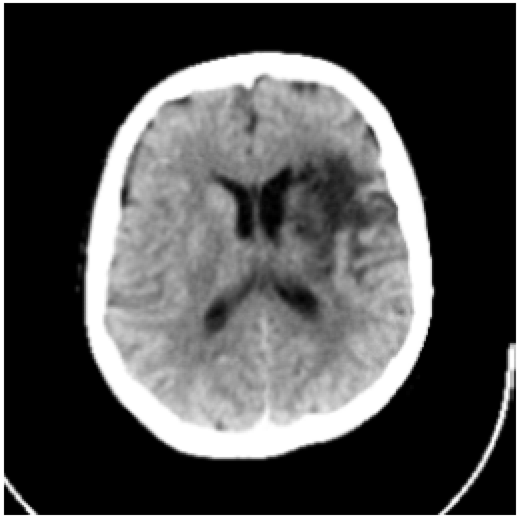
the experiment

- test images [resolution:128^2, greyscale 8bit [0:255]]

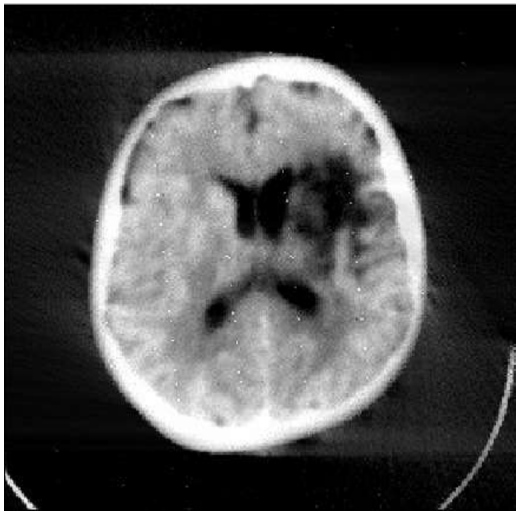


some experimental results

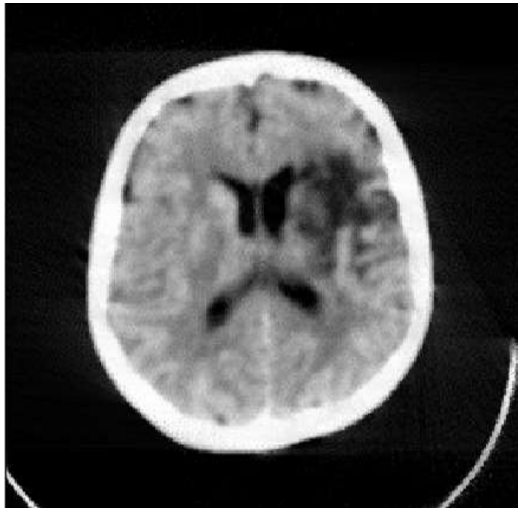
- brain 256x256



original image



art without “smart“ initial guess
1 iteration, 100 projections, 256*1.5 rays per projection



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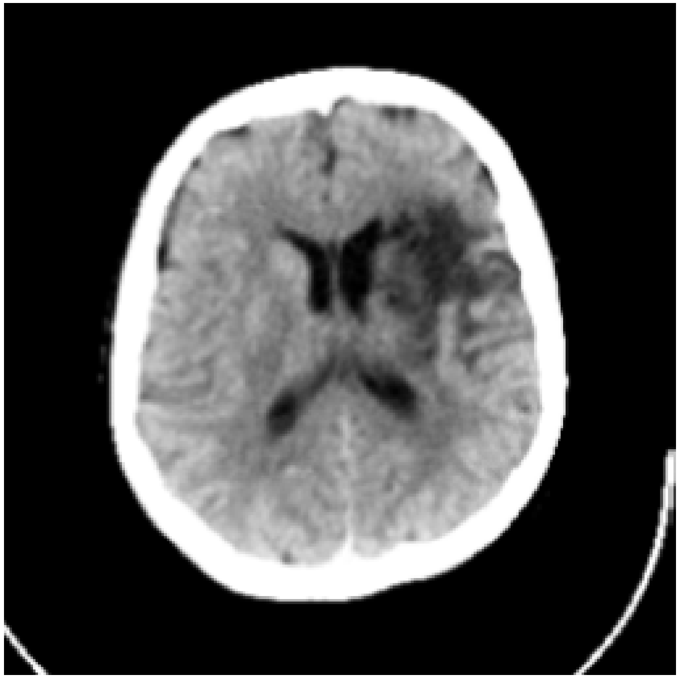
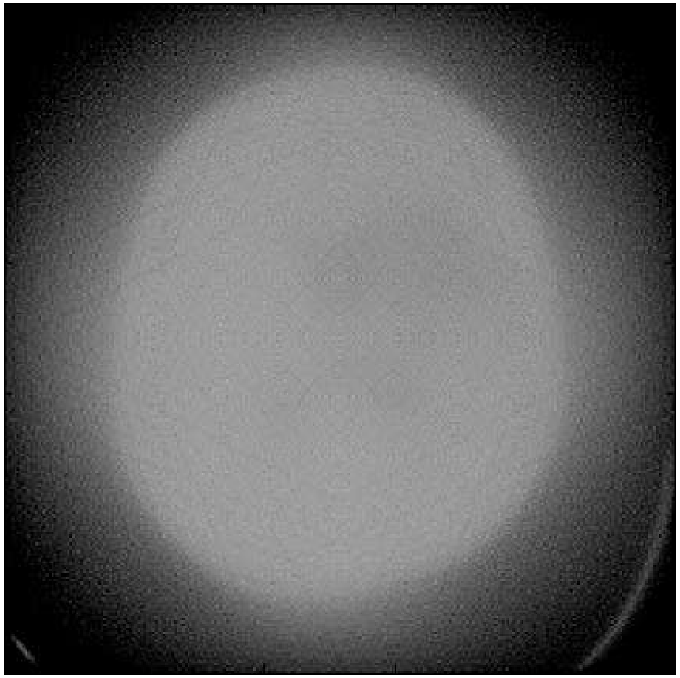


original image



sirt
3 iterations, 100 projections,
256*1.5 rays per projection

some experimental results

- lena 256x256

original image

art
3 iterations, 100 projections,
256*1.5 rays per projection

fbp
matlab in-built fbp [iradon],
90 projections

comparison of ART and FBP

ART	FBP [filtered back projection]
+ better noise tolerance + needs less projections + better handling of non-uniformly distributed projection datasets	+ more computationaly efficient
– aliasing effects for large fan-beam angles [>20°]	

readings

- Kak, Slaney “Principles of Computerized Tomographic Imaging“
- Albert Macovski “Medical Imaging Systems“
- Klaus Mueller “Fast and Accurate Three-Dimensional Reconstruction from Cone-Beam Projection Data Using Algebraic Methods“
- G. T. Herman “Topics in Applied Physics“
- Henrik Turbell “Cone-Beam Reconstruction Using Filtered Backprojection“
- online resources:
  - Hiroki Yoshikawa, “X-Ray Computed Tomography“, http://ctlab.bk.tsukuba.ac.jp/~hiroki/blind/x-rayCT.html
  - Siemens Medical Solutions Website: http://www.medical.siemens.com
  - General Electric Medical Systems Website: http://www.gemedicalsystemseurope.com
  - http://www.amershamhealth.com/medcyclopaedia
  - http://en.wikipedia.org
  - http://www.impactscan.org
  - http://imaginis.com/