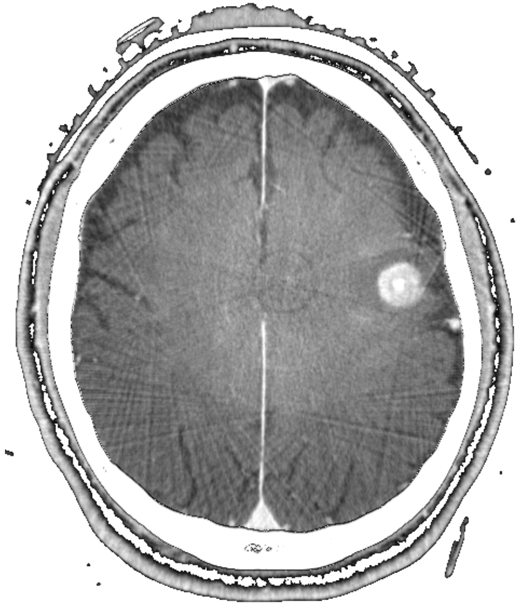
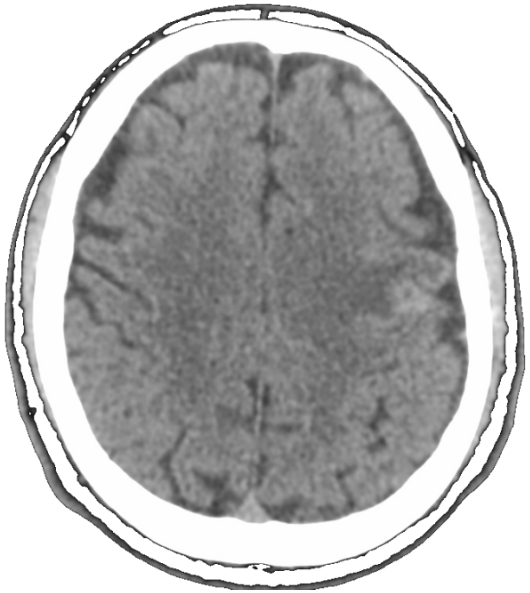
Qualitative comparison

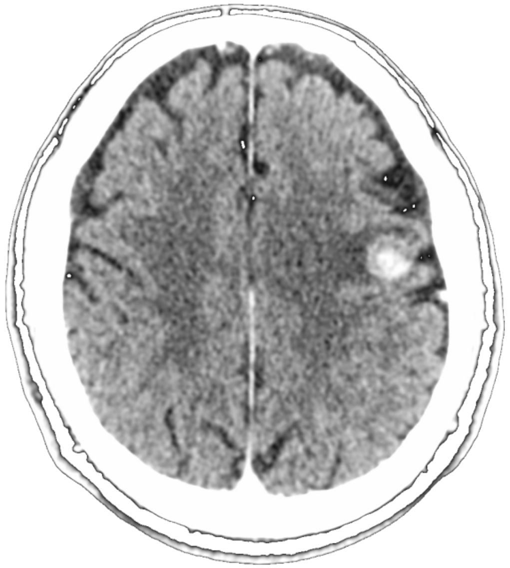
ESRF
(without contrast agent)



ESRF
(with contrast agent)



Hospital
(without contrast agent)



Hospital
(with contrast agent)

Phase Contrast Imaging

Tackling the contrast sensitivity and the dose issue in the same time

X-ray conventional imaging

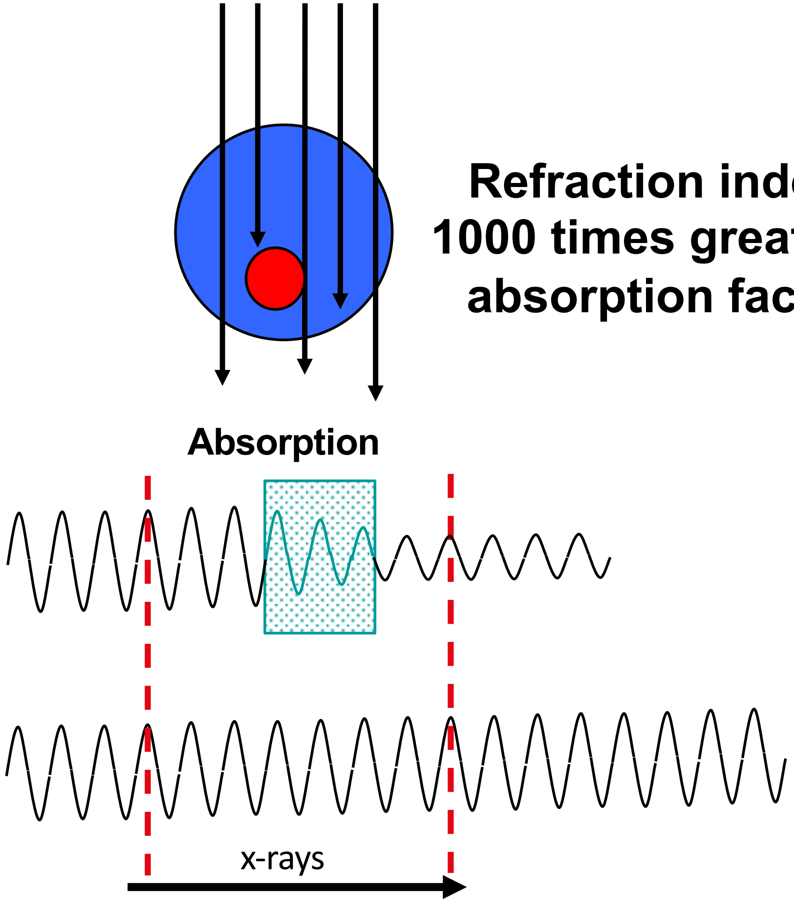
1895
Anna Rontgen

120 years of evolution:
Better contrast & resolution
3D imaging

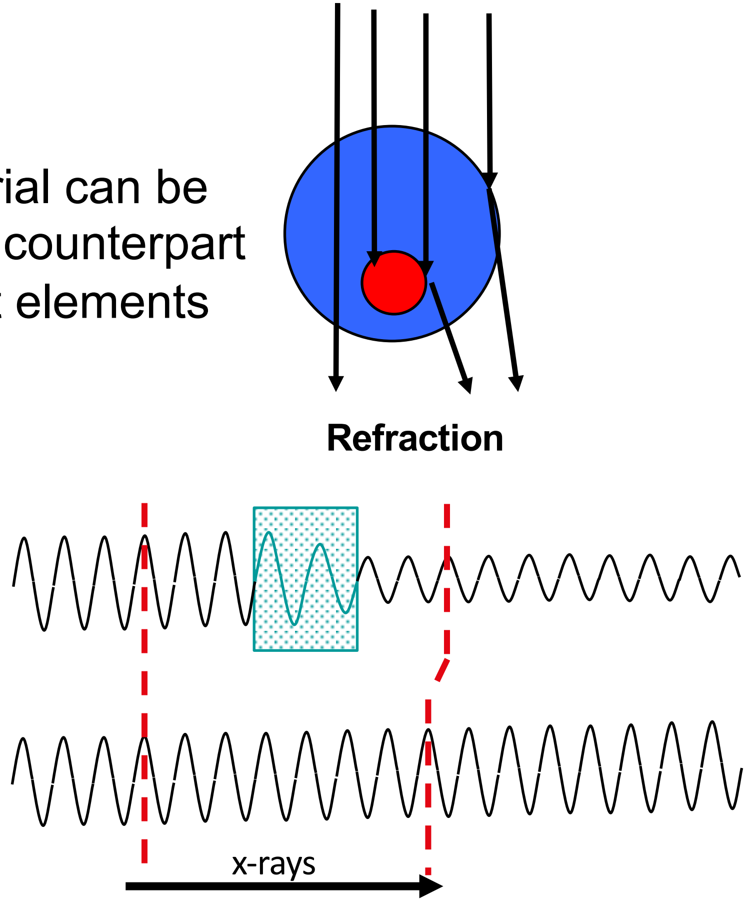
Based on the same principle:
X-Ray Attenuation

2014
Emmanuel Brun

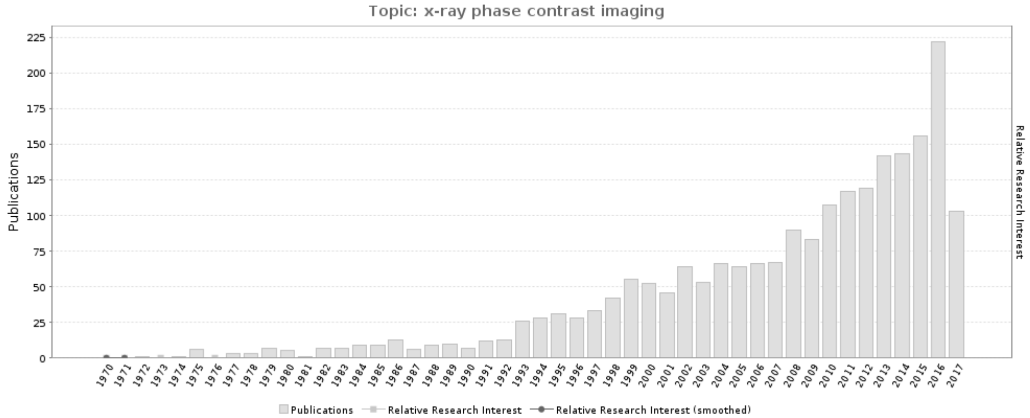
X-Ray Refraction Imaging



Refraction index of material can be **1000 times greater** than its counterpart **absorption factor** for light elements

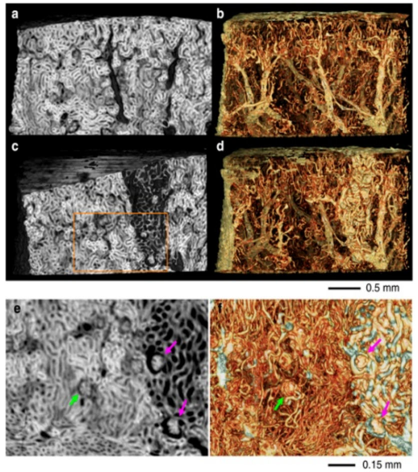


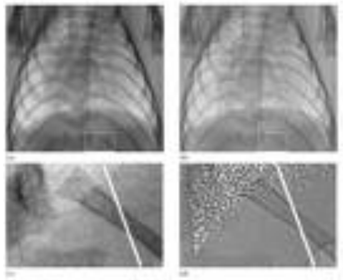
X-Ray Phase Contrast Imaging



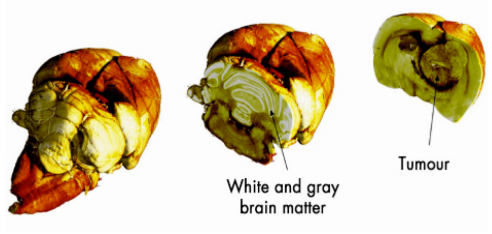
Source gopubmed

Credit: Wu et al

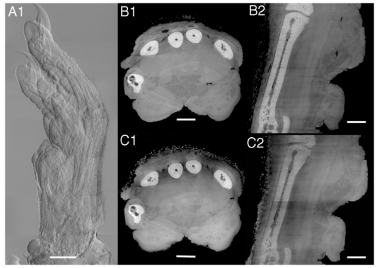




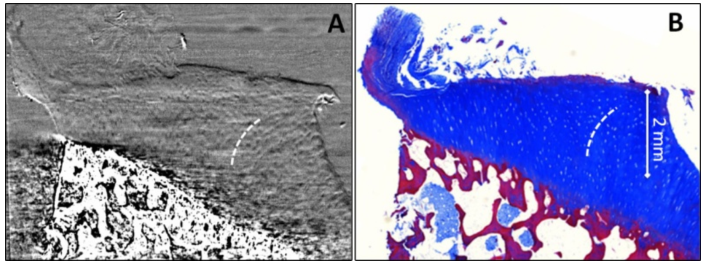
Lewis et al.,
Phys. Med. Biol. 2005



Credit: Pfeiffer et al



Credit: Zhu et al.



Credit: ESRF/P. Coan

Breast Phase Contrast Imaging

- **Clinical routine dual view Mammography has limitations :**
  10%-20% of tumors are not visible.
  40% of biopsied lesions are malignant

- **Main Reasons :**
  3D diagnosis would be a great help but breast are radiosensitive organs :
    - Tomosynthesis : only partial 3D
    - Full CT : spatial resolution is limited and deposited dose is still too high

  No difference in absorption between normal and abnormal mass

- **Phase Contrast Measure not only absorption but phase variations.**
-
  Differentiation is possible
- **Refraction is much higher than absorption contrast (2 orders of magnitude for breast) also at high energy**

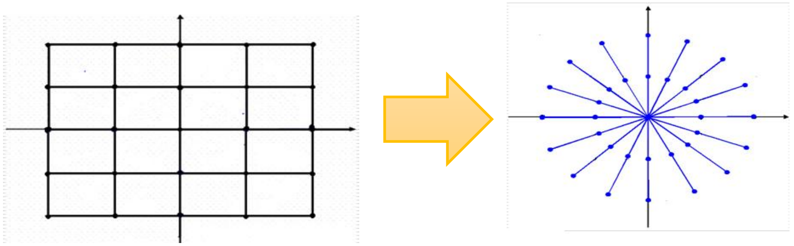
BUT

Breast Screening needs high resolution

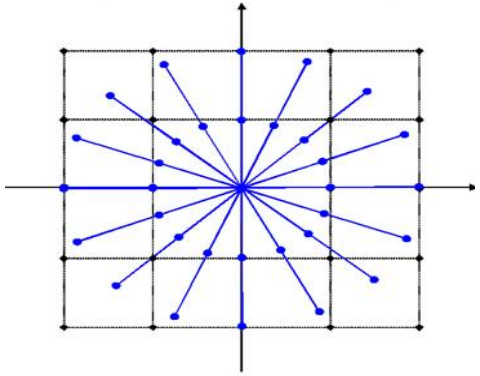
⇒ High number of projections for CT

⇒ Can we reduce the number of projections?

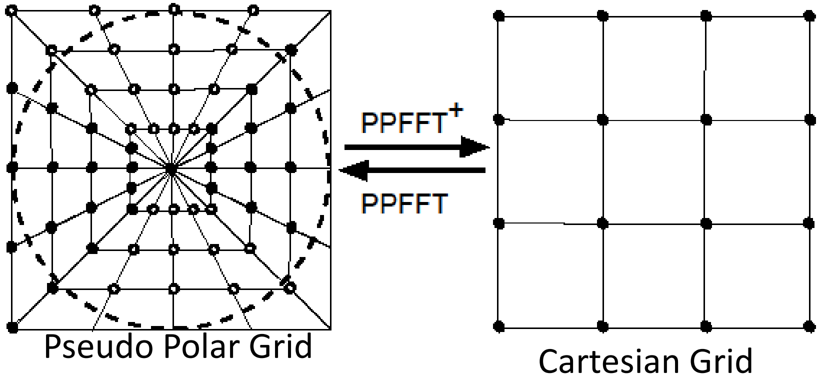
Acquisition Scheme



- Real space image is in Cartesian grid while the Fourier space data is in Polar Grid
- **<u>There is no exact and direct FFT between polar and Cartesian Grid</u>** [3]



- Grid points in the Fourier domain are lying on the equally-sloped lines instead of equally-angled lines
- For a N*N Cartesian grid, corresponding PPG is a set of 2N lines consisting of 2N grid points mapped on **N concentric squares**.
- **<u>There exists a PPFFT between PPG and Cartesian Grid</u>** which is algebraically **<u>exact</u>**, geometrically faithful and **<u>invertible</u>**

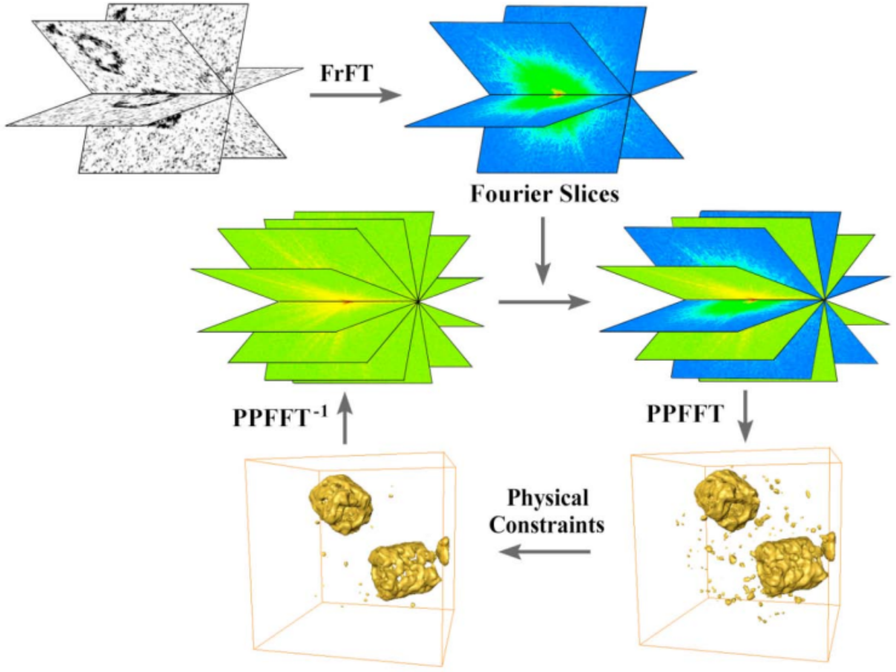


Equally Slopped Tomography iterative algorithm

- Start with Conversion of projections to Fourier slices in the pseudo polar grid fractional FFT.

- **Iterative process** is initiated :
  - Inverse PPFFT is applied to the frequency data
  - A new object is obtained through constraints
  - Forward PPFFT onto modified image
  - Frequency data is updated with the measured Fourier slices

- Real domain constraints :
  - Positivity of the coefficients
  - Zero-density region outside the object



Experiments : 3D PCI Reconstruction of Breast

Among all Phase Contrast Techniques **Analyzer Based Imaging** shows the **highest** sensitivity for breast.

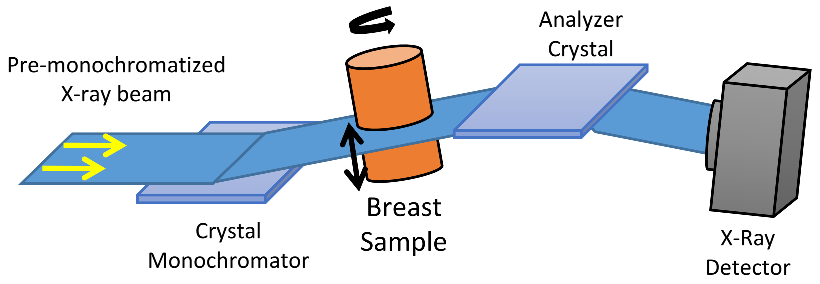
- Full human tumor bearing breast was used. **Pixel size : 92microns** (clinical dual view mammogram is 100um)
- Dual view screening mammography in Germany and US : Mean Glandular Dose (MGD) in Germany and US is 3.5mGy
- Reconstructions parameters :

  FBP 2000projections MGD 7.7 mGy

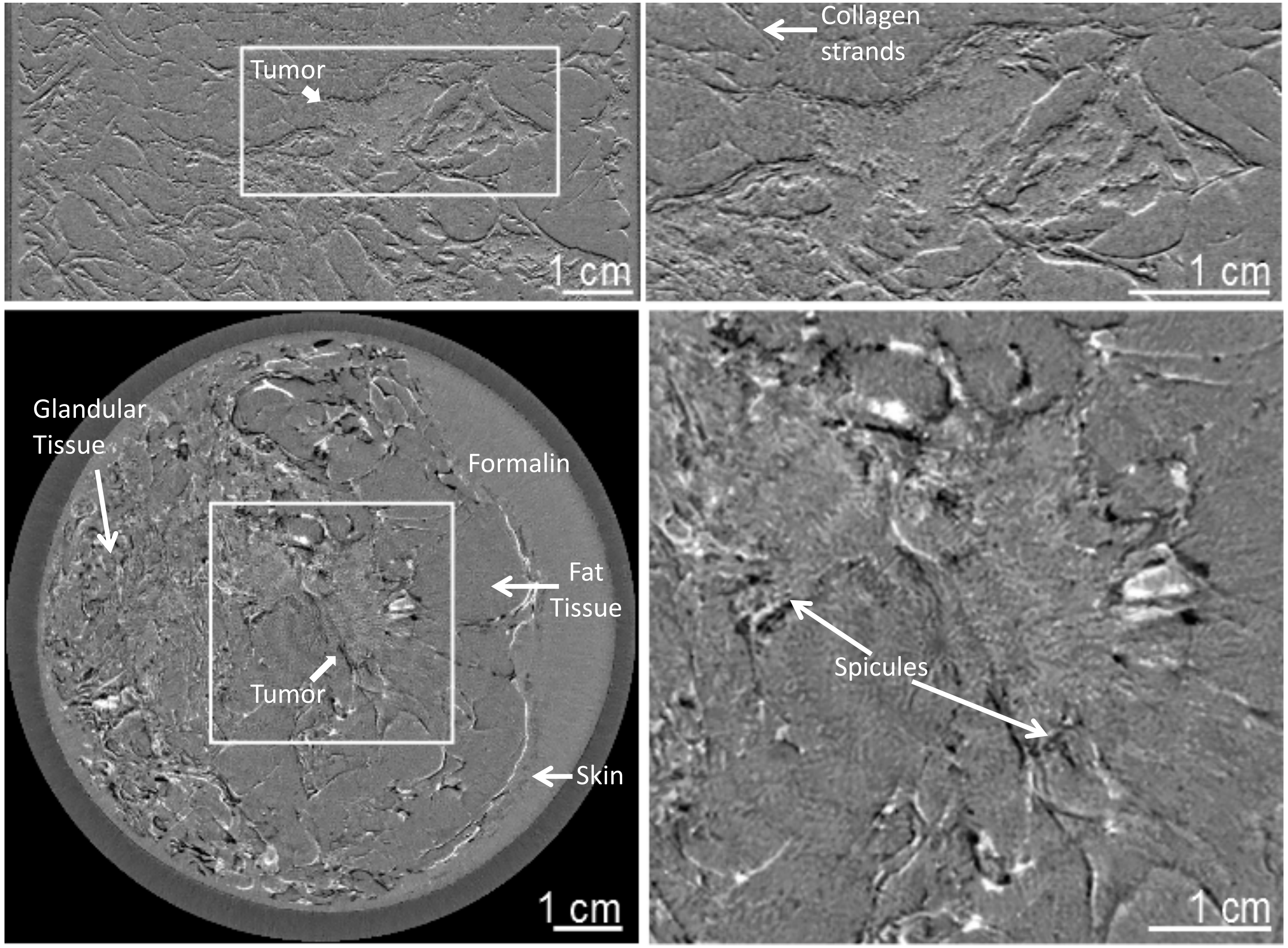
  FBP 512 projections MGD 1.7 mGy

  EST 512 projections MGD 1.7 mGy

  EST 200 projections MGD 0. 7mGy



Result of reconstruction by EST 512projections



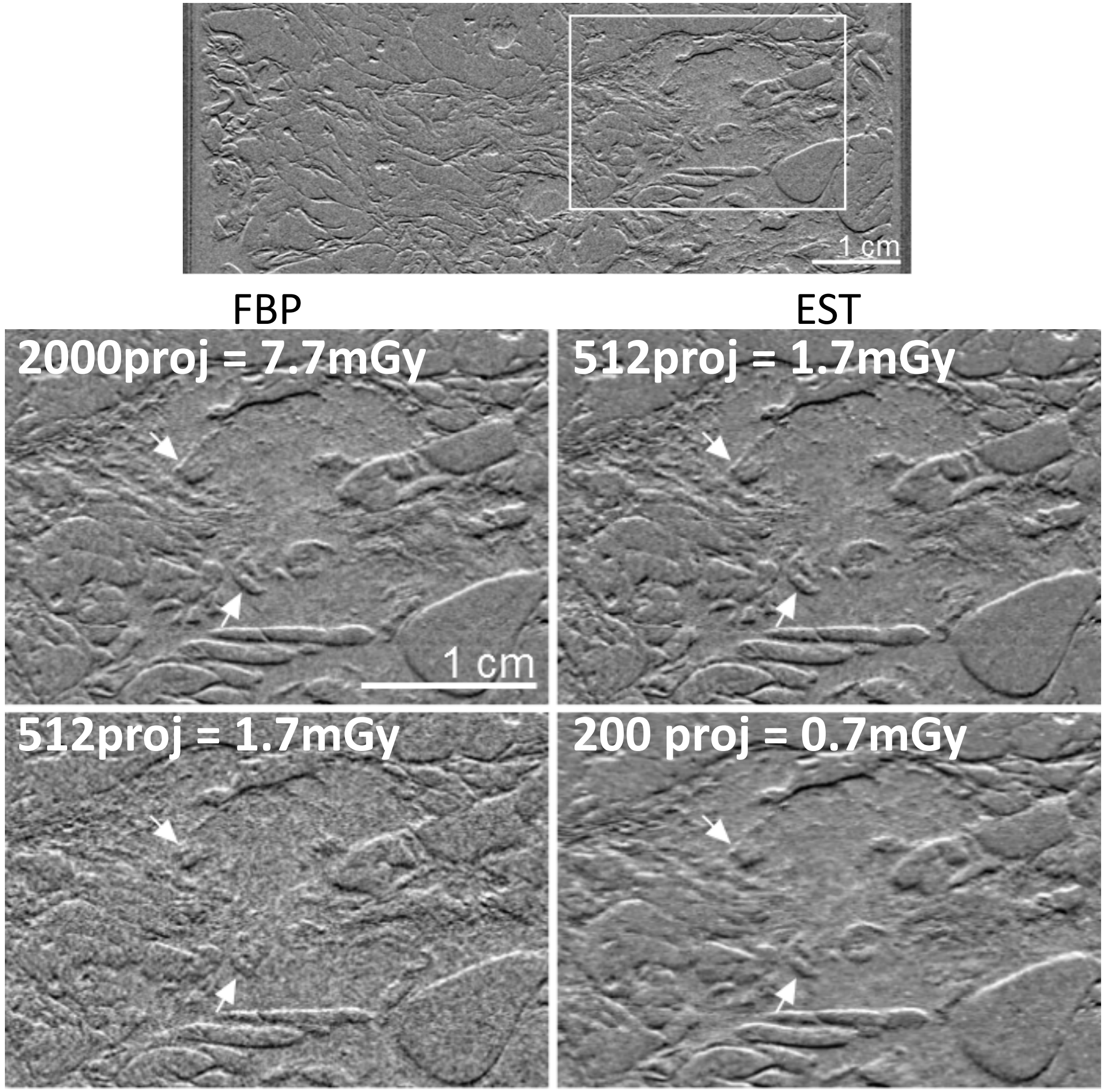
<u>MGD</u>

<u>1.7mGy</u>

Zhao et al. PNAS 2012

Visual Comparison

- **Fine structures are preserved by EST512.** Contrast and noise are **equivalent or better.**
- FBP 512 exhibits high noise degraded features and blurred boundary of the tumour
- Loose of spatial resolution in **EST 200** compared to EST512 but **clinically relevant features are observable**



Zhao et al. PNAS 2012

Quantitative Comparison

- Standard Comparison :

$$SNR = Mean(I_{ROI}) / Std(I_{ROI}) \qquad (Eq.1)$$

$$CNR = [Mean(I_{ROI_1}) - Mean(I_{ROI_2})] / [2 \times (Std(I_{ROI_1}) + Std(I_{ROI_2}))] \qquad (Eq.2)$$

	FBP 512	FBP 2000	EST512
Signal to Noise Ratio	2.89	6.13	5.98
Contrast to Noise Ratio	0.51	0.91	0.98

- Blind Test made by 5 radiologists from the Radiology department of Ludwig Maximilians University

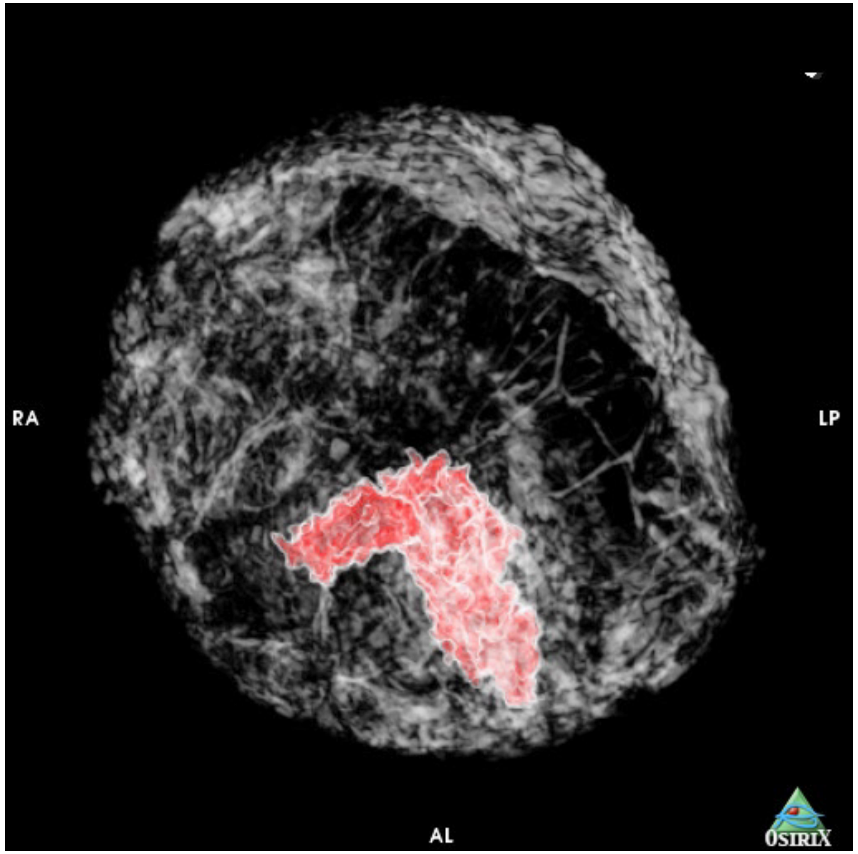
Radiologist were asked to mark form 1 to 5 on the following criteria.

	FBP 512	EST 200	FBP2000	EST512
Image quality	2.2 ± 0.4	2.7 ± 0.9	4.3 ± 0.9	4.5 ± 0.5
Sharpness	3.3 ± .0	2.2 ± 0.8	4 ± 0.7	4.3 ± 0.5
Contrast	3.0 ± 0.7	3.4 ± 0.9	4 ± 0.5	4.8 ±0.4
Evaluation of different structure	2.7 ± 0.5	2.9 ± 1.	4.1 ± 0.6	4.8 ± 0.4
Noise	1.8 ± 0.7	3.3 ± 0.8	4.2 ± 0.7	4.8 ± 0.3

Zhao et al. PNAS 2012

Conclusion on EST reconstruction

- 3D information of soft tissues at **higher resolution** and **better contrast**, but also **less radiation** doses to the sample
- Very low dose **(<1 mGy)** 3D imaging is possible if one is ready to lose a bit of spatial resolution and accept an increased noise
- BUT it is NOT quantitative….



TV minimization

- The CT reconstruction problem may be solved as an optimization problem :

$$x = argmin_x(\|y - Px\|_2^2 + f(x))$$

- Total Variation (L1 norm of the gradient) can be used

$$x = \mathrm{argmin}_x(\|y - Px\|_2^2 + \beta TV(x))$$

- Minimizing the L1 norm promotes sparsity

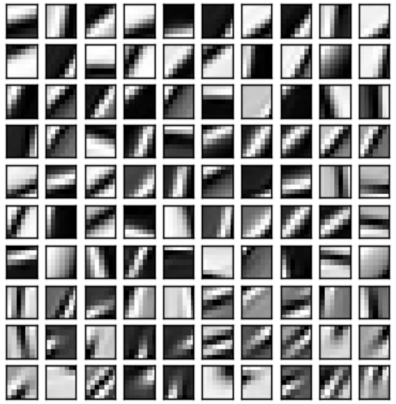
Dictionary Learning reconstruction

- For non piece wise constant images traditional iterative methods (TV minimization) fails.
- Idea of the method :

Database of **patchworks** of images close to the images to be reconstructed

To express a given sub-image to reconstruct as a linear combination of the basis patches

To find the solution which gives the maximum likelihood by minimizing the number of entries in the dictionary




Dictionary “learnt” from Lena image and used for reconstructing the image of interest

Noisy image

Denoised image

A. Mirone, E. Brun, P. Coan. Plos One 2014

Reconstructing Lena

- **Experiment :**
  512*512 pixel Lena image
  80 projections

- **Remark :**
  To avoid aliasing 800 projections should be used (Nyquist-Shanon sampling criterion)

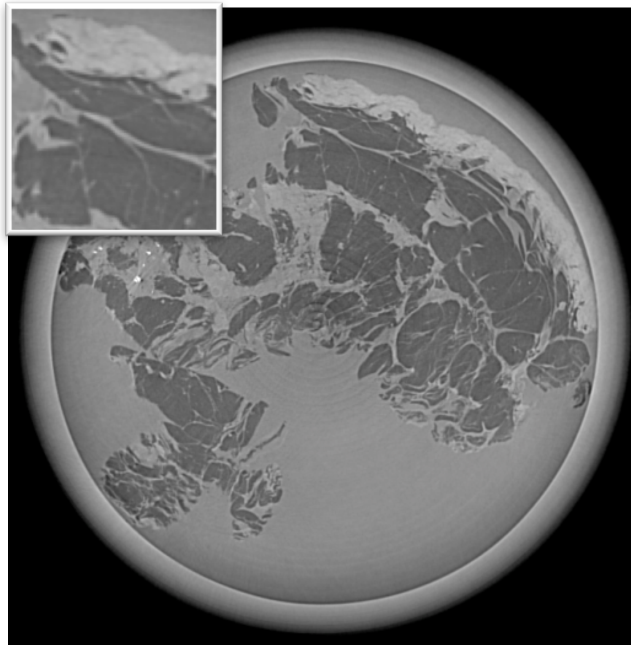
Lena image to reconstruct

Results

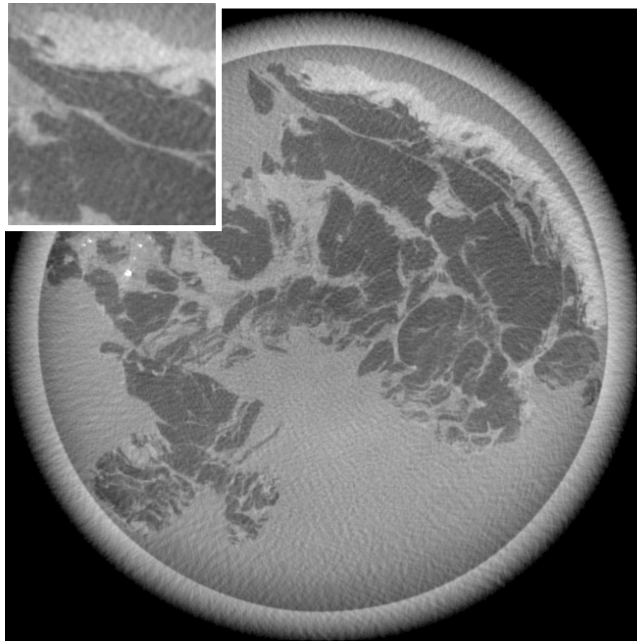
Additive White Poisson Noise = 0.3% max of sinogram

FBP EST TV DL Original

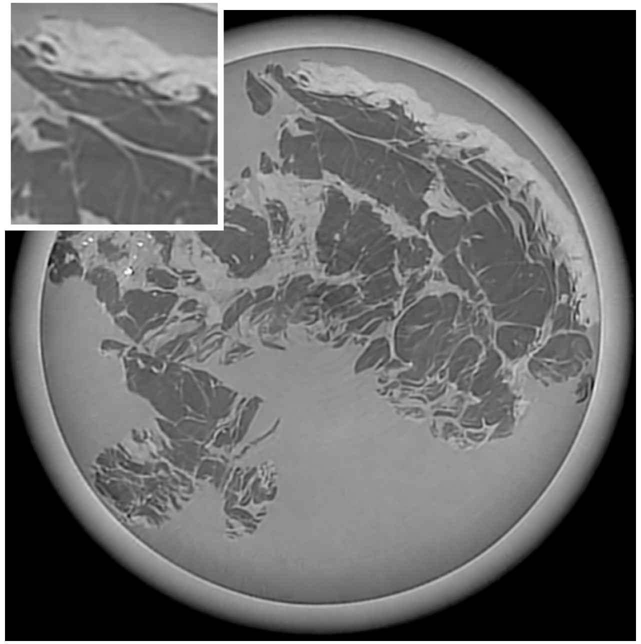
Breast Phase Contrast Imaging



FBP 1000 projections



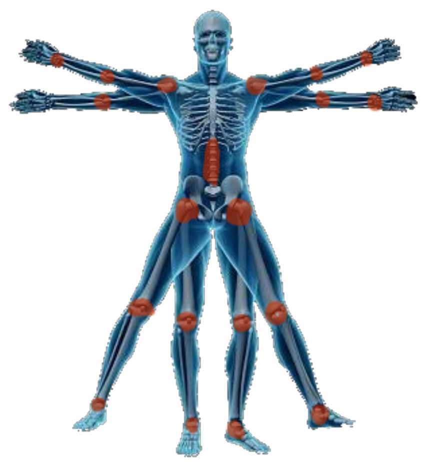
FBP 200 projections



Dictionary Learning
200 projections

Osteo Articular diseases

- **A major socio-economical burden**
  - Cost of illnesses was estimated to be 1 – 2.5% of Gross National Product[1]
  - Up to 10% of total health expenditure[2] (> cancer)
  - Most prevalent chronic pain and long term disability
  - 17% of the population and 22% in 2030



- **No proven curing strategies for joint disorders and cartilage degeneration**
  - Joint replacement = 85% of direct costs

- **Lack of imaging modality for a correct depiction of all tissues in a joint**
  - Cartilage is poorly visible in conventional radiography and in clinical CT
  - MRI is limited by the achievable spatial resolution and to soft tissue depiction
  - Ultra Sound useful for tendons but no visibility of the other tissues

[1] Chen *et al.* The Global Economics cost of osteoarthritis: how the uk compares. Arthritis 2012

[2] Heijnik et al. Cost of illness: An international comparison: Australia, Canada France Germany and the Netherlands. Health policy. 2008

Human knee imaging

- 2 human knees (72 & 83 y.o)
- Energy: monochromatic 60 keV
- Pixel size 46µm
- Propagation based imagng: 6.5m
- Dose: 46mGy

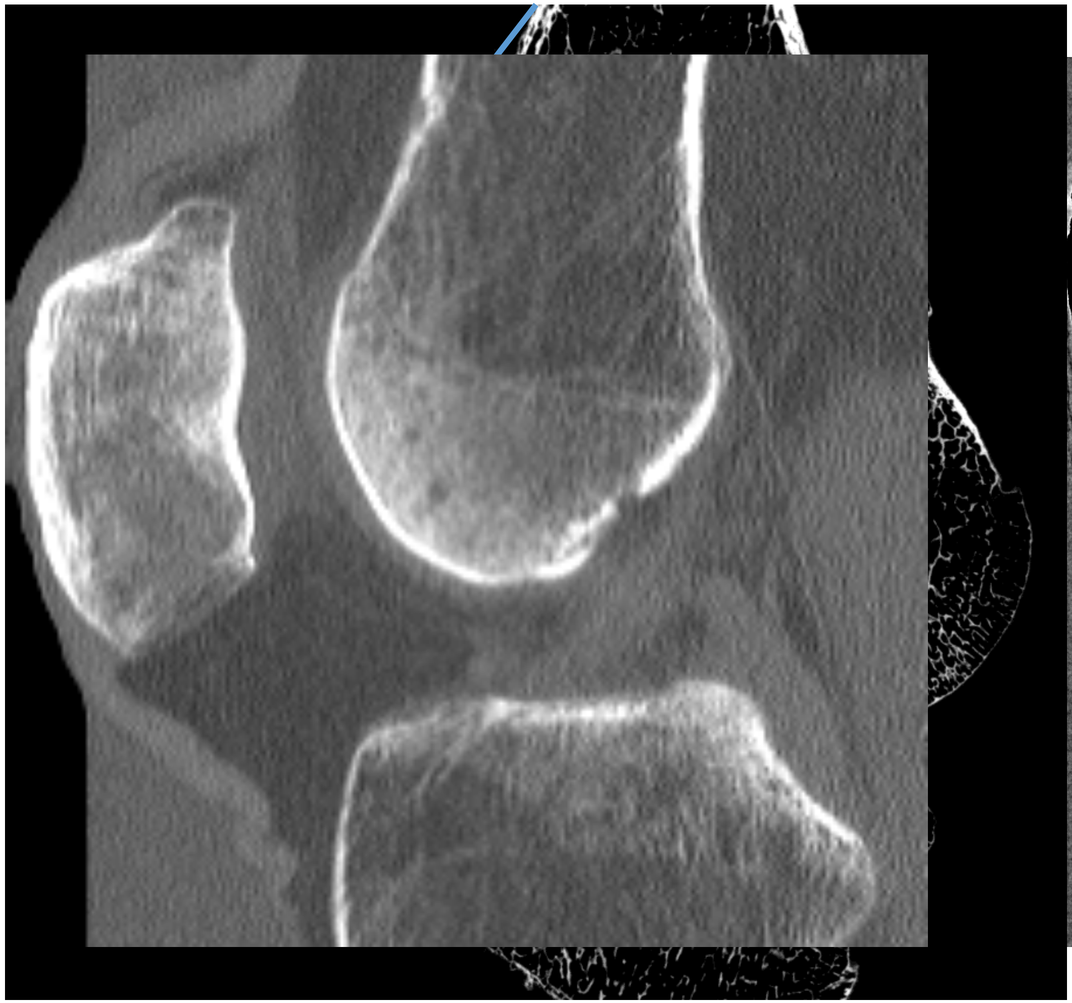
Material & Methods

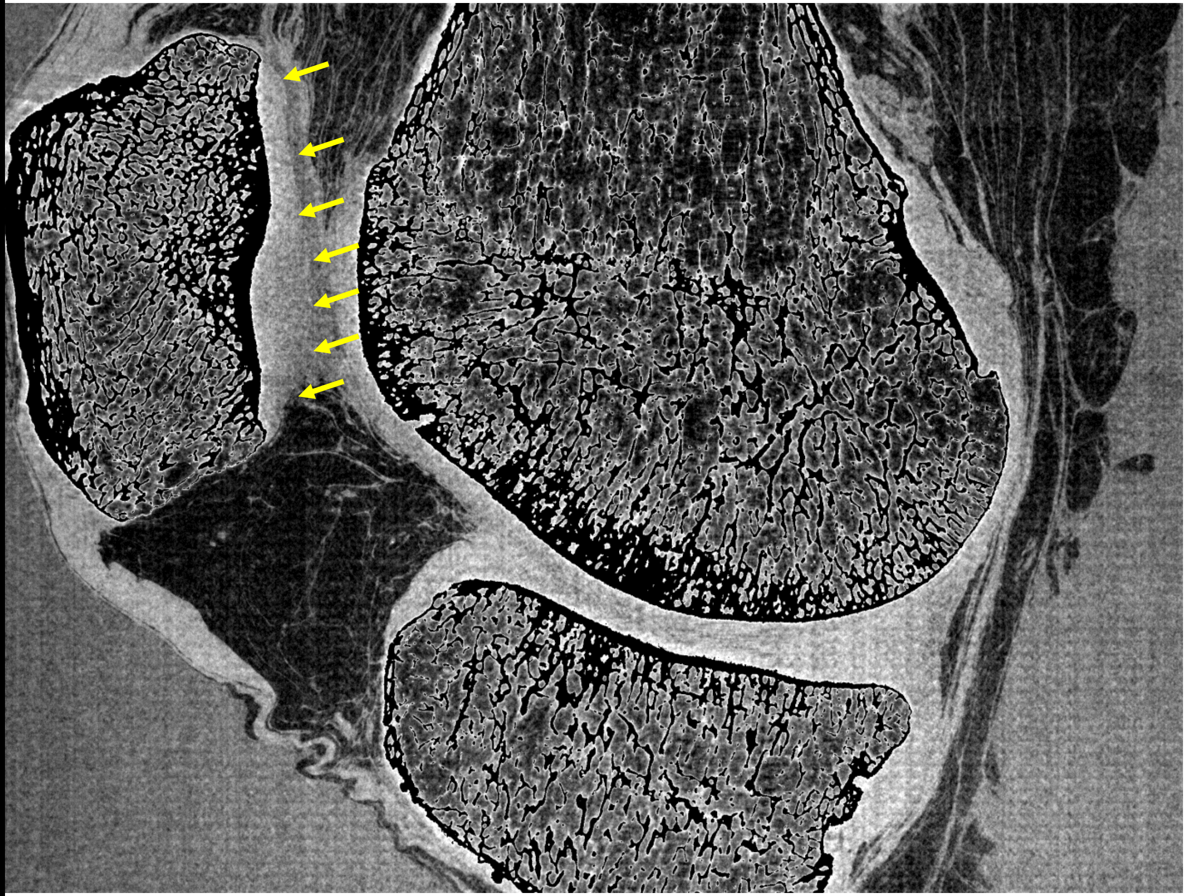
Phase Contrast CT	
Machine	ESRF
Energy	60keV
Current	180mA
Resolution	0.046 x 0.046x 0.046 mm
Acquisition Time	1min30s*

Dual source (2*128 slices) Clinical CT	
Machine	Somatom Definition Flash
Energy	120kvP
Current	110mA
Resolution	0.42 x 0.42 x 0.6 mm
Acquisition Time	40s

MRI sequence		
Machine	Magnetom Verio, Siemens Medical	
Parameter	PD-fs	FLASH
Repetition time (TR)	4050 ms	22 ms
Echo time (TE)	30 ms	9.8 ms
Flip angle	180°	15°
Band width	140 Hz	130 Hz
Parallel imaging acceleration factor (iPAT)	2	2
In-plane resolution	0.3 x 0.3 mm²	0.3 x 0.3 mm²
(Partition) Thickness	3 mm	1.5 mm
Matrix	512 x 512	512 x 512
Field of view	16 x 16 cm²	16 x 16 cm²
Partitions / Slices	29	56
Acquired orientation	axial, sagittal, coronal	axial, sagittal
Acquisition time	4:04 min	5:34 min

Why phase imaging for osteo articular diseases?



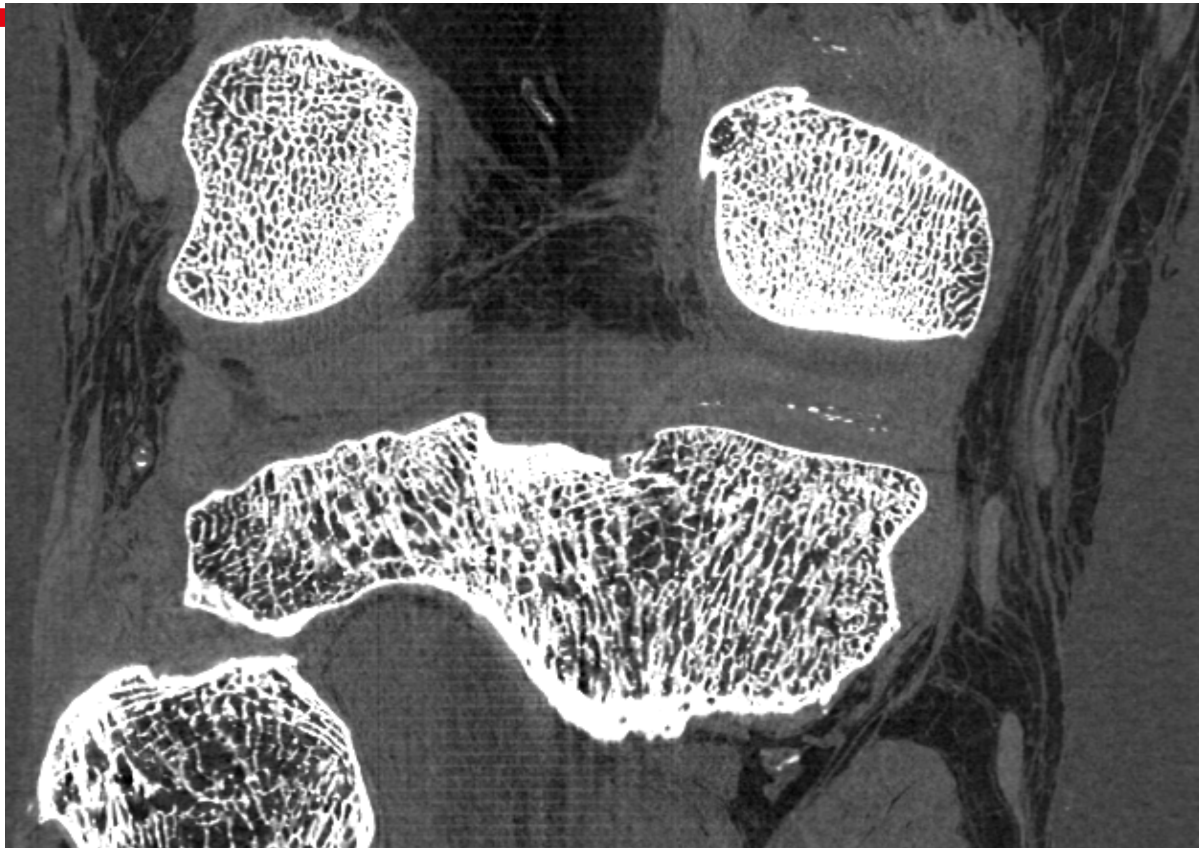


Why phase imaging for osteo articular diseases?

Human knee imaging

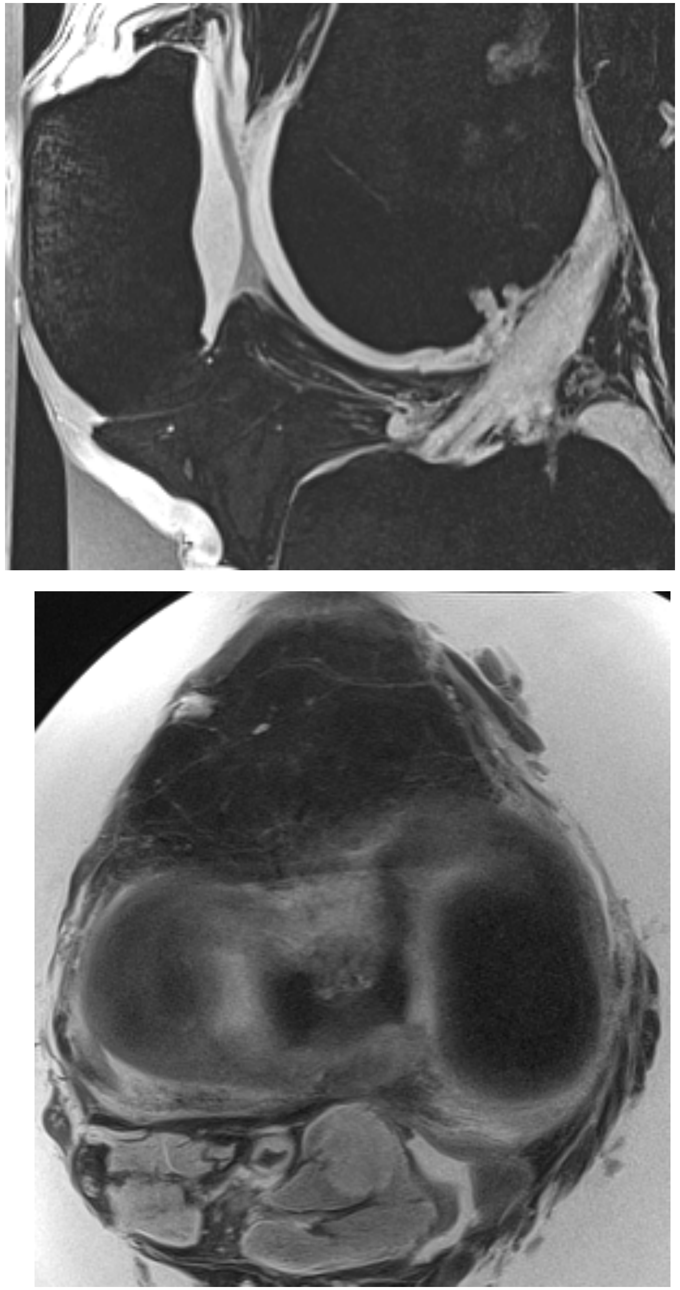
Clinical X-ray CT | Phase CT | Clinical MRI

A. Horng[#], E Brun[#], *et al*. ***Investigative Radiology***. 2014. [#]equal contribution

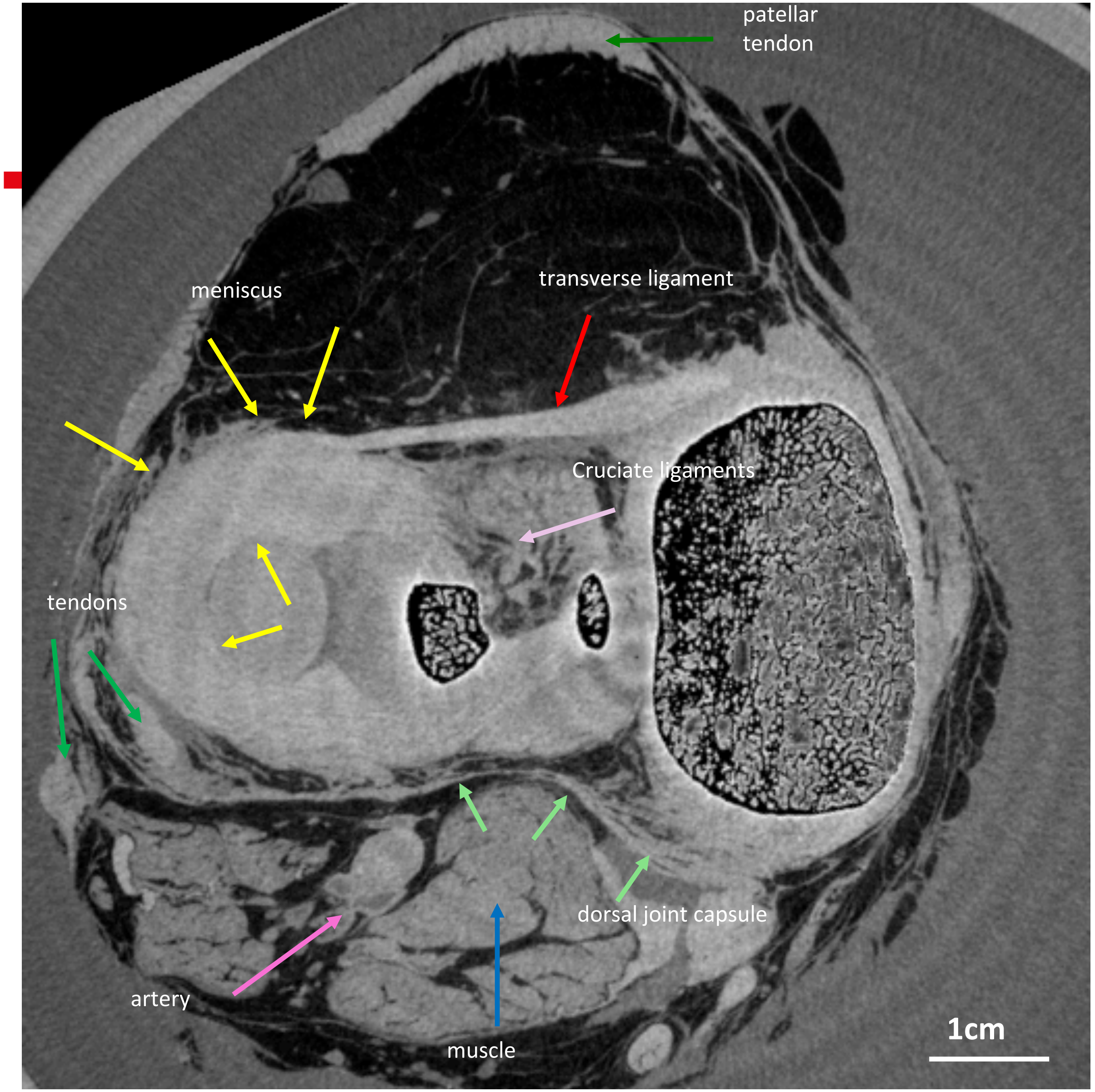


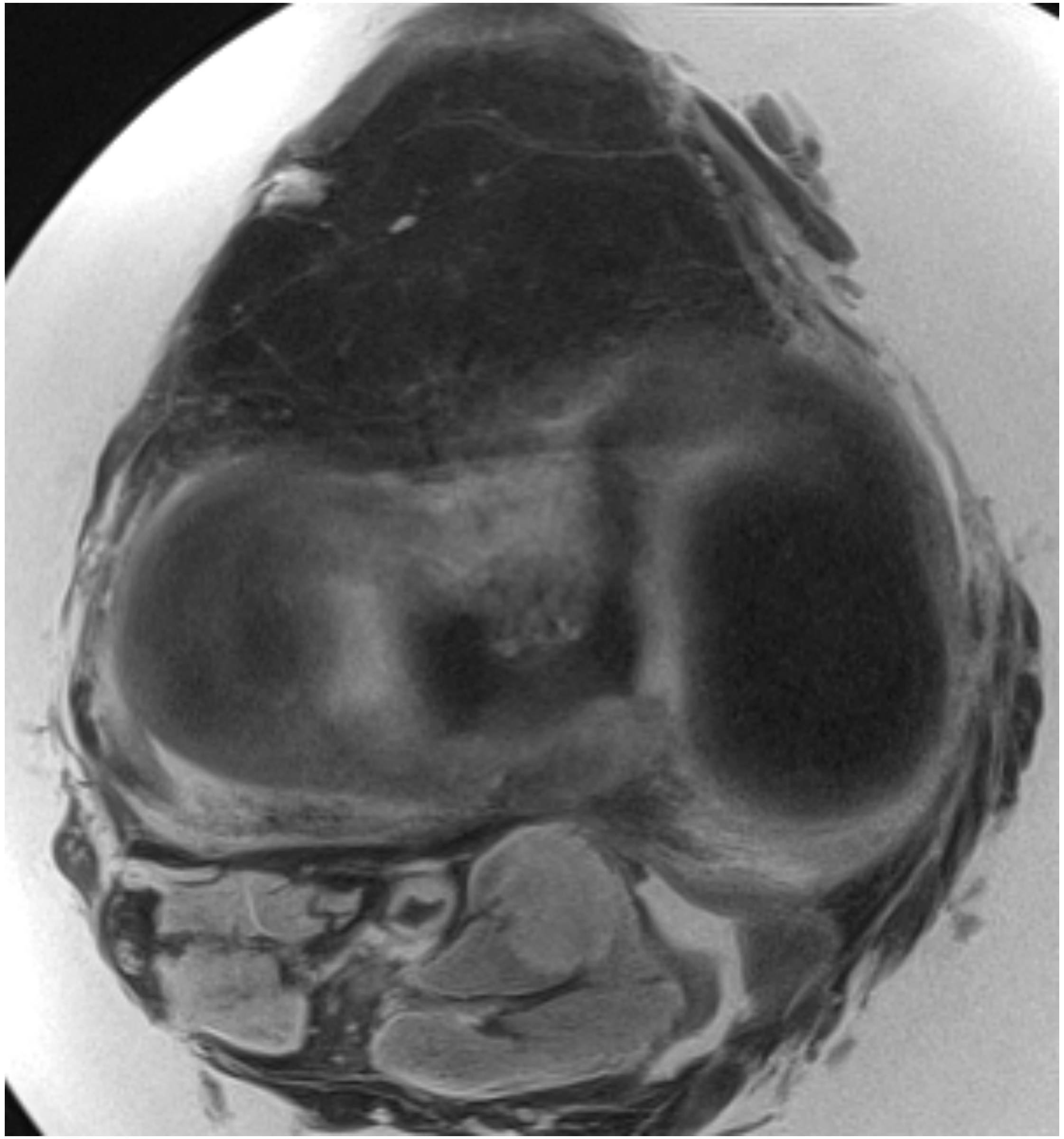

CT scan

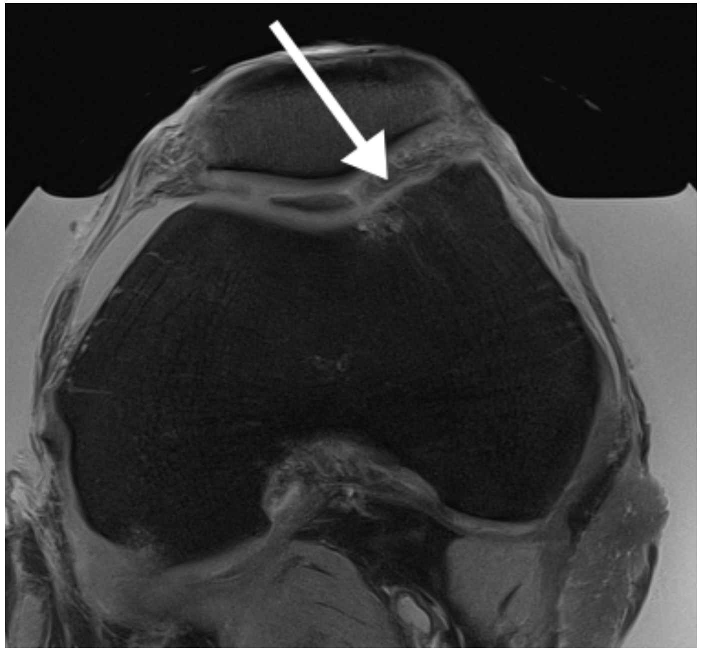
Phase

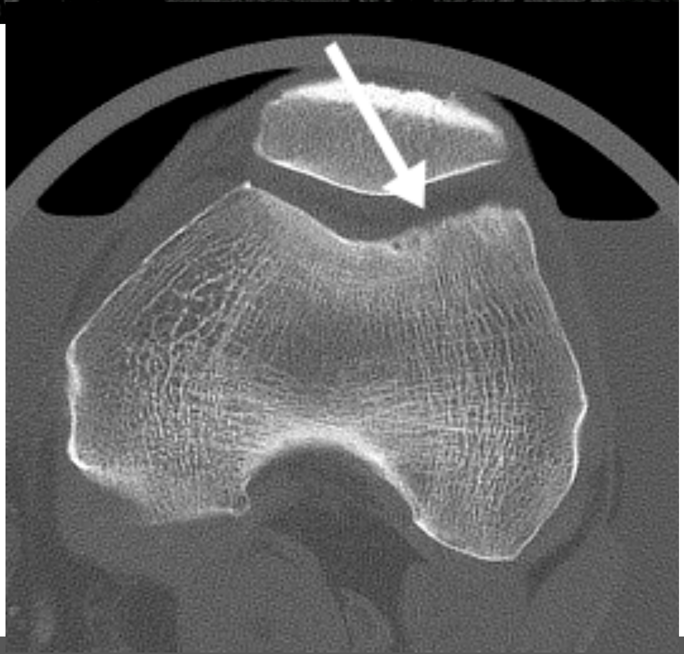


MRI


patellar
tendon
meniscus
transverse ligament
Cruciate ligaments
tendons
dorsal joint capsule
artery
muscle
1cm







Phase Contrast

MRI PD-fs

(Proton-Density weighted Fat saturated)

MRI FLASH

(Fast Low Angle shot)

T1