2013.10.24, TUM-IAS, Garching bei München

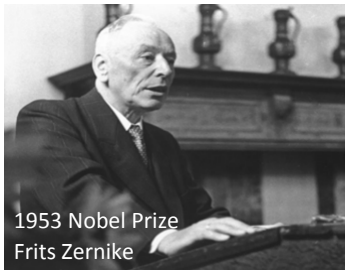
X-ray Phase-contrast CT with lab-based X-ray sources

Martin Bech
Technical University Munich (TUM) and
Medical Radiation Physics, Lund University

Outline

- what is x-ray phase-contrast and dark-field imaging?
- synchrotron radiation setup – coherent beam
- laboratory setup – incoherent beam

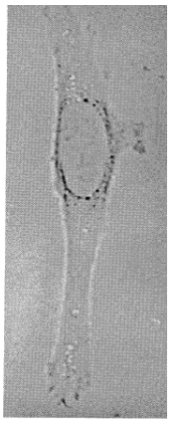
Visible light: Several contrast modalities



1953 Nobel Prize
Frits Zernike

Zeiss
microscope
www.zeiss.de

fibroblast cells



bright-field
contrast

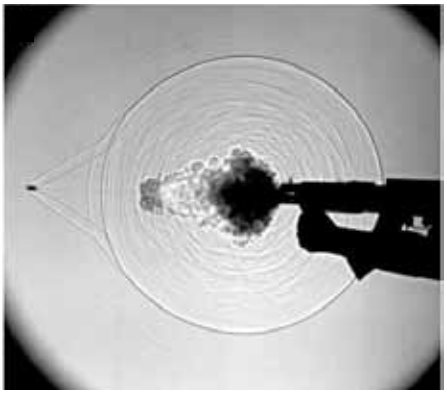
phase-contrast
(DIC)

dark-field
contrast

3

Visible light phase contrast

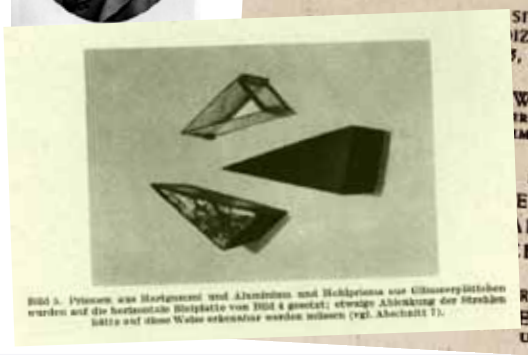
Shadowgraph



Wikipedia: (images by Gary S. Settles, Penn State Gas Dynamics Lab)

4

Röntgen was also looking for refraction...



W. C. RÖNTGEN

ÜBER EINE NEUE ART VON STRAHLEN

SITZUNGSBERICHTE
IZINISCHEN GESELLSCHAFT ZU WÜRZBURG
, S. 132 UND JAHRGANG 1896, S. 10

W. C. RÖNTGEN
R GESELLSCHAFT DIE ERSTE MITTEILUNG
M ENTDECKTEN STRAHLEN VOR

NEUDRUCK
ES 100JÄHRIGEN BESTEHENS
LISCH-MEDIZINISCHEN
HAFT ZU WÜRZBURG

RÜNDET 1849 VON
ECKER · J. SCHERER · R. VIRCHOW
UND ANDEREN

Wave propagation for pedestrians

Wave propagation regimes: **Fresnel number:** $F = \frac{a^2}{\lambda Z}$

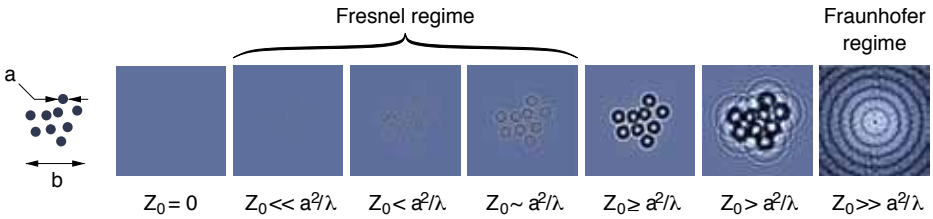


Figure courtesy: Timm Weitkamp; Phil Willmott

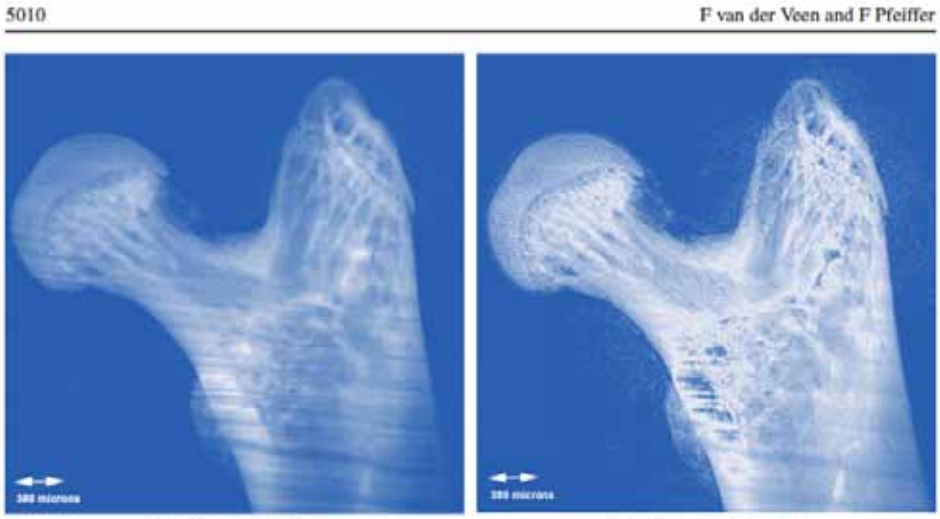
Contact mode imaging

X-ray tube and 2D detector

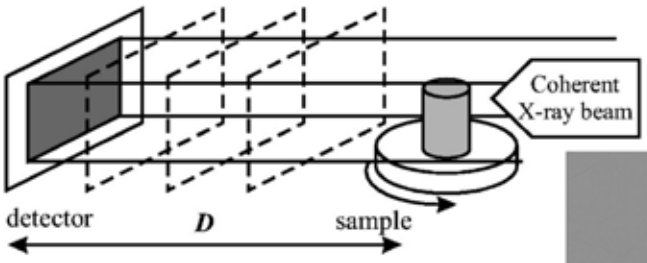
Fig. 1. (a) Ms. Röntgen's hand with ring (first X-ray image taken on December 22, 1895), (b) an early radiological workplace where the patient had to hold the film cassette himself, and (c) fluoroscopy in the Gynaecological Hospital, Erlangen (1918).

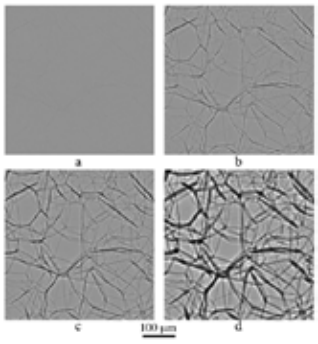
Synchrotron radiation

Holography



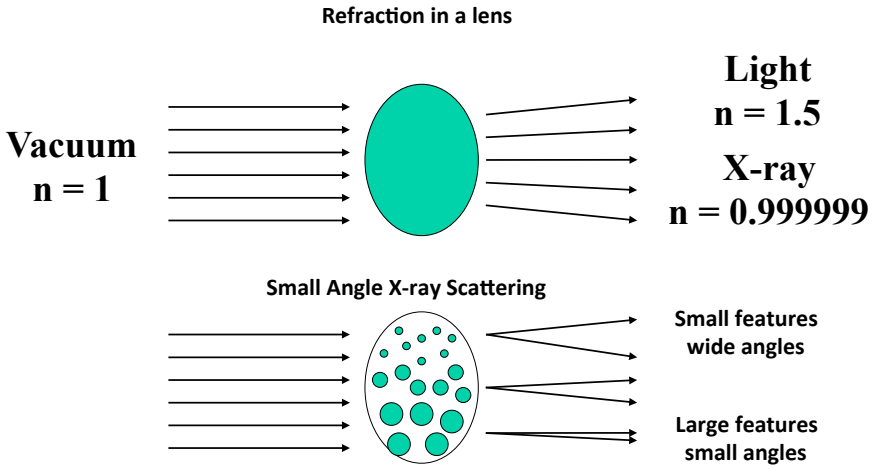
Holotomography





Polystyrene foam.
P. Cloetens 1999

Refraction and scattering



11

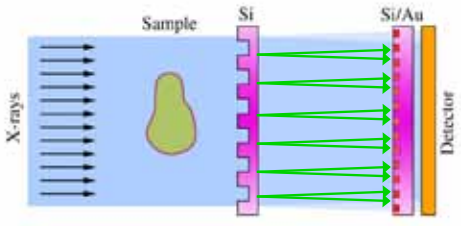
History of phase contrast imaging

Grating Interferometer:

Synchrotron
David 2002, Momose 2003
Weitkamp 2005

X-ray tube
Pfeiffer 2006

Darkfield
Pfeiffer 2008



A. Momose et al. *Jpn. J. Appl. Phys.* **42** L866 (2003)
T. Weitkamp et al., *Optics Express* **13**, 6296 (2005)
F. Pfeiffer et al., *Nature Physics* **2**, 258 (2006)
F. Pfeiffer et al., *Nature Materials* **7**, 134-137 (2008)

12

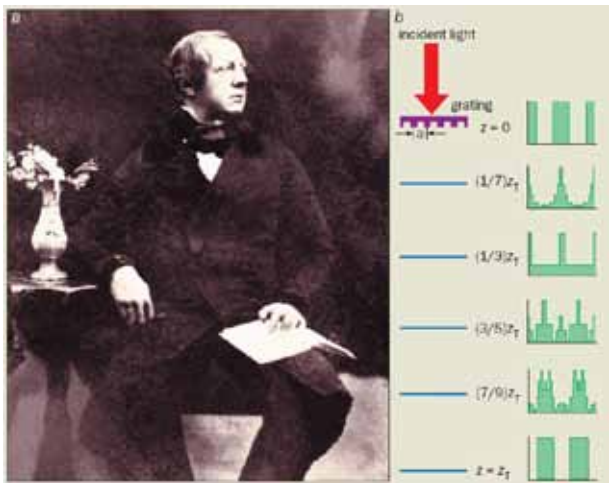
Three signals for imaging

- Absorption – Standard x-ray image
- Refraction – Phase-contrast image
- Scattering – Dark-field image

13

Talbot Effect

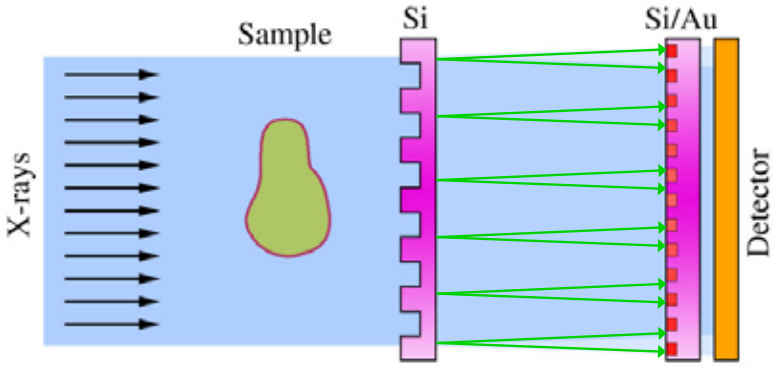
1800 - 1877



Sir Henry Fox Talbot 1836

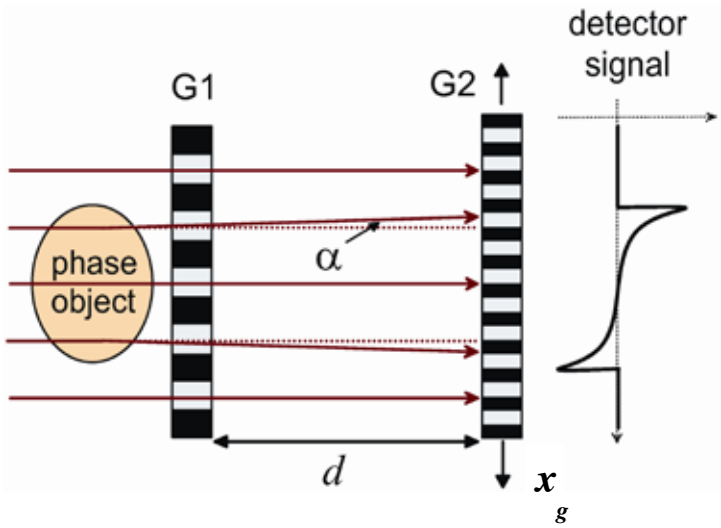
Talbot self imaging

$$d = n\frac{p^2}{8\lambda}$$



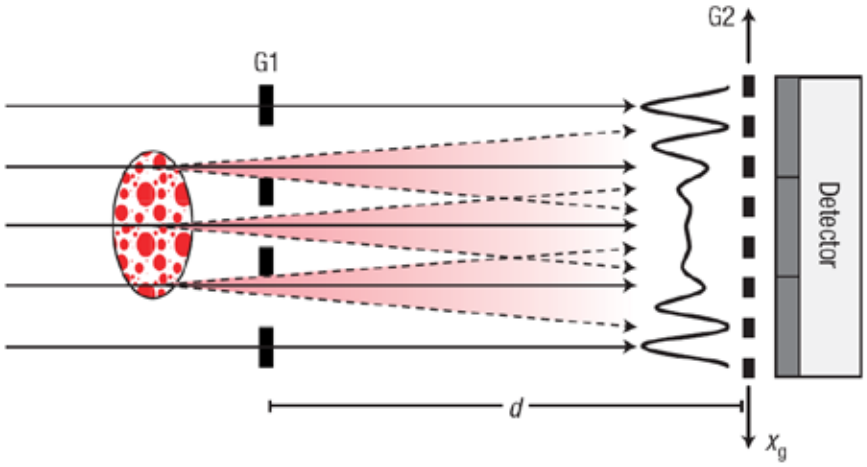
T. Weitkamp et al., Optics Express 13, 6296 (2005)
F. Pfeiffer et al., Nature Physics 2, 258 (2006)

Differential Phase Imaging

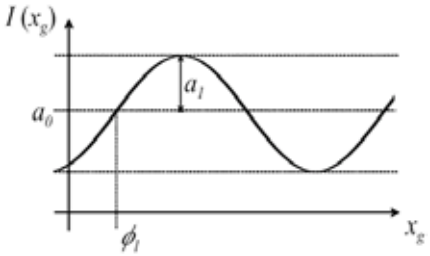


16

Scattering



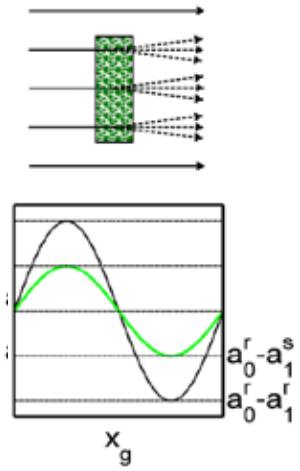
Extracting phase contrast image



$$I(m,n,x_g) = \sum a_i(m,n)\cos(ikx_g + \phi_i(m,n))$$

$$\approx a_0(m,n) + a_1(m,n)\cos(kx_g + \phi_1(m,n))$$

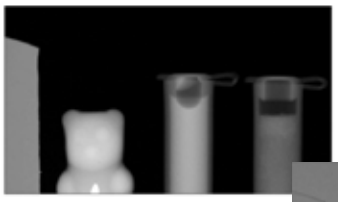
absorption — **local scattering power !** — **phase gradient**



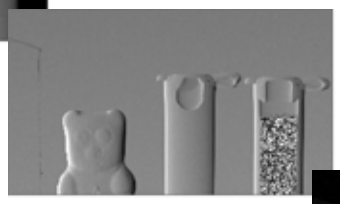
F. Pfeiffer et al., Nature Materials **7**, 134-137 (2008)

Three signals for imaging

Absorption – Standard x-ray image



Refraction – Phase-contrast image



Scattering – Dark-field image

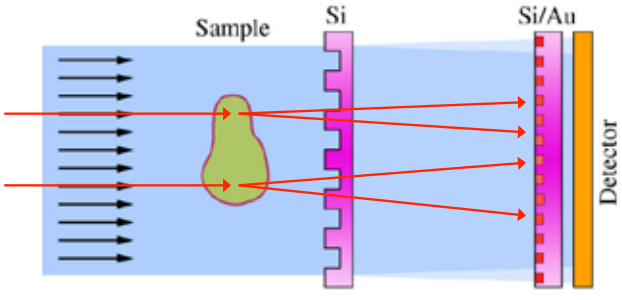
19

New material parameter: Linear diffusion coefficient

$$A(x) = \frac{1}{\sigma d\sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma^2 d^2}\right)$$

$$I^s(x) = I^r(x) \otimes A(x)$$

$$V \equiv \frac{V^s}{V^r} = \exp\left(\frac{-2\pi^2}{p^2}\sigma^2 d^2\right)$$



$$\sigma^2 = \int \epsilon(y)dy \qquad V(x) = \exp\left(\frac{-2\pi^2 d^2}{p^2}\int \epsilon(x,y)dy\right)$$

M. Bech et al, Phys. Med. Biol. 55, 5529 (2010)

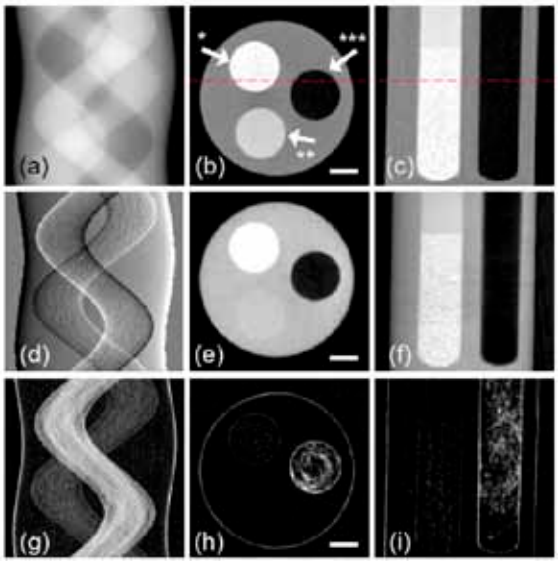
20

From 2D to 3D: Quantitative Phase-Contrast CT

Attenuation CT

Phase CT

Darkfield CT



Bech et al
PMB | 2010

Synchrotron radiation

At the Synchrotron Radiation Source

- Two gratings
- Holography / Holo-tomography possible

- Synchrotron radiation source
- Pros:
  - High Brilliance (high flux in narrow band)
  - Good coherence

- Cons:
  - Limited access
  - Limited field of view

23

ESRF ID-19

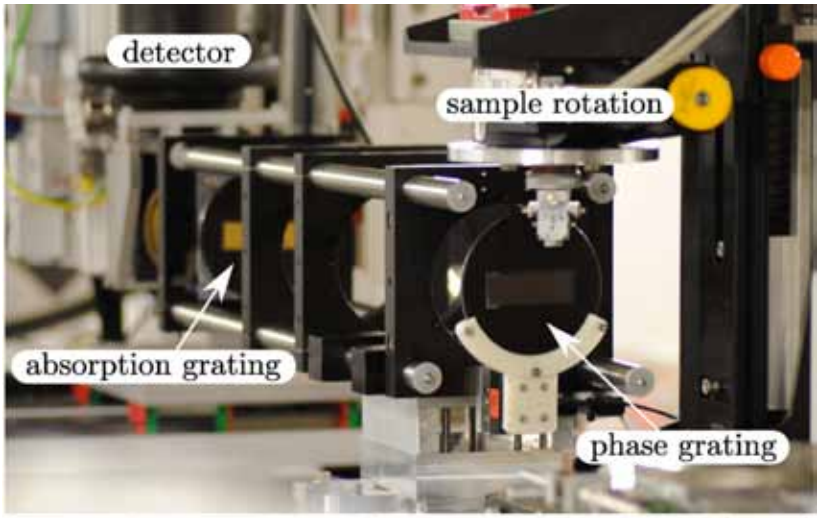
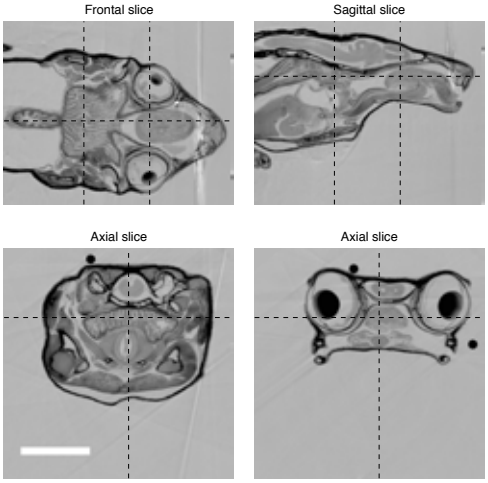


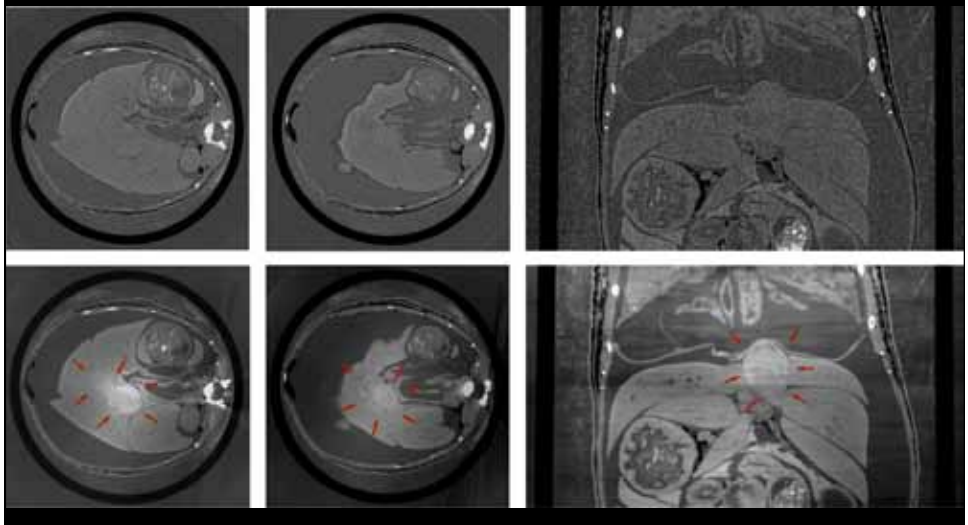
Figure courtesy: Irene Zanette, Arne Tapfer

Synchrotron, ESRF ID19, 2006

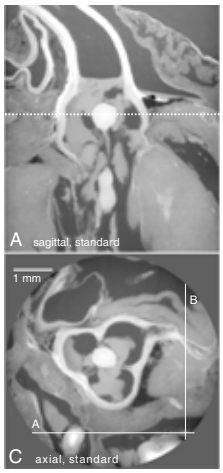


Christian David
Franz Pfeiffer
Christian Kottler
Peter Cloetens

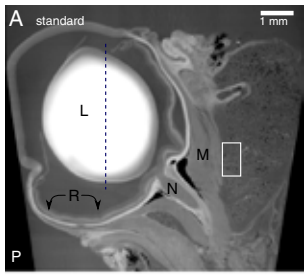
25

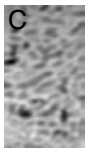


High resolution soft tissue imaging



Rat heart





Rat eye

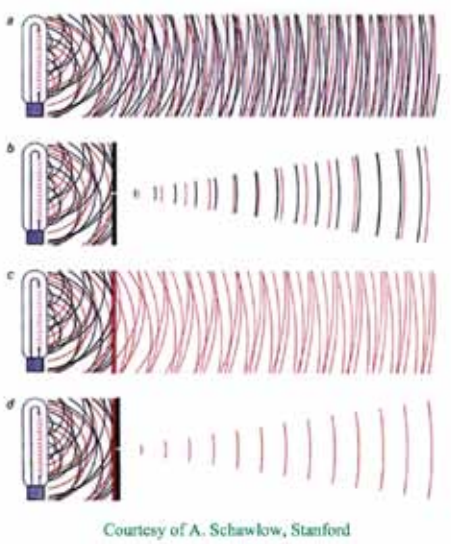
Zanette, Bech et al. 2012, PNAS

In the Laboratory

- Three gratings

- Traditional x-ray tube source
- Pros:
  - Large field of view
  - Cheap
  - Convenient
- Cons:
  - Low flux
  - Polychromatic
  - Poor coherence

Coherence



Three Grating principle

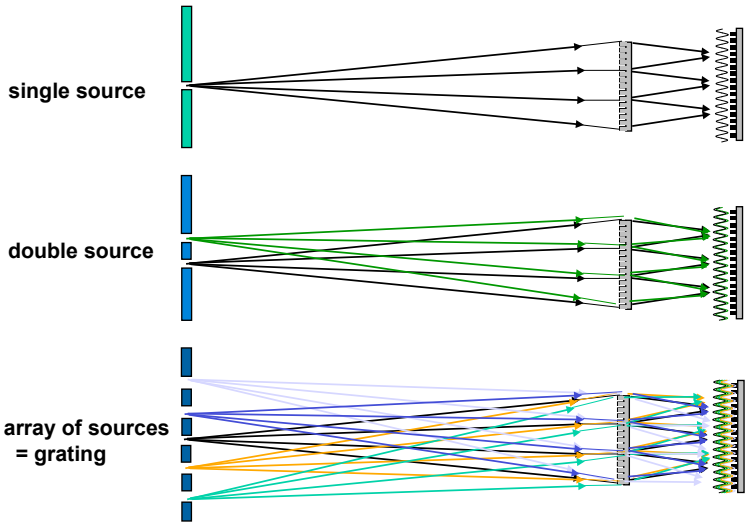
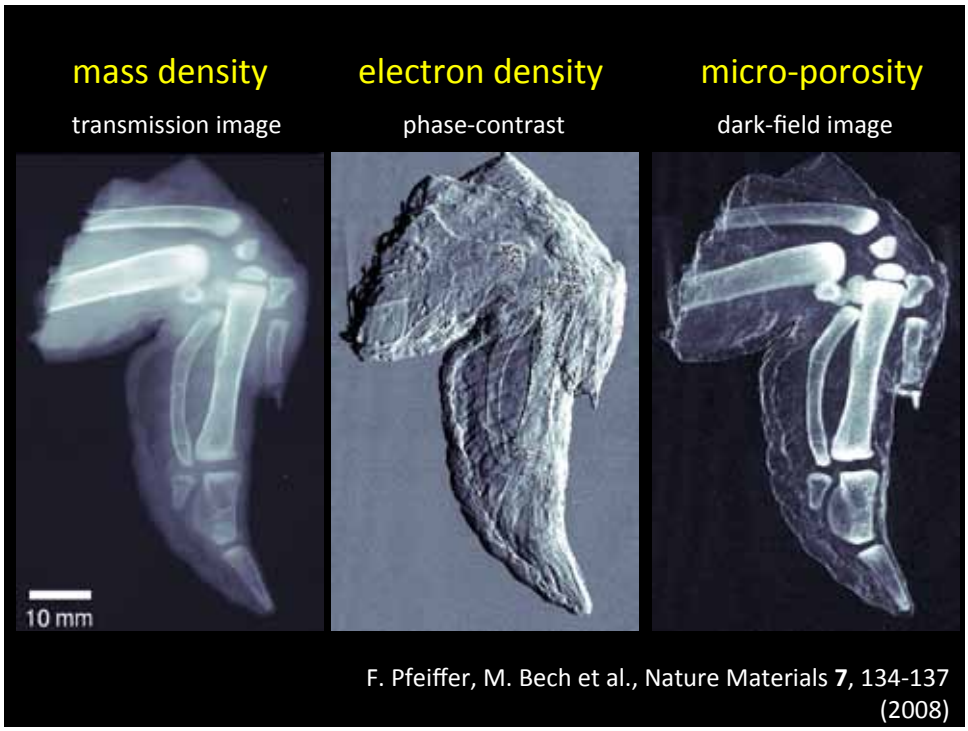


Figure courtesy: C. David, PSI



Phase Contrast micro-CT

SKYSCAN
now Bruker µCT

32

Requirements for in-vivo experiments

- Rotating gantry around small animal
  - Stable both in rotation as for the alignment of the gratings
  - Compact design
- Acceptable radiation dose for repetitive studies
- Fast – to limit time of anesthesia of the animal

33

Skyscan 1190, GBI phase-contrast scanner

34

1190 phase scanner gantry

Setup in Rotating Gantry

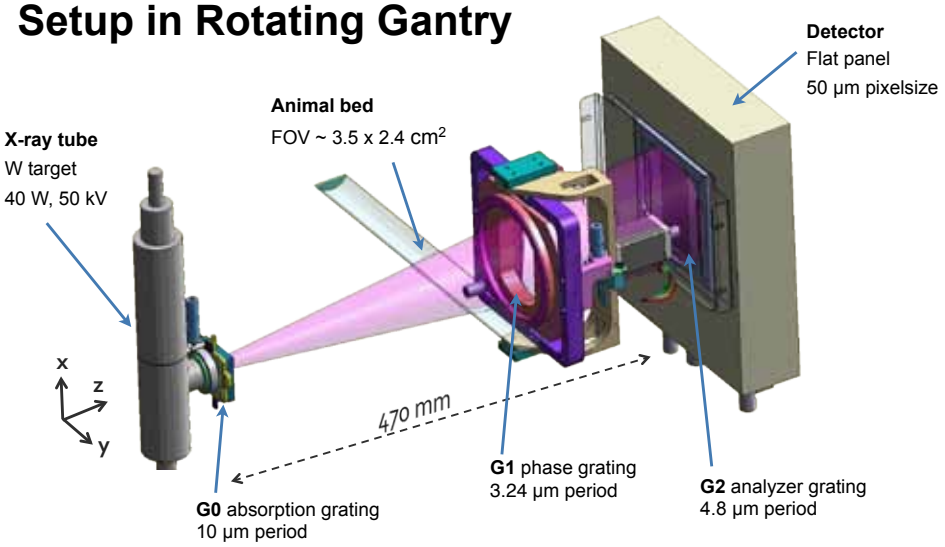


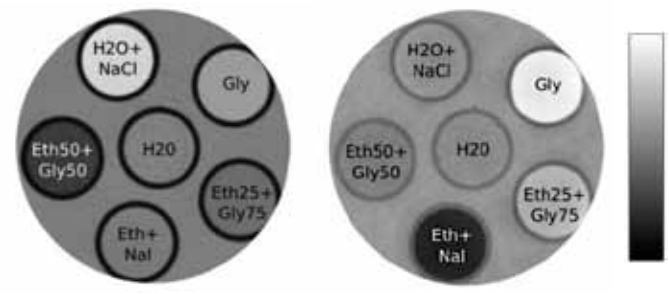
Image courtesy: Bart Pawels, Skyscan

35

Complementarity of information

'conventional'
Hounsfield Units

'phase-contrast'
Hounsfield Units

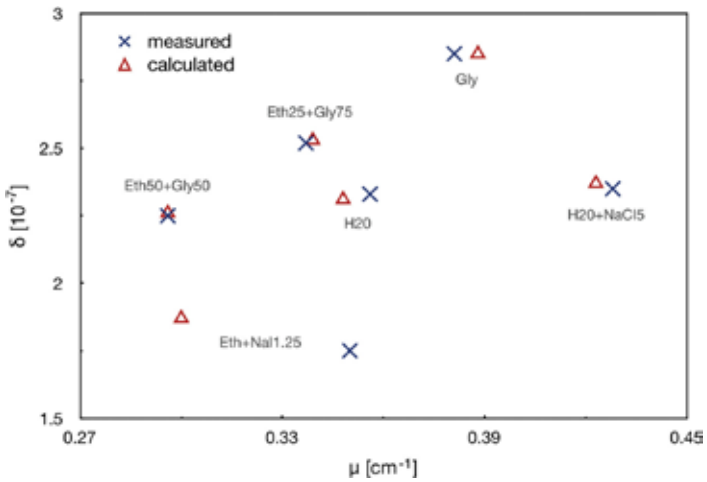


$$\frac{\mu - \mu_{water}}{\mu_{water} - \mu_{air}} \qquad \frac{\delta - \delta_{water}}{\delta_{water} - \delta_{air}}$$

Tapfer et al | Med Phys | 2011 & Tapfer et al | PNAS | 2012

Quantitative results

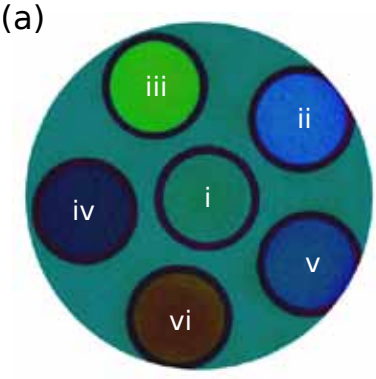
Complex index of refraction
$n = 1 - \delta + i\beta$



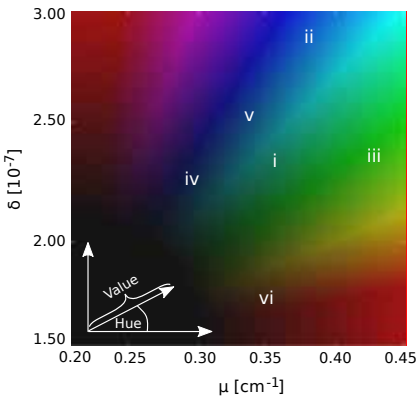
A. Tapfer *et al.*, Medical Physics 38 (11) 2011, 5910-5915

Quantitative results

(a)

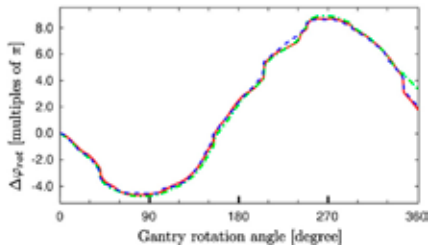


(b)

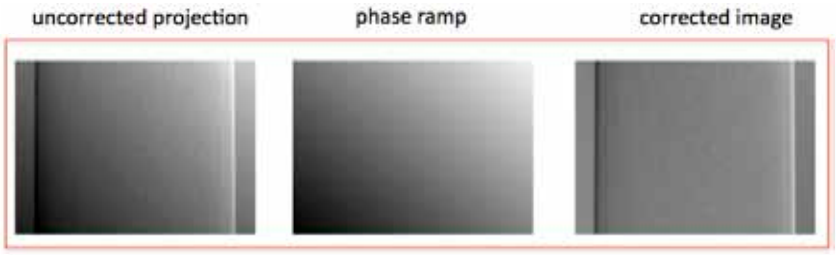


A. Tapfer *et al.*, Medical Physics 38 (11) 2011, 5910-5915

Effect of gantry rotation on phase stability

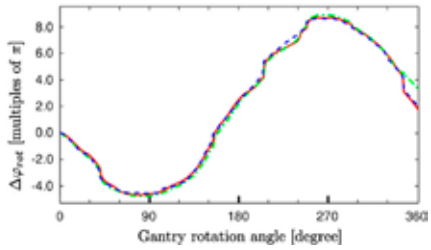


Measured interferometer phase shift upon gantry rotation (3x)

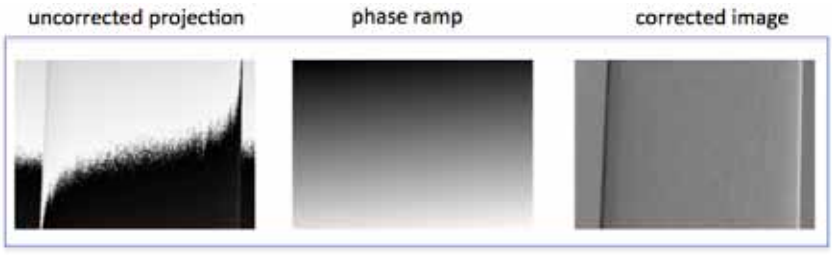


Tapfer et al | PNAS | 2012

Effect of gantry rotation on phase stability

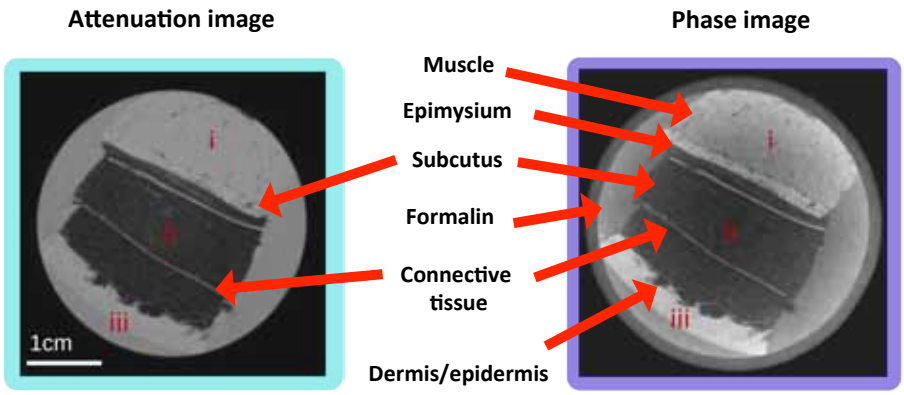


Measured interferometer phase shift upon gantry rotation (3x)



Tapfer et al | PNAS | 2012

Formalin fixated porc

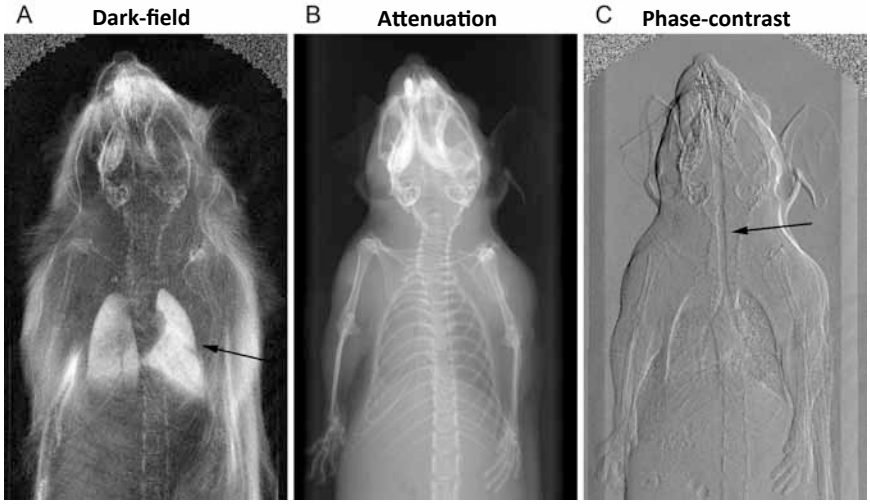


40 kV/750 µA
rot. step of 0.24°
8 phasesteps

41

Medical imaging

Mouse, in-vivo



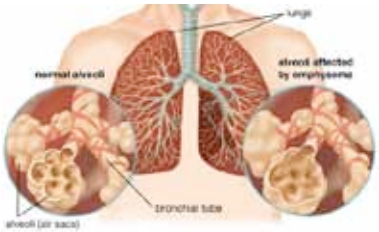
Bech et al. Scientific Reports, accepted 2013

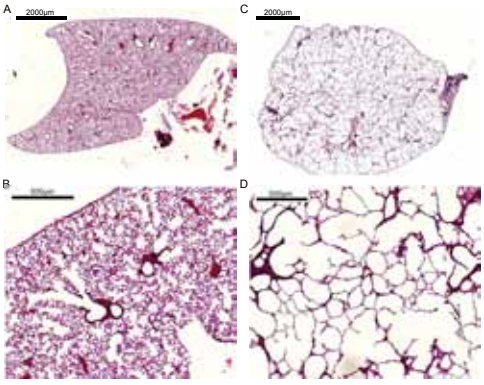
Dark-field imaging for lung emphysema diagnostics

S. Schleede, A. Yaroshenko, A. Malecki, M. Bech, J. Herzen, K. Achterhold, F. Pfeiffer
Technical University Munich, Germany
F. Meinel, S. Adam-Neumaird, S. Thieme, F. Bamberg, K. Nikolaou, M. Reiser
Radiology Department, Ludwig Maximilians University Munich, Germany
A.Ö. Yildirim, A. Bohle, O. Eickelberg
Helmholtz Center for Health, Munich, Germany

Lung imaging

Chronic Obstructive Pulmonary Disease (COPD)

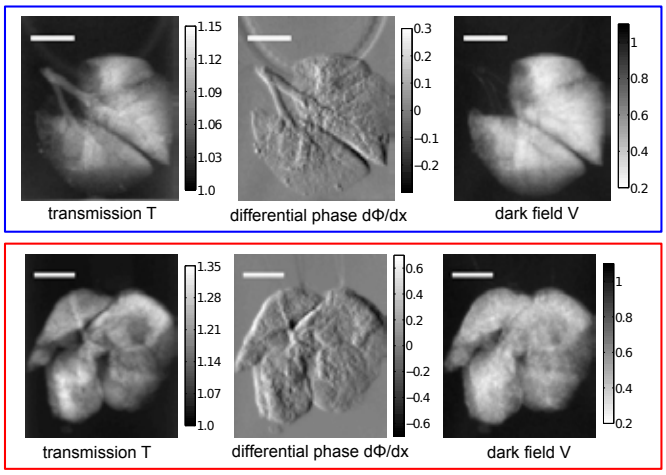




pulmonary emphysema: mouse model

Medical imaging

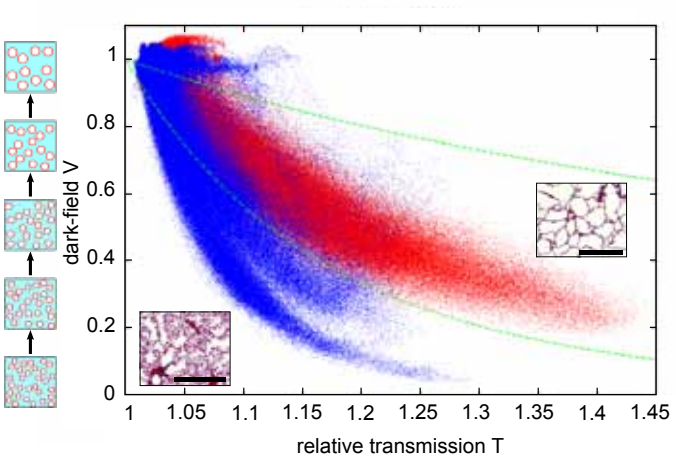
Emphysema lung, Synchrotron radiation



Schleede, Meinel, Bech et al. 2012. PNAS

Medical imaging

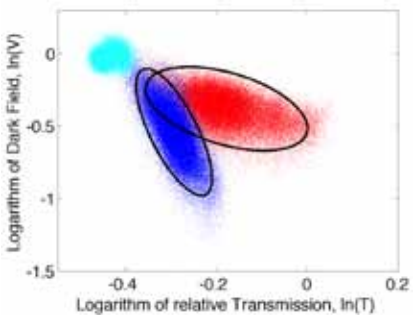
Emphysema lung, Synchrotron radiation

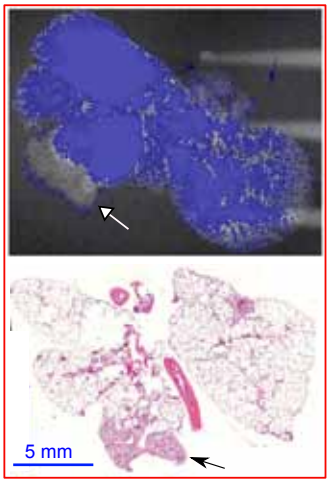


Schleede, Meinel, Bech et al. 2012. PNAS

Medical imaging

Emphysema lung, X-ray tube

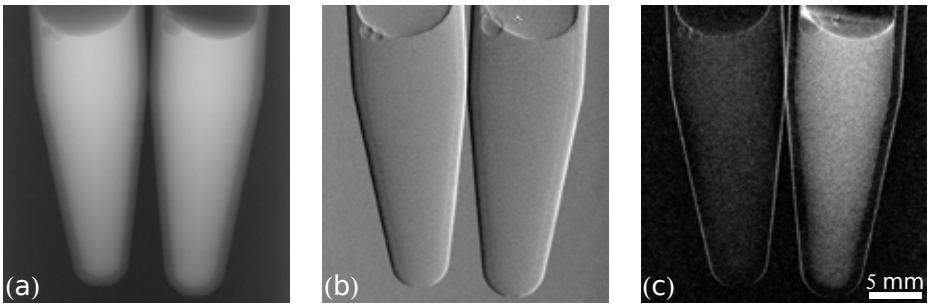




Yaroshenko, Meinel, Bech et al. Radiology 2013

Dark-field contrast - contrast agents

Optison microbubbles



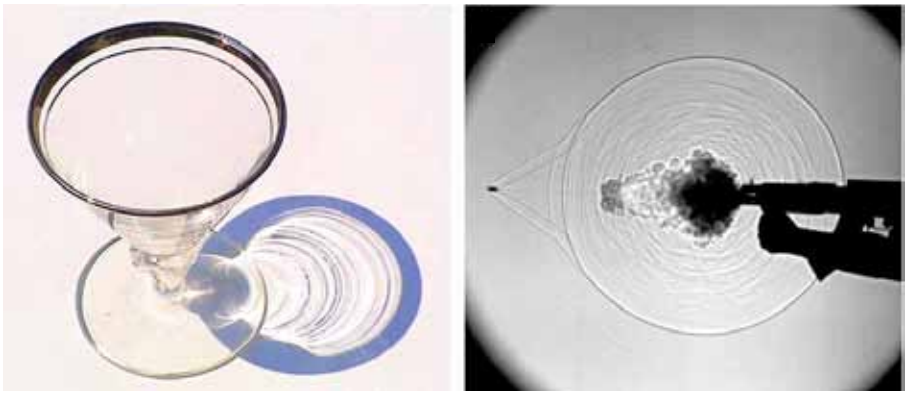
Absorption contrast | Differential phase contrast | Dark-field contrast

Scan parameters: 30 kVp, 10 phase steps, 10 sec exposure time

Velroyen, Bech et al. Physics in Medicine and Biology 2013

Thank you for your attention

Shadowgraph



Wikipedia: (images by Gary S. Settles, Penn State Gas Dynamics Lab)

49

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