# Review of X-ray Detectors for Medical Imaging

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Innovations – Future Concepts
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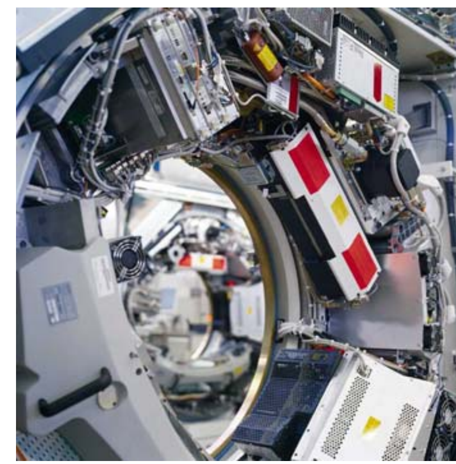
# Outline


Ms. Röntgen's hand (1895)



8 History of X-ray imaging

8 The medical point of view

- 7 Different imaging modalities depending on application

8 The physical point of view

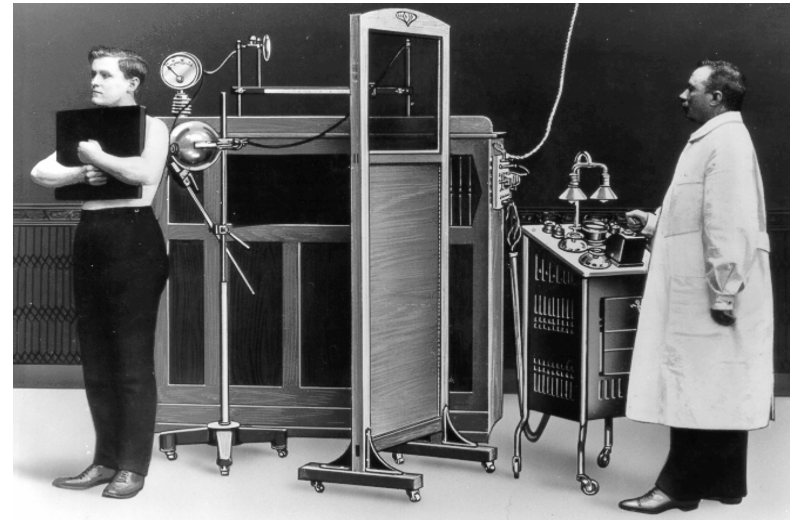
- 7 Radiation detectors (excluding ultrasound and magnetic resonance)

8 New concepts

- 7 New detectors
- 7 New sources
- 7 New energies
- 7 New methods

# History

8 X-ray detectors started with film, screen, and film/screen systems (screen = scintillator)



Ms. Röntgen's hand with ring
(first image, Dec. 22, 1895)

Erlangen, Gynaecological Hospital
(1918)

# History

- X-ray detectors started with film, screen, and film/screen systems (screen = scintillator)
- X-ray radiography became digital with storage phosphor systems (“Computed Radiography”)

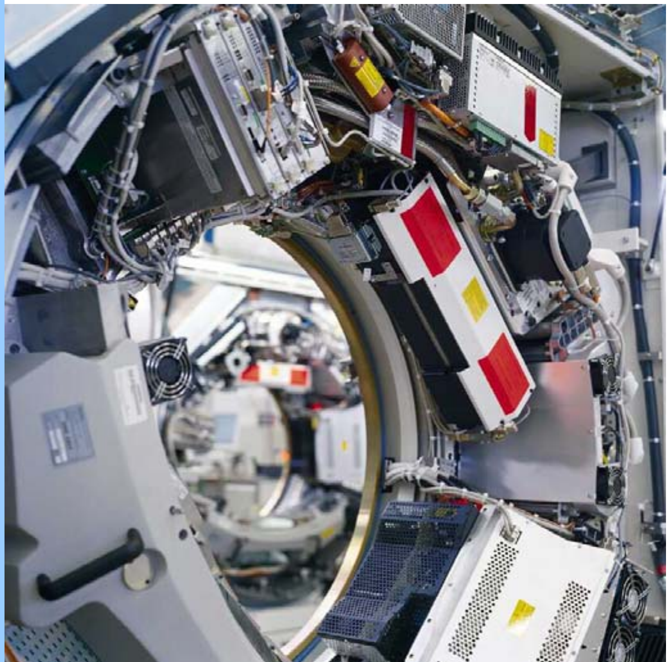
- X-ray fluoroscopy is performed with X-ray image intensifier TV systems

- State-of-the-art X-ray imaging is done with flat-panel detectors

# Different points of view

8 The medical point of view

- 7 **Application-driven**
- 7 Diagnosis or intervention ?
- 7 Morphological or functional imaging ?
- 7 Parameter requirements (size, speed, spatial and contrast resolution ...)
- 7 Workflow



8 The physical point of view

- 7 **Technology-driven**
- 7 Wavelength (X-rays, gamma rays, visible light, NIR, Terahertz ...) ?
- 7 Feasibility determined by available sources, materials, electronics, computing power ...

8 And the economical point of view ...

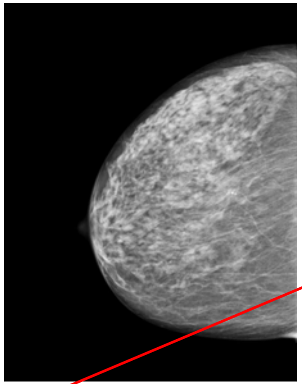
# The medical point of view

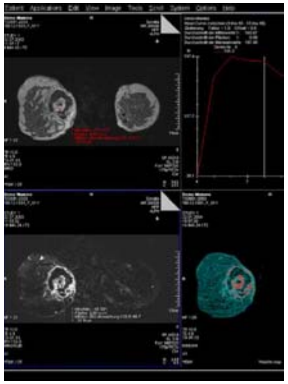
- Morphology and function
  - Morphology: bones, tissue, vessels ...
  - Function: perfusion, flow rate, diffusion, oxygen concentration, metabolism, receptor affinity for specific molecules ...
  - Image fusion
- Projection and reconstruction imaging
  - Projection yields 2-dimensional images
  - Reconstruction of a set of 2D images provides a 3D data set
- Screening, diagnosis, and interventions
  - Screening performed on presumably healthy persons
  - Diagnostic imaging if patient is suspected of having a disease
  - Image-guided interventions facilitate precise therapy

# Examples



- Hand examination
  - Bones (high contrast)
  - Vessels visible with contrast agent by Digital Subtraction Angiography (DSA)

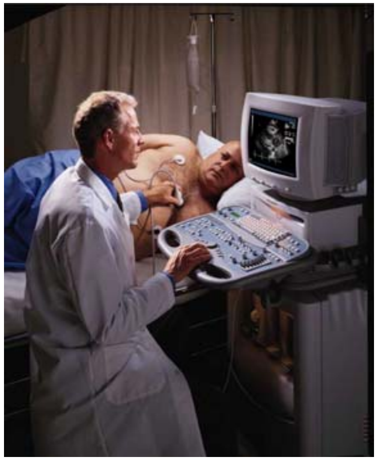



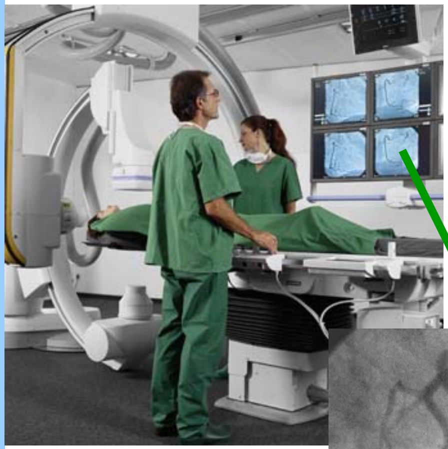



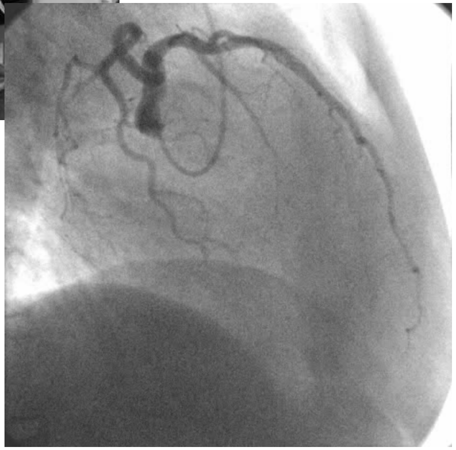
- Breast cancer
  - Mammography with specific geometry (e.g. compression, oblique view)
  - High spatial resolution, zooming
  - Computer-Aided Diagnosis (CAD) contributes a second opinion
  - Additional methods (e.g. ultrasound, MRI, optical tomography)

# More examples (2)

- Cardiac disorder
  - ECG-triggered CT scan
  - Ultrasound examination
  - Catheter examination using iodine-based contrast agent

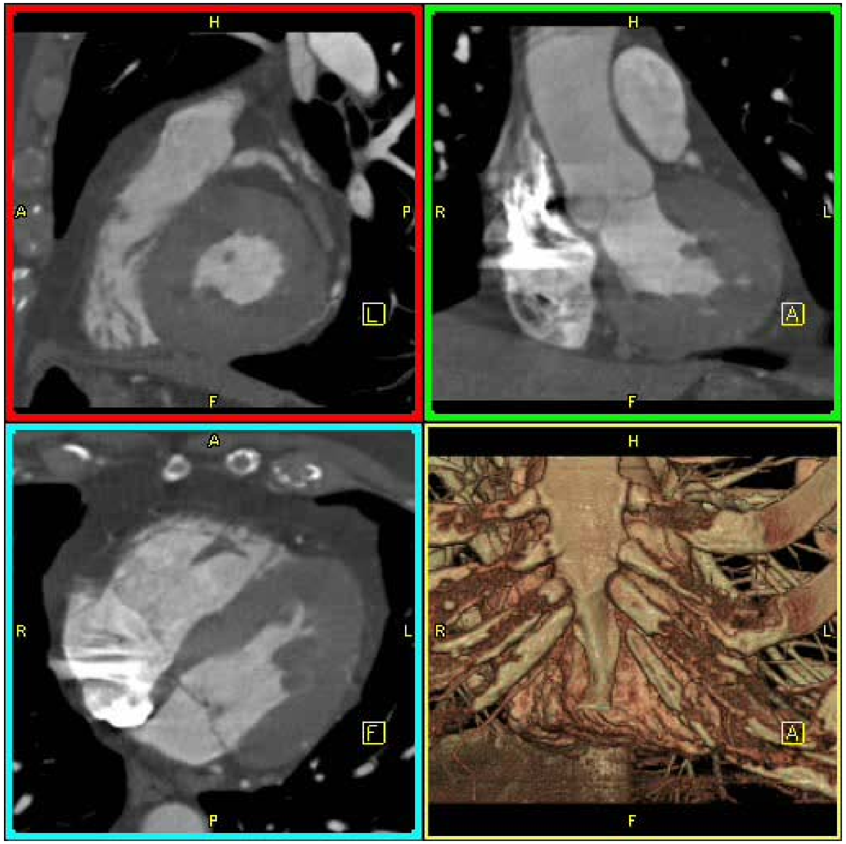






Stenosis?

Plaque?



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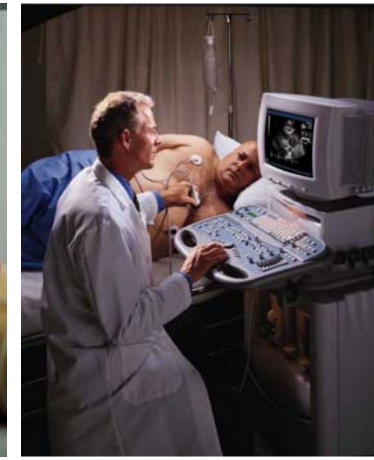
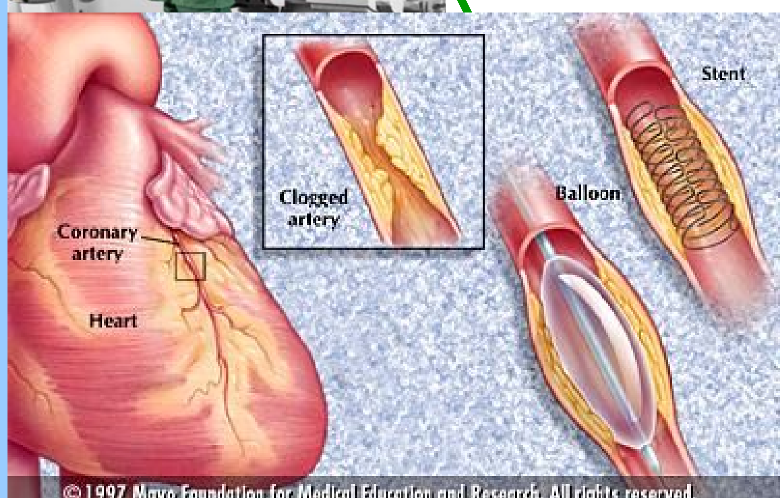
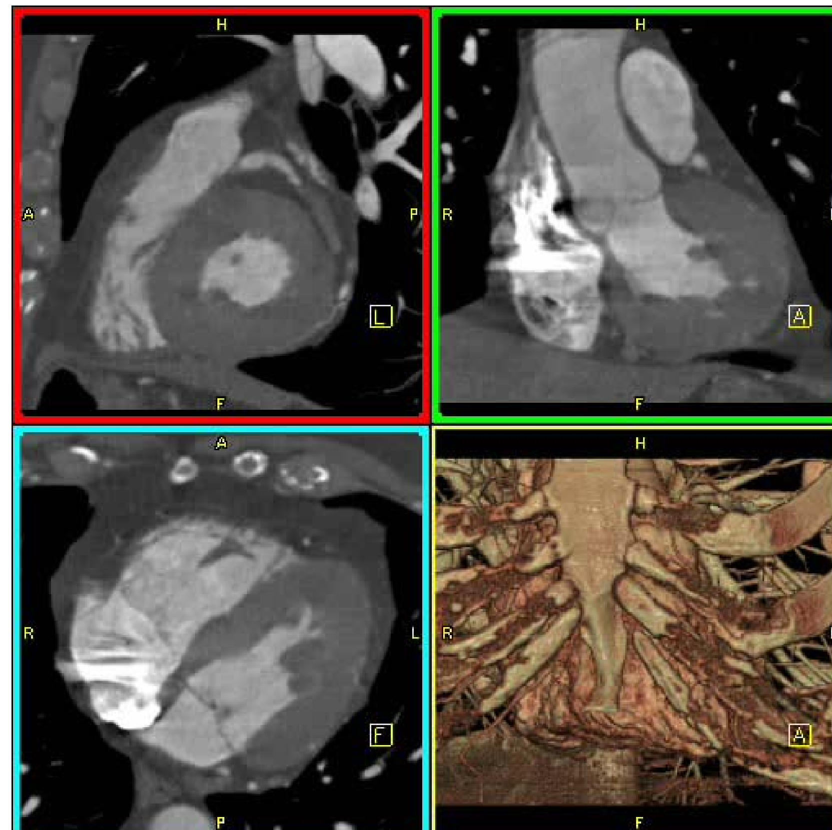


Stenosis?
Plaque?

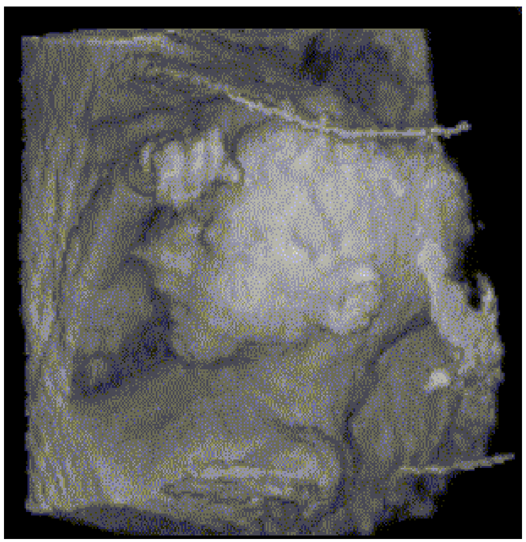


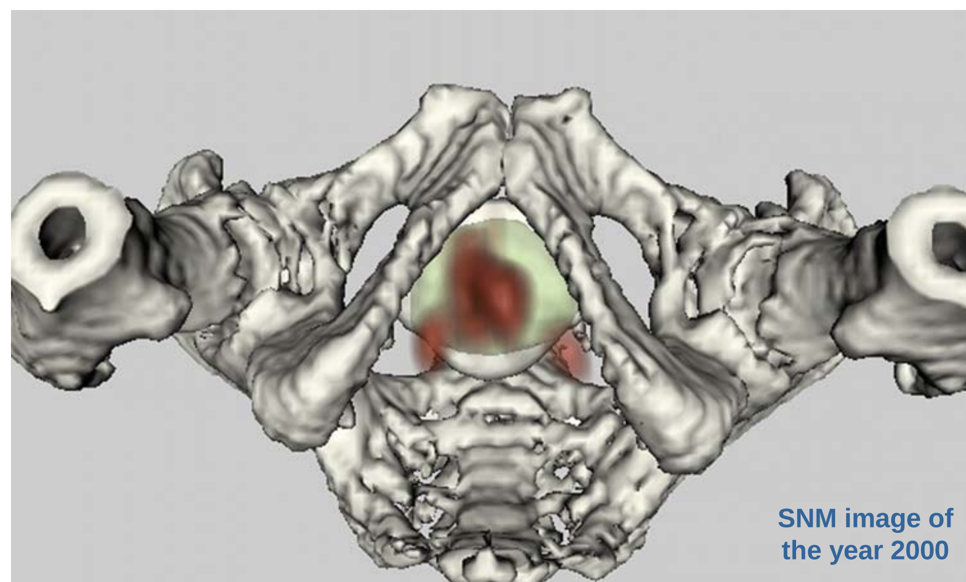
- 7 Balloon dilatation
- 7 Stent placement

# More examples (3)

- Pregnancy monitoring with ultrasound
  - Important to avoid ionizing radiation
  - Panoramic ultrasound gives overview
  - 3D ultrasound shows many details

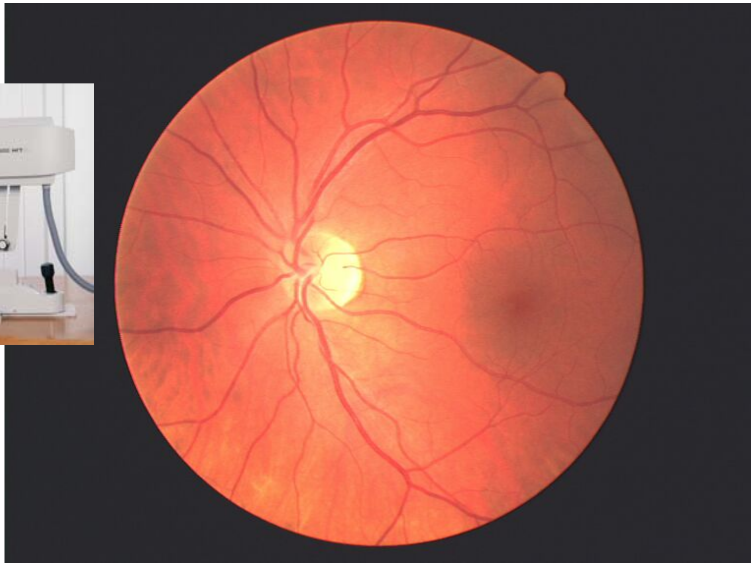


- Prostate cancer
  - Bones (CT)
  - Prostate (MR)
  - Cancer (SPECT)
  - **Image fusion**

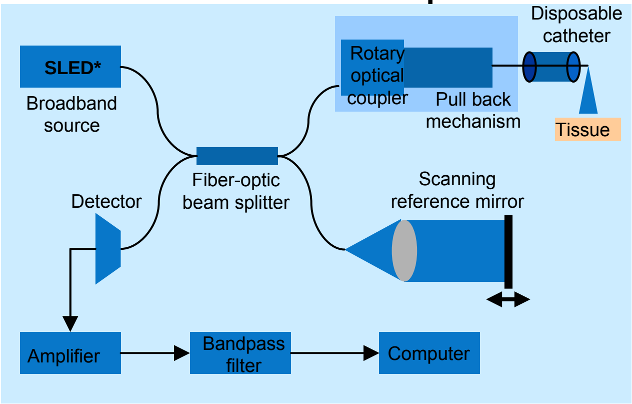


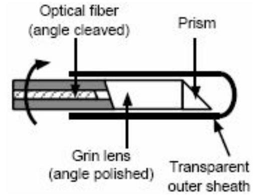

By Dr. D. Bruce Sodee and Dr. Zhenghong Lee,University Hospitals of Cleveland / Case Western Reserve Univ.
The image uses (111In)MoAb 7e 11.C5.(ProstaScint™).

# More examples (4)



- Imaging of the retina
  - The only way to examine veins directly
  - Prediction of vascular diseases, e.g. stroke, diabetes
  - Tele-ophthalmology
- Optical Coherence Tomography (OCT)
  - Examination of vessels
  - Lesion pathology (visualization of coronary vulnerable plaques, calcifications)
  - Check stent placement



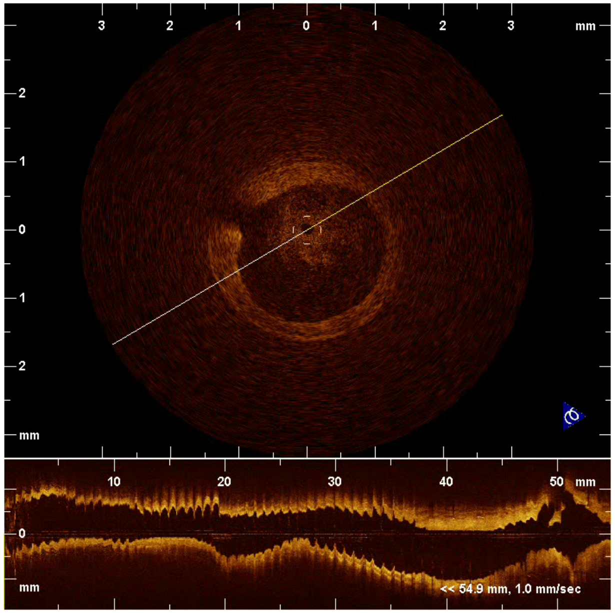
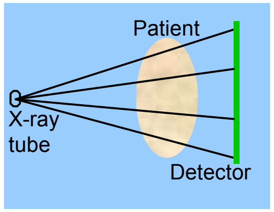



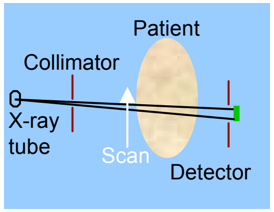

Image courtesy of Prof. Reiser, Klinikum Großhadern, München, Germany

# Different medical X-ray imaging techniques

- Full-field imaging
  - Detector size = patient region of interest x magnification factor
  - X-ray exposure time = duration of X-ray tube emission

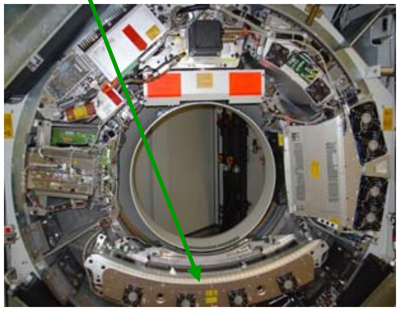



- Scanning imaging
  - Linear line detector (one pixel wide)
    - Extremely narrow collimator not feasible in the majority of cases
  - Slot detector (several pixels wide)
    - Requires Time-Delay and Integration (TDI) technique
  - Collimator restricts beam to detector width
    - Radiation loss due to penumbra effect (limited focus size)
  - X-ray exposure time = scan time
    - Long scan time leads to motion artifacts
  - High tube load may cause problems
    - Current X-ray tubes operate close to their technological (thermal) limit
  - Precise mechanical setup necessary



# Requirements for medical X-ray detectors

- Size
  - Radiography — 43 cm x 43 cm
  - Angiography — 30 cm x 40 cm
  - Full field mammography — 24 cm x 30 cm
  - Cardiology — 20 cm x 20 cm
  - Mammography biopsy — 5 cm x 9 cm
  - Computed tomography — 4 cm x 70 cm (curved)



- Frame rate
  - Computed tomography — 2000 – 6000 $s^{-1}$
  - Fluoroscopy, cardiology — 15 – 60 $s^{-1}$
  - Angiography — 2 – 30 $s^{-1}$
  - Radiography, mammography — 0.05 – 2 $s^{-1}$
- Spatial resolution (pixel size)
  - Computed tomography — 1 $mm^{-1}$ (1 mm)
  - Soft tissue — 1 – 2 $mm^{-1}$ (400 – 150 µm)
  - Bones — 3 – 4 $mm^{-1}$ (165 – 125 µm)
  - Mammography, dental — 5 – 20 $mm^{-1}$ (100 – 25 µm)

# The physical point of view

8 Imaging needs ...

7 ... a radiation source,

- spectrum (monoenergetic, energy range)
- spatial extent, coherence

7 ... interaction with the object to be imaged,

- absorption (energy dependent)
- reflection, scattering, diffraction, refraction
- interaction differences of details of interest result in **contrast**

7 ... registration of the radiation carrying information about the object,

- interaction (e.g. absorption)
- conversion into an electrical signal
- **integrating** detection or **counting** detection

7 ... and signal processing

- corrections, enhancement, storage, display

# Example: imaging by (e.g. X-ray) absorption

- Select appropriate energy or spectrum
  - Absorption too high → reduced signal in detector
  - Absorption too low → reduced object contrast
  - Optimum energy for maximum contrast (depends on object)
  - Typical energies:
    - Mammography 17 … 25 keV
    - Radiography 40 … 60 keV
    - Computed tomography 60 … 70 keV
    - Angiography 33 keV (K edge of iodine)
  - Choose anode material, tube voltage, filter material and thickness
    - Monochromatic radiation has in most cases only minor advantages
- Additional factors influencing image quality
  - Focus size
  - Scattered radiation (remedy: anti scatter grid)
  - Detector properties (e.g. MTF, DQE, image lag)

# Example: imaging by X-ray absorption

8 Source

7 X-ray tube with W anode (Mo and Rh also used for mammography)

7 Filters (Al, Cu, Mo, Rh) to cut off low-energy part of spectrum

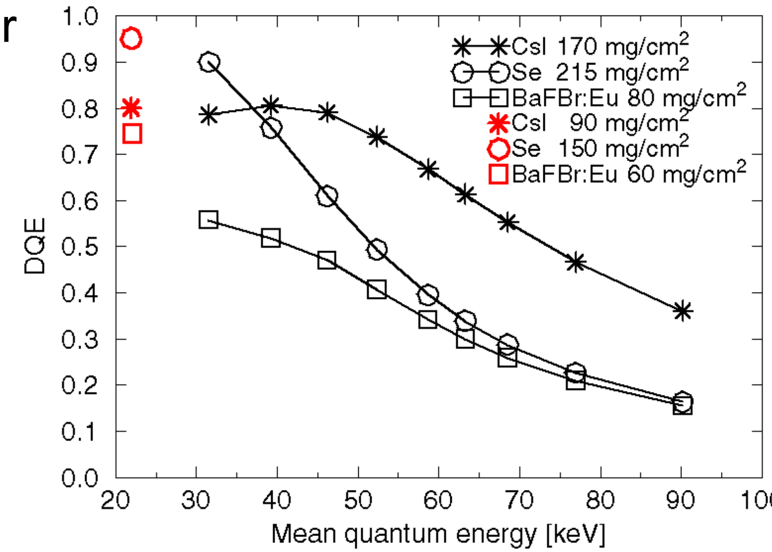
8 Detector

7 Flat-panel Detector (FD) with a-Si readout matrix

7 Directly converting a-Se layer for low energies (mammography)

7 Evaporated CsI scintillator on a-Si photodiodes for higher energies

7 Fast ceramic $Gd_2O_2S$ scintillator with c-Si photodiodes for CT




8 … and

7 Anti scatter grid

7 Collimator for CT detectors

7 Signal processing and ADC 12 – 16 bit (18 – 20 bit for CT)

# Nuclear medicine, an alternative principle

- Determination of source distribution
  - No external radiation used to scan the object as in X-ray imaging
- PET = Positron Emission Tomography
- SPECT = Single Particle Emission Computed Tomography
  - Injection or oral administration of tracers with radioactive isotopes
  - Await distribution and accumulation in region of interest, e.g. tumor
  - Mapping of emitted radiation by collimator (SPECT) or coincidence using two detectors (PET)
  - 2D or 3D iterative reconstruction, filtered back projection, attenuation correction
- Detectors use scintillators such as $BaF_2$, $Bi_4Ge_3O_{12}$ (BGO), $Lu_2SiO_5$ (LSO), or NaI coupled to photomultiplier tubes
- Alternative: Semiconductor detectors such as CdZnTe (CZT)

# New concepts

8 CCDs for very high spatial resolution

8 Organic semiconductors

8 Fast volume CT scanners

8 Energy-resolved methods

8 Quanta-counting detection

8 Monochromatic X-ray imaging

8 Phase contrast imaging

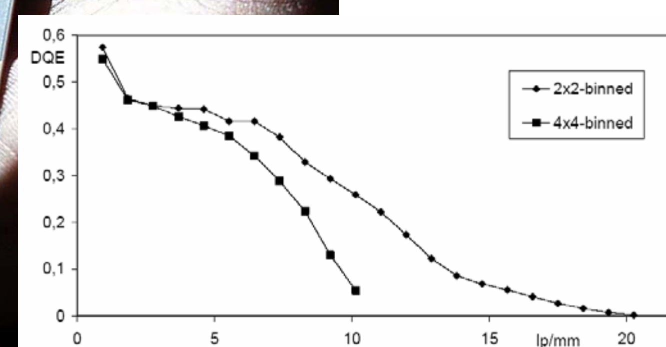
8 Terahertz imaging

# CCDs for very high spatial resolution

8 Flat-panel detectors based on a-Si read-out matrix
    7 Pixel size down to 70 µm

8 Very high spatial resolution required for mammography
    7 Pixel size 12 µm (binned to 24 µm or 48 µm)
    7 CCD with 4K x 7K matrix, total area 49 mm x 86 mm

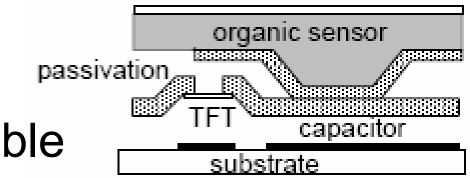

**Largest CCD in serial production in the world !**



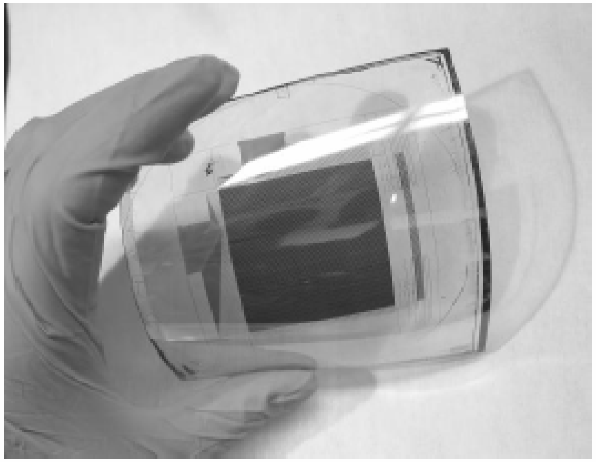
# Organic semiconductors

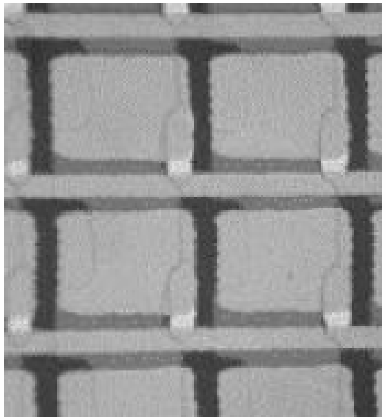
- Motivation

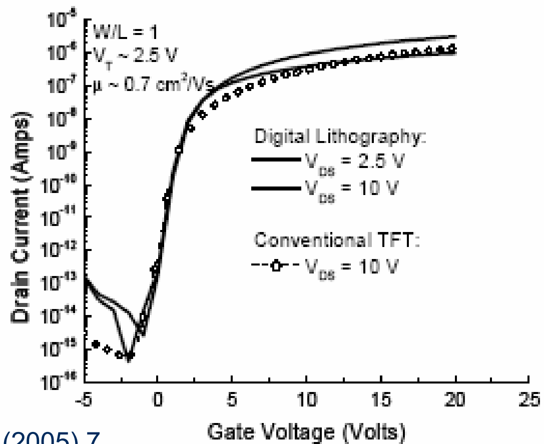
| Amorphous silicon | Organic semiconductors |
|---|---|
| Glass substrates | Plastic substrates |
| rigid, heavy, fragile | flexible, light-weight, unbreakable |
| Structured by photolithography | Structured by jet printing |
| High-temperature processing | Low-temperature processing |
| Expensive | Cheap |




- Result
  - Organic photodiodes and transistors are feasible



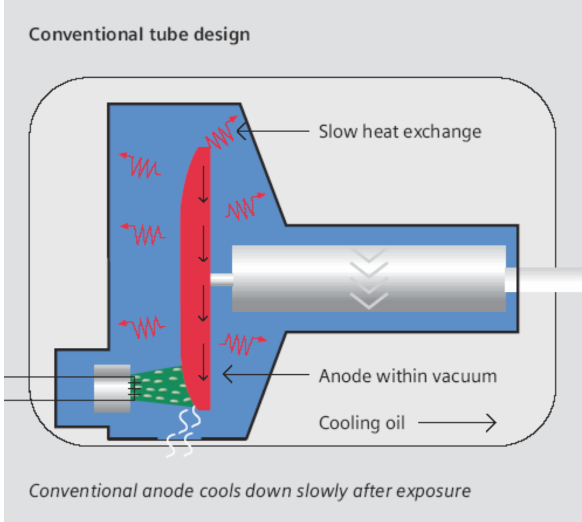




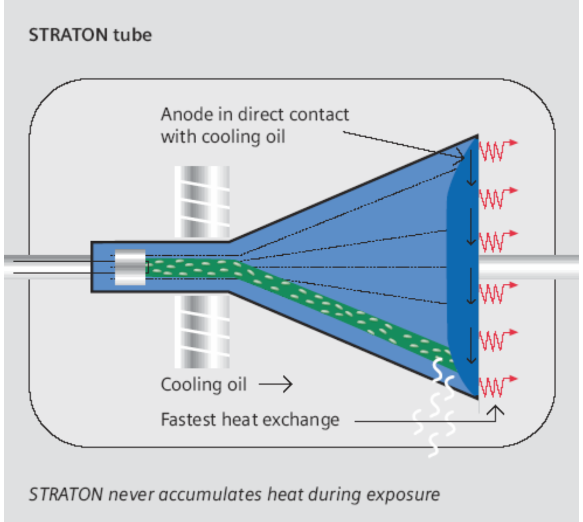

From Street et al., Proc. of SPIE 5745 (2005) 7

# Fast volume CT scanners

- Outstanding features
  - Can scan a whole body in 25 s
  - Can image a beating heart
- Technological highlights
  - Gantry rotation time 0.33 s
  - Multi-slice detector recording 64 slices per revolution
  - Ceramic $Gd_2O_2S$ scintillator with > 90% absorption for high DQE
  - Directly cooled X-ray tube (STRATON™) for high permanent load



Conventional anode cools down slowly after exposure



STRATON never accumulates heat during exposure

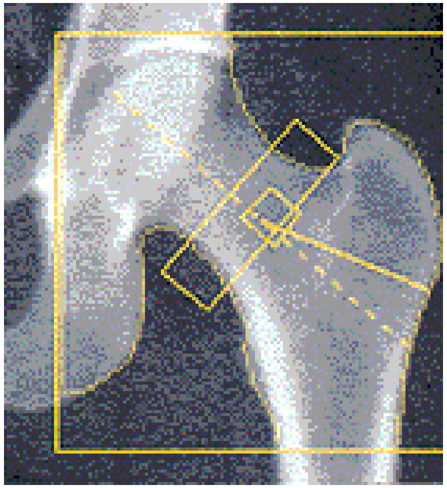
# Energy-Resolved Methods (ERM)

8 Situation at the outset
- 7 All conventional X-ray systems (film, storage phosphor, image intensifier, FD scintillator + photodiode, FD directly absorbing, CT) image the total absorption of an object
- 7 Different combinations of objects can produce equal absorption
- 7 ERM can differentiate between these different objects

8 Goal
- 7 Improve detectability of details
- 7 Improve signal difference-to-noise ratio (SDNR)
- 7 Discriminate different materials / different types of tissue
- 7 Enhance visibility of contrast media

8 Chance
- 7 Allow for dose reduction, maintaining image quality / SDNR
- 7 Save contrast media (patient stress, costs)

# Examples for ERM



8 Baggage inspection

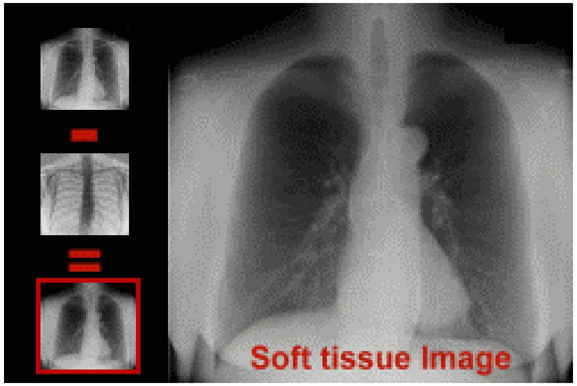
8 Automatic exposure control in mammography

8 Bone mineral density measurements by

  7 Dual-Energy X-ray Absorptiometry (DEXA)

  7 Dual-Photon Absorptiometry (DPA)

8 Discrimination of bones and soft tissue



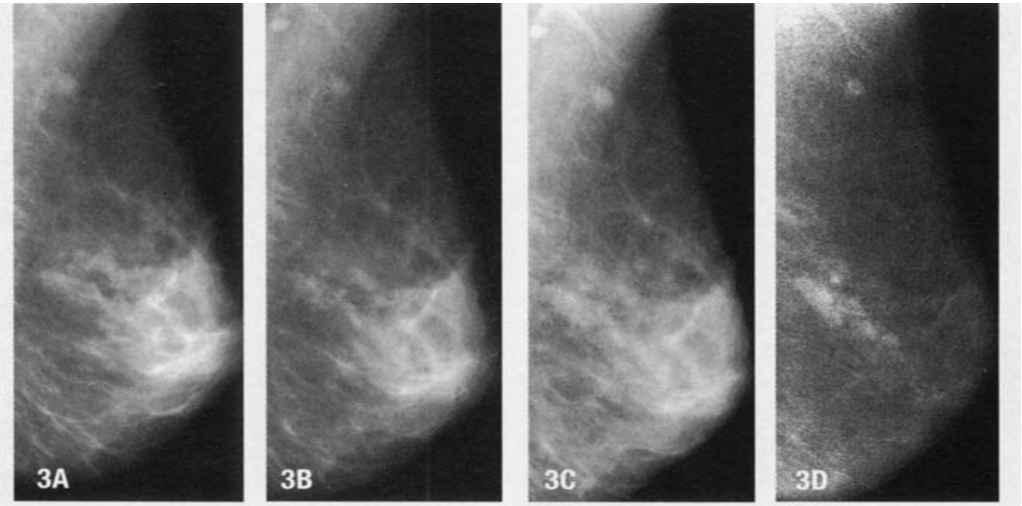



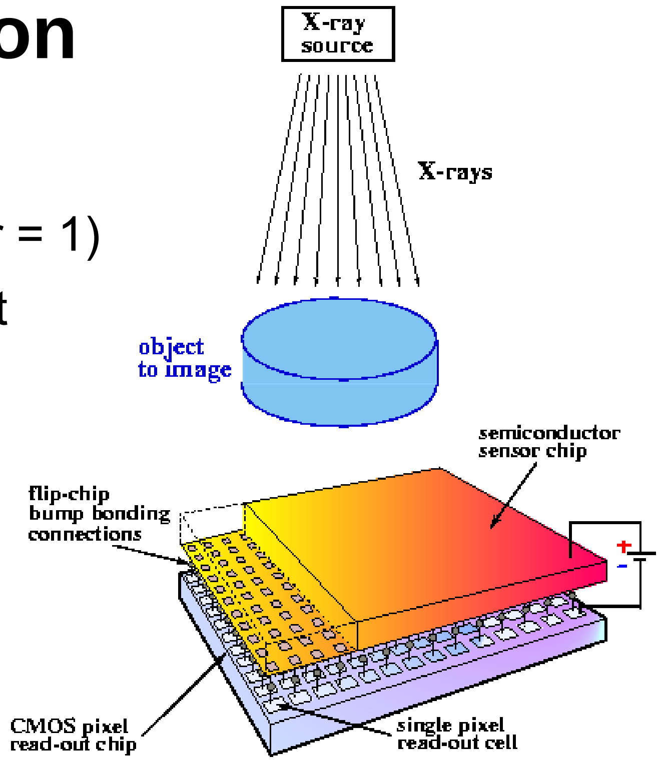

FIGURE 3. Nonpalpable invasive ductal carcinoma and ductal carcinoma in situ (DCIS). A: Precontrast digital mammogram shows calcifications of DCIS. B: Postcontrast low-energy mammogram. C: Postcontrast high-energy mammogram. D: Dual-energy contrast-enhanced digital subtraction mammogram. Enhancing masses corresponding to the invasive cancer are easily visible after subtraction but are not readily appreciated on the unsubtracted images, B and C.

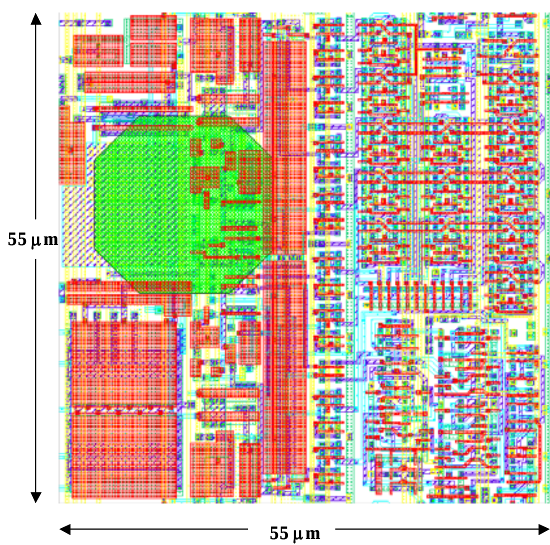
8 Dual-energy contrast-enhanced digital subtraction mammography

From J. M. Lewin (Denver, CO)

# Quanta-counting detection

- Advantages of counting
  - Higher DQE possible (Swank factor = 1)
  - No electronic noise, only zero effect and quantum statistics
  - No digitization necessary
  - Energy discrimination is feasible
- Advantages of integrating
  - High dose rates are easy to handle
  - Simple and cheap
- Medipix-2 chip 14 x 14 mm$^2$ with 256 x 256 pixels á 55 µm
- Semiconductor layer (Si, GaAs, CdZnTe, CdTe, $HgI_2$, InSb, TlBr, PbI) with high-Z as an absorber for good DQE
- Amplifier, discriminators and counters have to fit in pixel area



# Monochromatic X-ray imaging

8 Monochromator: bent HOPG (Highly Oriented Pyrolytic Graphite) directs radiation onto a slot

8 Slot system

8 Detector TDI-CCD Thales TH9570

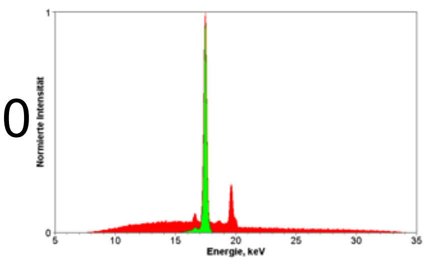
8 Scan time ≈ 4 s, 2 mAs per scan

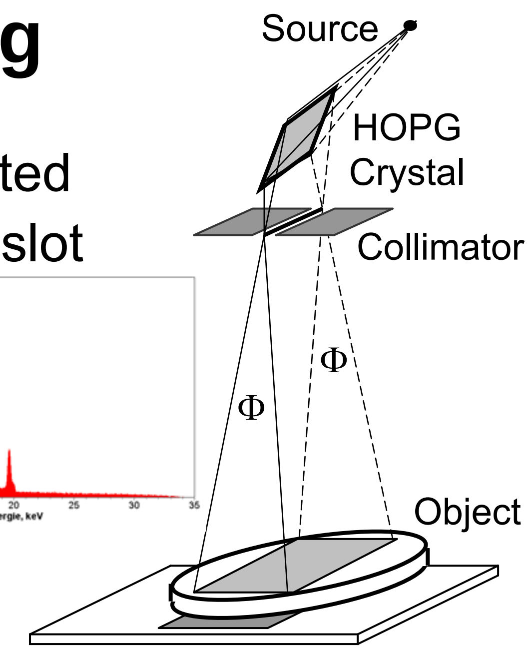
8 Advantages

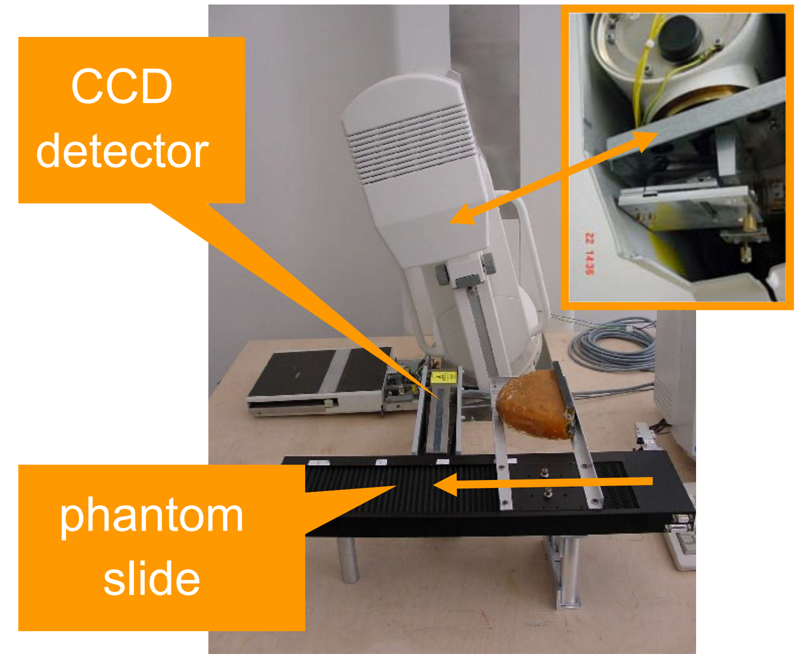
- 7 Cheap and easy to realize
- 7 Monochromatic spectrum with high energy resolution
- 7 Contrast enhancement

8 Challenges

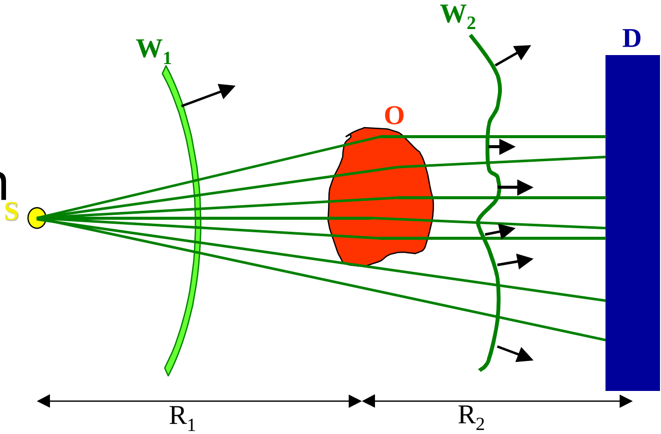
- 7 Slot system
- 7 High tube load, only small fraction of radiation hits slot
- 7 Long scan time
- 7 Multiple scans required



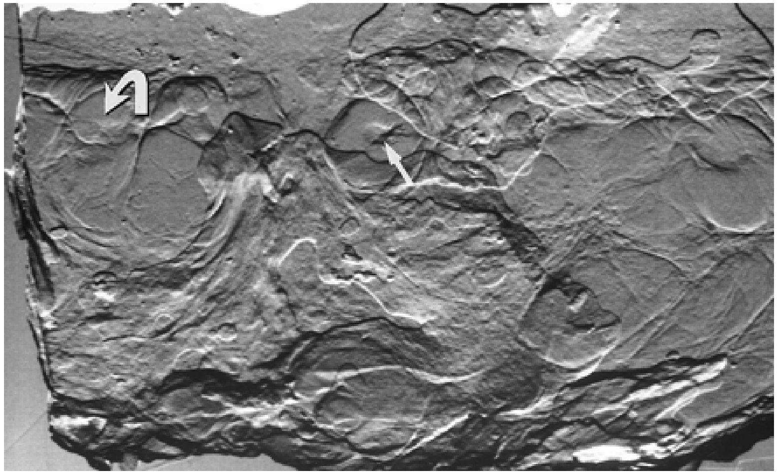



# Phase contrast imaging




- Phase differences allow discrimination of details which remain barely visible with conventional methods
  - Coherent radiation required
  - Synchrotron experiments have demonstrated the method
  - Micro-focus tube delivers sufficiently coherent radiation
  - Mammography tube (100 µm focus) also works at some distance



Digital radiogram (Fischer) Diffraction enhanced image taken at 18 keV

*In-vitro* infiltrating ductal carcinoma (E. Pisano et al., Radiology 214 (2000) 895)

# Phase contrast imaging, summary

8 Advantages

- 7 High contrast resolution → potential dose saving
- 7 High spatial resolution
- 7 Scatter suppression by crystals or large object-detector distance

8 Challenges

- 7 Synchrotrons are rarely available in clinical practice
  Coherent X-ray beams with “small“ tubes ?
  Intensity sufficient for fast imaging ?
- 7 Scanning systems need long exposure time
- 7 Image interpretation not established

8 Status

- 7 *In-vitro* experiments with breast tissue, cartilage etc.
- 7 Small animals
- 7 Proof of principle

# Terahertz imaging

- 1 THz = $10^{12}$ Hz
  - Frequency range 0.1 THz … 30 THz ( = FIR, far infrared)
  - Quantum energy range 0.4 meV … 120 meV
  - Wavelength range 3 mm … 10 µm
- Strong absorption in water
  - Only skin examination ( ≈ 1 mm)
- Sources are costly
  - Lasers, optical mixing
  - Photoconductive dipole antennas
- Applications
  - Dermatology, dentistry
  - Airport security (but THz waves will not penetrate a soaked coat)

# General trends in medical imaging

8 All images become **digital**

8 **3D** methods are gaining preference over 2D

8 **Combination** of different modalities

8 **Functional** imaging

7 Time-dependent, dynamic measurements

7 Aims at molecular methods

7 Quantitative methods

8 Imaging for **therapy**

7 Image-guided interventions and operations

7 Individual treatments

7 Therapy planning and virtual reality

8 **Connectivity**

7 Availability of images throughout the whole health care system

7 Tele-medicine

7 Electronic patient record

8 **Computer-Assisted Diagnosis** (CAD)

**Aims**

- better diagnosis
- targeted therapy
- cost optimization
- prevention

Siemens medical
Solutions that help