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Advances in Photon Counting Detectors in X-ray Imaging:

Photon Counting Detectors for Mammography

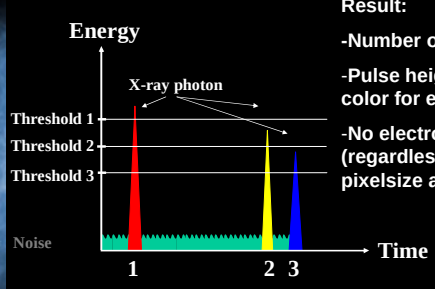
Mats Danielsson
Royal Institute of Technology
Stockholm, Sweden
md@mi.physics.kth.se

Disclosure statement:

-Founder Sectra Mamea
-Shareholder Sectra

Work in progress - FDA approval pending for all devices described in this presentation

To Count Photons – What does it mean?



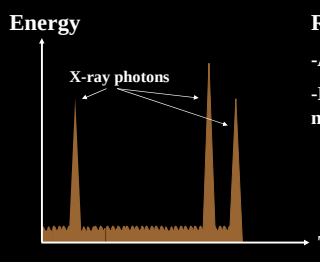
Result:

-Number of X-rays

-Pulse height give the color for each X-ray

-No electronic noise (regardless of pixelsize and dose!)

Integrating Current: Today's praxis in X-ray Imaging



Result:

-Area of

-Indirect estimate of number of photons

Mammography

- 100 M women examined every year
- Mortality in breast cancer reduced 30-50%
- Glandular tissue sensitive to radiation
- High requirements on spatial and contrast resolution
- Low kVp
- Relatively low count rate
- Object relatively still

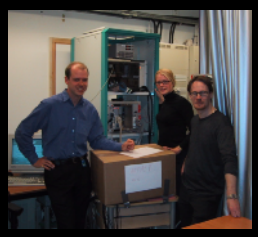
Photon Counting Mammography Today

Sectra – Silicon detectors
-200 systems in 15 countries

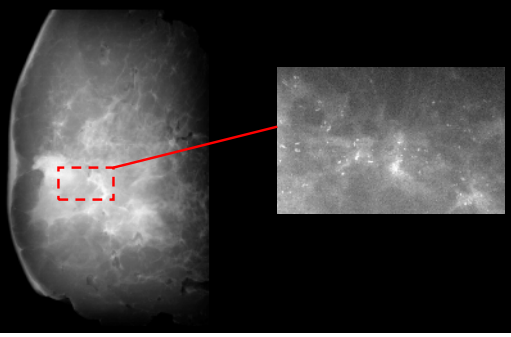
XCounter – Gas detectors
Research and development

Both are scanned-slit

In the basement Sectra mammography started 9 years ago..



First Image Jan 2001



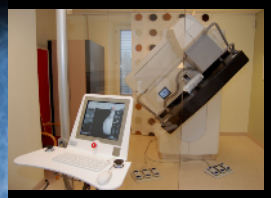
Sectra – Photon Counting Mammography Today

Development of Sectra Photon Counting Mammography

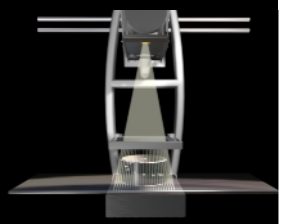
First model 2003 (D20)
"heavy and large"

Current model 2007(L30)
"light and slim"

XCounter Photon Counting Mammography with Gas Detector

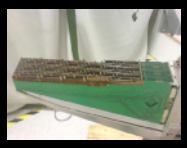


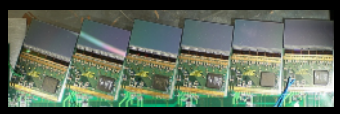
Prototype at Karolinska Sjukhuset, Stockholm



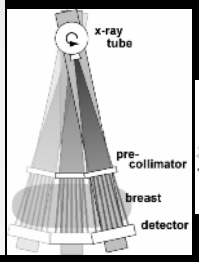
Outline of technology

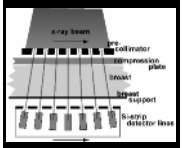
Crystalline Silicon Detector





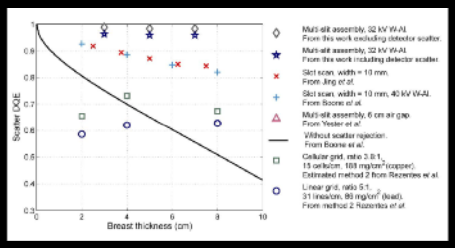
Sectra Photon Counting Mammography





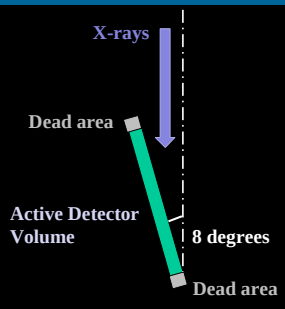
Scanned Slit – Efficient Scatter Rejection

Geometry for photon counting (diamonds) increases system DQE with 40% compared to typical grid

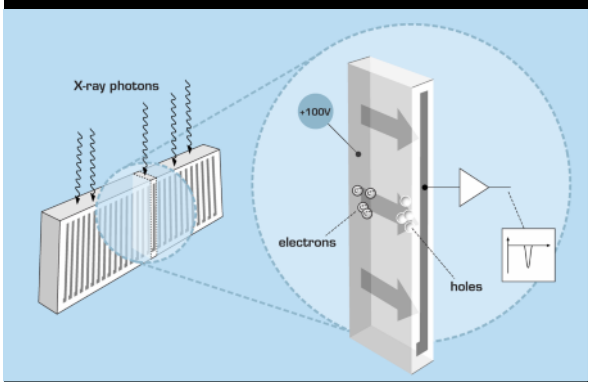


* M. Åslund et al. Med Phys, vol. 33, pp. 933-940, 2006

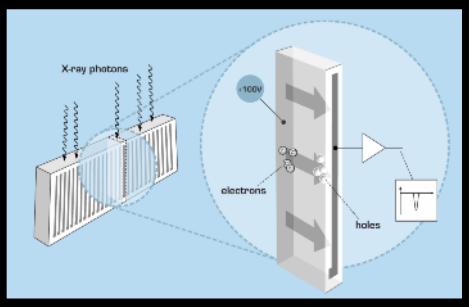
Sectra Silicon Detector Geometry



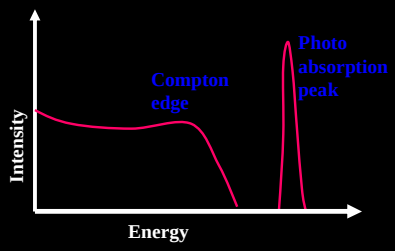
Silicon for Photon Counting



Silicon for Photon Counting

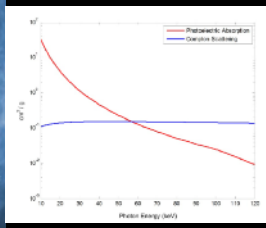


Detector Response to High Energy X-rays

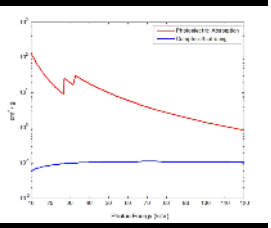


Cross sections for interaction

Silicon



CdZnTe



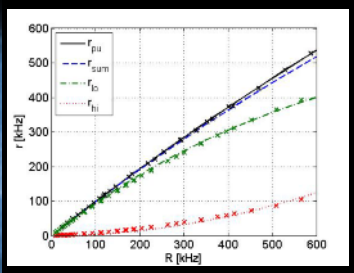
Summary of Crystalline Silicon Properties for Mammography

Mobility electrons	1350 cm^2/Vs
Mobility holes	480 cm^2/Vs
Fano factor	0.1
Signal	5500 electron-holes pairs for 20 keV x-ray
Noise (dark current)	~ 1 electron
Breakdown voltage	3×10^5 V/cm
Fluorecence Generation	No

…is already a major industry standard and easily available in large production volumes

Dead time

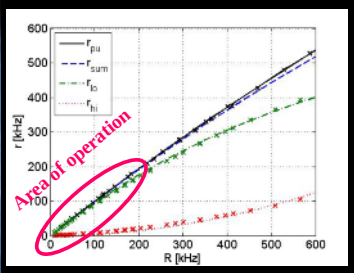
Measured Effect of Dead Time



$$N \approx \frac{N_m}{1-\tau N_m}$$

R.L. Lucke Rev. Sci. Instrum. 47 (6):766 (1976)
E. Fredenberg et al. SPIE 7258 (2009)

Measured Effect of Dead Time



Deadtime per event 189 ns

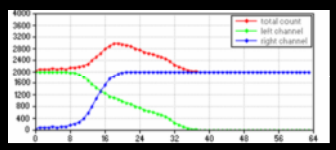
Deadtime at 20 kHz 0.4%

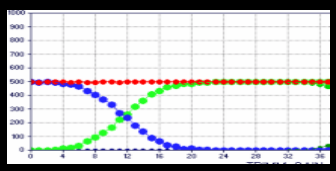
Deadtime at 200 kHz 3.7%

E. Fredenberg et al. SPIE Physics of Medical Imaging 2009

Charge sharing

How to avoid problems with charge sharing: “Co-incidence Logic”





Effect of charge sharing

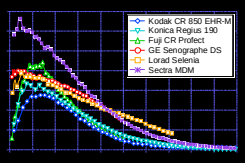
$$\frac{\mathrm{NPS(u)}}{\langle s \rangle} = \frac{(1-\chi)\widehat{K_{\mathrm{s}}}(x) + \chi\widehat{K_{\mathrm{d}}}(x)}{G\,\langle S \rangle\,(1+\chi)} = G\frac{1+\chi[1+2\cos(2\pi u/p)]}{1+\chi},$$

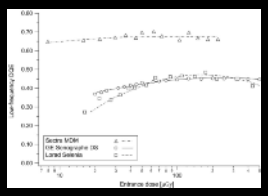
$$\mathrm{NPS}(0) = G(1+3\chi)/(1+\chi)$$

**E Fredenberg et al, Submitted to Nuclear Instr Meth A*

DQE + clinical data

DQE for all different mammography detector materials (Se,CsI, Si)*



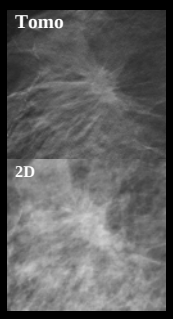


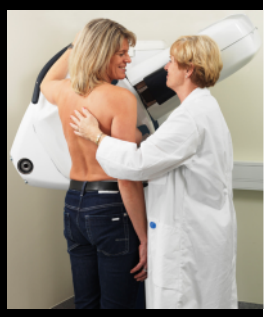
Note: DQE does not incorporate effects of energy weighting which benefits photon counting (10-15%)**

Elimination of electronic noise give low dose extra advantage for photon counting

** Monnin et al. Med. Phys., Vol. 34 (3), pp. 906-914, 2007*
*** R.N. Cahn et al. Med. Phys., vol. 26 (12), pp. 2680-2683, 1999*

Sectra Tomosynthesis





Clinical Studies
dose, sensistivity and specificity

B. Heddson, K. Rönnow, M. Olsson, D. Miller "Digital versus screen-film mammography: A retrospective comparison in a population-based screening program" European Journal of Radiology, Volume 64, Issue 3, Pages 419-425 (2007)

-75% dose reduction, increased cancer detection rate at same call-back rate

M. Wallis "Evaluation and clinical assessment of digital mammography screening using a Sectra Microdose full field digital x-ray unit and Sectra breast imaging PACS" NHSBSP REPORT 0601 MAY 2006 UNITED KINGDOM

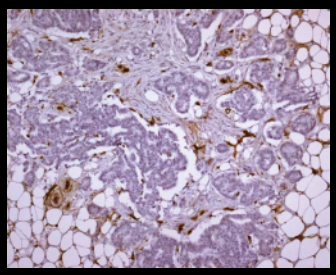
-70% dose reduction, same cancer detection rate and call-back rate

Future applications: measuring the energy and using the spectral information

“Experimental evidence suggests that the growth of a tumor beyond a certain size requires angiogenesis”

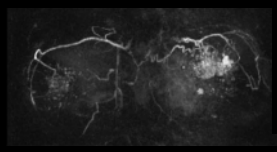
N Weidner et al. New England J. Med. 1991;324:1–8.

Numerous Microvessels in Stained Section

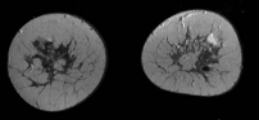


Dromain et al. AJR 2006; 187:528–537

Typical MRI Images



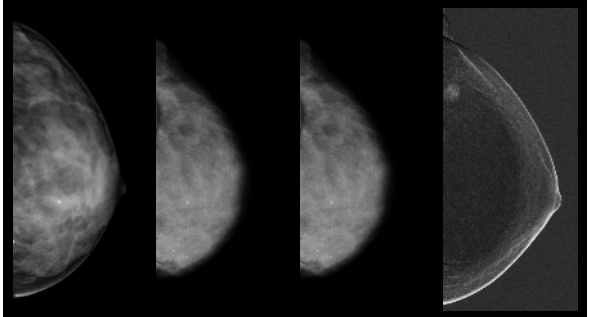
Maximum-Intensity-Projection (MIP)



contrast-enhanced T1-weighted coronal image

Multicentric invasive ductal carcinoma with extensive DCIS component (S:t Goran Hospital, Stockholm Sweden)

Contrast-enhanced Digital Mammography



Diekmann et al: 14-mm invasive ductal carcinoma(occult on mammography)

Challenges with Temporal Subtration CEM

1. Compression may interfere with blood flow
2. Motion blurring because of long time between exposures (5-10 min)
3. Compromise in image quality of "standard" mammogram since the kvP is to high (40-50 kVp)

Dual Energy Contrast Enhanced Mammography (DE-CEM)

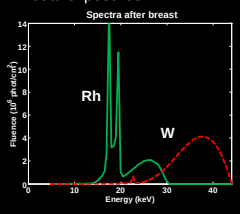
1. **High Energy Exposure**
   40-45 kVp, 200 mA, eg Rh anode, heavy filtering
2. **Low Energy Exposure**
   30 kVp, 140 mA, eg Mo anode
3. **Combine the high and low energy images into one image**
   Subtract the tissue, enhance Iodine signal

Advantages: Less motion blur, compression not a problem

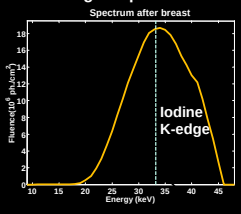
Lewin *et al.*
Radiology,
2003

Spectral Imaging

Previous example:
dual exposures



Photon-counting:
single exposure



Non-overlapping spectra ⇒ better tissue cancellation
Concentrated around K-edge ⇒ improved I-contrast
No motion blurring, easy to implement

Breast MRI v. Spectral Mammography

Spectral Mammography
-a Future Alternative to Breast MR?

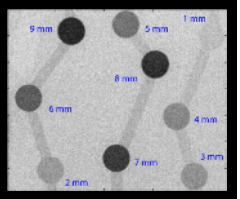
Same diagnostic information?
-Faster (no motion)
-Improved spatial resolution
-Similar appearance as normal mammograms
-Contrast to noise ratio better for MRI?
-10 years more of clinical experience with breast MR

Easier in combination with biopsy?

-Cancer outside of the breast will not be detected

Phantom study

1 - 9 mm deep iodine containers in 15 mm PMMA
Anatomical clutter:
35 mm PMMA and oil
Previous study with a single detector line:



E. Fredenberg et al. SPIE (2008)

Dual Energy Subtraction

Logarithmic subtraction with 2 energy bins:

$$\ln I = w \ln n_{\mathrm{lo}} - \ln n_{\mathrm{hi}} \;\text{ª}\; w d \mu_{lo}^{eff} - d \mu_{hi}^{eff} + K$$

$$S = \ln I_1 - \ln I_2 = w(d_1 \mu_{lo,1}^{eff} - d_2 \mu_{lo,2}^{eff}) + (d_2 \mu_{hi,1}^{eff} - d_1 \mu_{hi,2}^{eff})$$

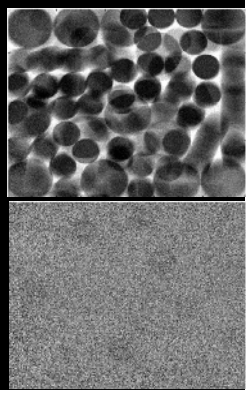
$\Rightarrow S = 0$ for proper choice of w (if $d_1 = d_2$)

Cost of increased quantum noise?

Phantom study

Results with the full system:

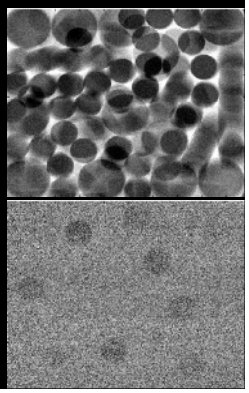
- **40 kV, 3 mm Al, 1.13 mGy, ~10 s**
- **3 mg/ml**
- **> 6 containers visible in the subtracted image**



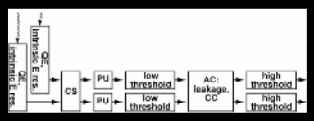
Phantom study

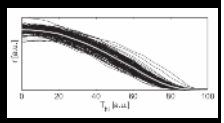
Results with the full system:

- **40 kV, 3 mm Al, 1.13 mGy, ~10 s**
- **6 mg/ml**
- **9 containers visible in the subtracted image**



Detector model*



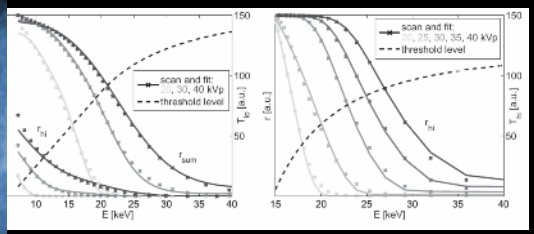


- Quantum efficiency, Intrinsic energy resolution of silicon
- Charge sharing: simulated**
- Pile-up: dead time measured to 247 ns
- Anti-coincidence logic: ~20% leakage, ~150 ns AC window ⇒ chance coincidence
- Spread of thresholds: measured from threshold scans

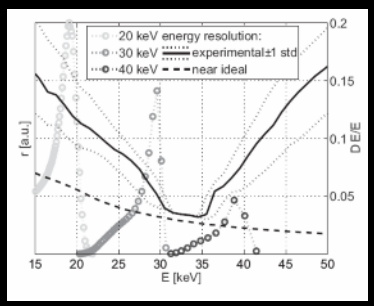
**E Fredenberg et al, Submitted to Nuclear Instr Meth A*
***M Lundqvist et al, IEEE Trans Nucl Sci, 2000*

Detector model

Threshold scans



Energy Resolution



Detector model verification

Measurements of the PMMA-iodine phantom

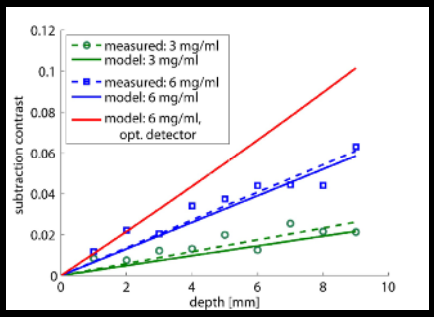
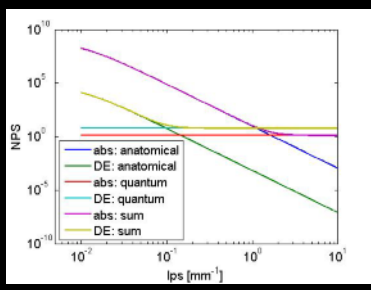


Image Noise

- quantum noise dominates at high *f*
- anatomical noise at low *f*

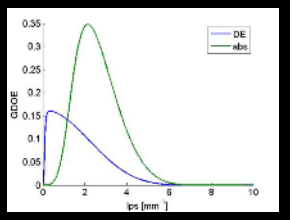


Generalized DQE*

$$\mathrm{GDQE} = \frac{\mathrm{MTF}^2}{q_0(\mathrm{NPS}_{\mathrm{quantum}} + \mathrm{NPS}_{\mathrm{anatomical}} \cdot \mathrm{MTF}^2)}$$

MTF, $\mathrm{NPS}_{\mathrm{quantum}}$ measured

$\mathrm{NPS}_{\mathrm{anatomical}}$ modeled as $1/f^{3.9}$



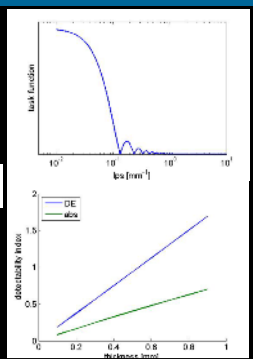
Richard et al, Med Phys (2006)

Detectability index

Contrast + GDQE + task function ⇒ detectability index

$$d^2 = \iint \mathrm{GDQE} \cdot \mathrm{F}^2 \cdot C^2 \, \mathrm{d}u \, \mathrm{d}v$$

~2.2 times improvement compared to the absorption image



Can we use the new technology in mammography screening?

Challenge

No contrast agent acceptable (?) except for high risk groups

But, spectral x-ray imaging may work anyway to improve the results in dense breasts

Theory of Photon Counting

$$\mu \approx \underbrace{C_1 \frac{r}{A} Z^4 f_{PE}(E)}_{\text{photoelectric effect}} + \underbrace{C_2 \frac{r}{A} Z f_{KN}(E)}_{\text{Compton scattering}},$$

$f_{PE} \propto E^{-3}$, **discontinuities at absorption edges**

f_{KN} **is the Klein-Nishina cross section**

Alvarez et al. Phys. Med. Biol. 1976

Composition of the Female Breast
(% of wet weight)

Tissue	Density (g/cm3)	Hydrogen	Carbon	Nitrogen	Oxygen	Ash (S P K Ca)
Fat	-	11.9	76.4	0.2	11.5	0.1
Skin	1.09	9.8	17.8	5.0	66.7	0.7
Adipose Tissue	0.93	11.2	61.9	1.7	25.1	0.1
Gland	1.04	10.2	18.4	3.2	67.7	0.5

R. Hammerstein et al. Radiology 130:485-491 (1979)

Elements in the Female Breast

Element	Normal Tissue (median µg/g)	Malign Tissue (median µg/g)
Al	13	28
Br	22	35
Ca	294	653
Cl	10140	15225
Co	1.19	1.95
Cs	0.51	1.1
Fe	94	194
K	2620	14400
Na	9200	13230
Rb	11.5	28.5
Zn	3.5	57

15 paired samples

Kwan-Hong et al. "Differentiation of Elemental Composition of Normal and Malignant Breast Tissue by Instrumental Neutron Activation Analysis Appl. Radiat. Isot. (4) 1993, p 511-516

Additional Elements in the Female Breast

Element	
Silicon	Breast implants
Iodine	Contrast agent (X-ray)
Gadolinium	Contrast agent (MR, X-ray)

The Highrex Project

Clinical Participants

Addenbrook's Hospital, Cambridge, UK (M. Wallis)
S:t Goran's Hospital, Stockholm, Sweden (K. Leifland)
Health Unit of Pistoia, Florence, Italy (M. Rosselli del Turko)
Charite Hospital, Berlin, Germany (F. Diekmann)
Munster University Hospital, Munster, Germany (W. Heindel)
Arcades, Marseille, France (B. Seradour)

Aim

Test 3D and Spectral Mammography (with and without contrast) versus standard mammography and breast MRI, enriched populations of 3*200 women

Status

2 units deployed with 3D imaging (around 200 cases collected)
1 unit deployed with spectral detector

Conclusions

- For mammography photon counting is out there in clinical reality (except for US)
- Low radiation dose advantage
- Spectral information most valuable for large objects (> a few mm)
- Promising results for contrast mammography with Iodine
- Spectral information may be used to increase cancer detection
- Spectral information easy to implement as “add-on” information in mammography at almost no cost “to be used when desired”