Development and Characterization of Phase Sensitive X-ray Imaging Systems

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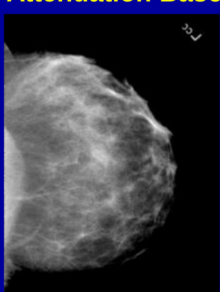
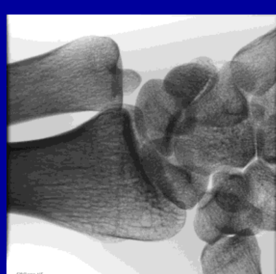
What To Discuss Today

- Attenuation vs phase: theoretical investigations.
- System development: phase contrast imaging systems
- Dual-detector phase imaging system and phase retrieval algorithms
- Work in progress: phase contrast tomosynthesis.

Attenuation Based Digital X-ray Images



Mammogram



Oblique

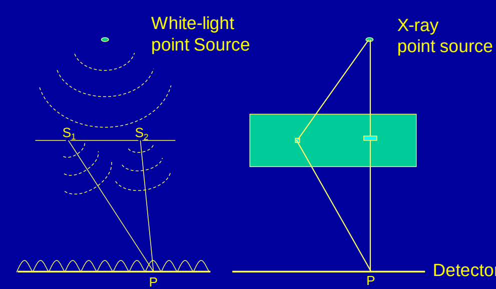
Current Breast Cancer Statistics

- **One in eight** women will develop breast cancer.
- **200,000**+ women were diagnosed with breast cancer in 2003.
- **43,600** women died from breast cancer in 2002.
- **30%** of early stage breast cancers go undetected at the time of screening.

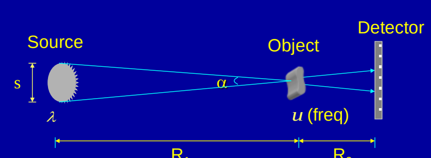
New Technology is Needed: Phase contrast x-ray imaging

- Current techniques:
  - Image contrast relies on tissue attenuations
- X-ray imaging with mono-energetic /coherent source
  - Image contrast could also be produced by phase variations
- Is mono-energetic / coherent x-ray source available?
  - X-ray laser or synchrotron sources with x-ray optics
- Is it clinically feasible?
  - No; high expenses, technical complexity et al, for now

Recording Phase Info with Polychromatic Source



Partially Spatial Coherence



Lateral Coherence : $\frac{\lambda R_1}{s}$; Phase space shearing: $\frac{\lambda R_2 u}{M}$

Ratio : $C = \frac{R_2 s u}{R_1 + R_2}$

C << 1, fully coherent, C < 1 Partially coherent , C **> 1, incoherent**

X. Wu and H. Liu, JXST, 11 (2003)
X. Wu and H. Liu, Medical Physics 34 (2007)

Guidelines for System Design

A Figure of merit for the phase-visibility: *RPF(u)*

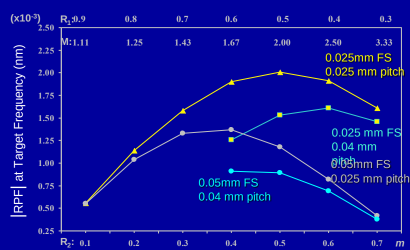
$$RPF(\vec{u}) = c^2 h^2 \tilde{\mu}_{in}\left(\frac{\lambda R_2 \vec{u}}{M}\right) OTF_{det}\left(\frac{\vec{u}}{M}\right)\left[\int \frac{\pi R_2 \vec{u}^2}{ME^2} S_{Exit}(E)\, dE\right]$$

That considers:

- Limited Spatial Coherence of the Incident X-ray
- Polychromatic X-ray Spectrum
- Body Parts Attenuation
- Imaging-detector's Resolution
- Radiation Dose to Patients

X. Wu and H. Liu, Med. Phys. 31, (2004)

| RPF | For a Phase Contrast Mammography System

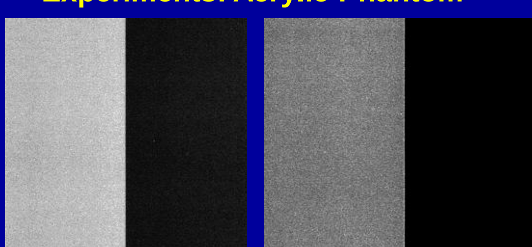


R_1: Source to Object; R_2: Object to Detector, M: Magnification

X. Wu and H. Liu, Applied Optics 44 (2005)

A Prototype Phase Contrast Imaging System

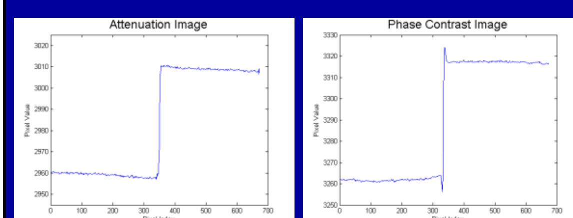
Experiments: Acrylic Phantom



(a) (b)

(a) 40KV, 60mAs, SID=10ft, M=1.0; (b) 40KV, 60mAs, R_1=5ft, R_2=5ft, M=2.0

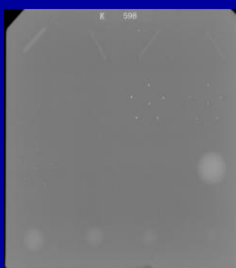
Experiments Result: Acrylic Phantom



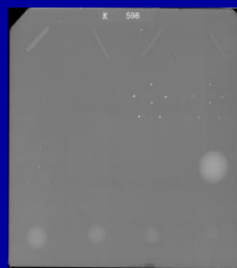
(a) (b)

(a) 40KV, 60mAs, SID=10ft, M=1.0; (b) 40KV, 60mAs, R_1=5ft, R_2=5ft, M=2.0

ACR Mammography Phantom, 40KV, 60mAs

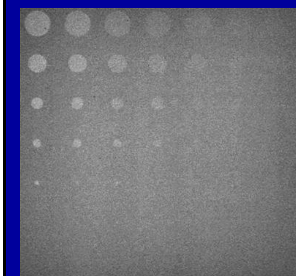


Attenuation image, SID=5ft, M=1.0

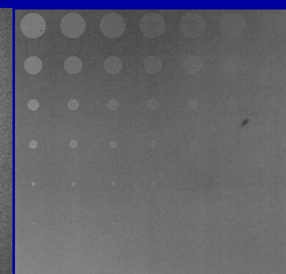


Phase contrast image, R_1=R_2=5ft, M=2.0

Observer Based Evaluations: Phantom Imaging

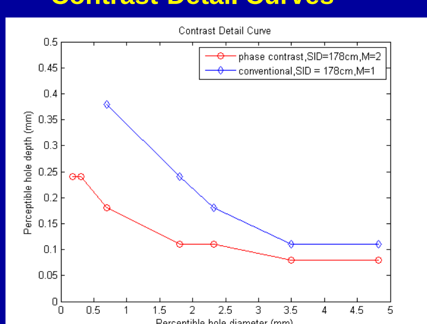


(a) Attenuation at 40kVp,30mAs

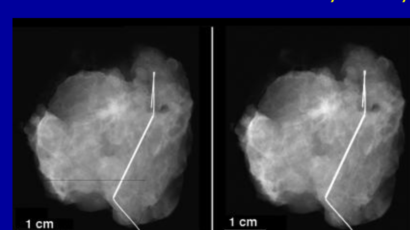


(b) Phase contrast at 40kVp,30mAs

Contrast-Detail Curves



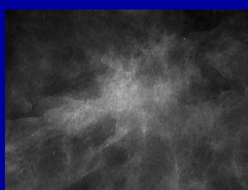
Lumpectomy Specimen:
Conventional vs Phase Contrast; 40KV, 7.5mAs



Phase contrast Conventional

Phase contrast: improves visualization by edge enhancement

Lumpectomy Specimen:
Conventional vs Phase Contrast; 40KV, 7.5mAs



Phase contrast

Conventional

Phase contrast: improves visualization by edge enhancement

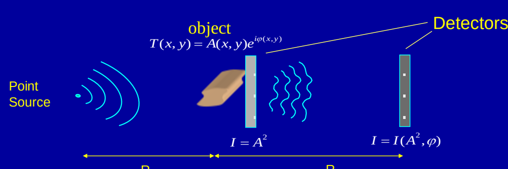
A Dual Detector Phase X-ray Imaging System and Phase-Retrieval Technique

- To retrieve the phase image ϕ from the
  - attenuation image A^2 and
  - phase-contrast image *I(A,f)*
- To enables a quantitative tissue characterization by their electron densities.

$$\varphi_{tissue} = -\bar{\lambda}\, r_e \rho_{e,p}$$

- It is the key step for phase contrast tomography to remove artifacts such as negative attenuation coefficients

Image Acquisition to Enable Phase Retrieval



- *Formula based on the Wigner distribution:*

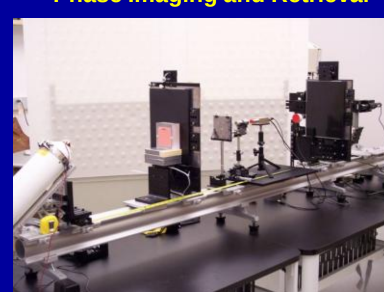
$$\hat{F}[I(M\vec{\rho})] = \frac{I_0}{M^2}\cdot \mathrm{OTF}\left(\frac{\vec{u}}{M}\right)$$

$$\left\{\cos\left(\frac{\pi\lambda R_2 u^2}{M}\right)\hat{F}\left[A^2(\vec{\rho})\right] + 2\sin\left(\frac{\pi\lambda R_2 u^2}{M}\right)\hat{F}\left[A^2(\vec{\rho})\phi(\vec{\rho})\right] - i\frac{\lambda R_2}{M}\cos\left(\frac{\pi\lambda R_2 u^2}{M}\right)\vec{u}\cdot\hat{F}\left[\phi(\vec{\rho})\nabla A^2(\vec{\rho})\right]\right\}$$

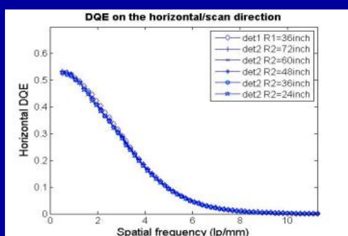
- *We presented an iterative algorithm for robust and quantitative phase retrieval for phase map Φ(x,y).*

X. Wu and H. Liu, JXST, 11 (2003)
F. Meng, H. Liu and X. Wu, Opt. Expre. 13, 2007

Dual Detector Prototype for Phase Imaging and Retrieval



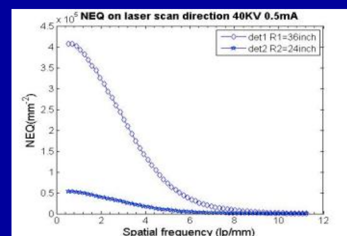
Detective Quantum Efficiency (DQE) Curves of the Two Detectors



- ❖ DQE of detector1 and detector2 at 40kV 12.5mA s with R_1=36inch and R_2=24, 36, 48, 60 and 72inch.
- ❖ The beam was filtered by a 4cm-thick BR-12 phantom.

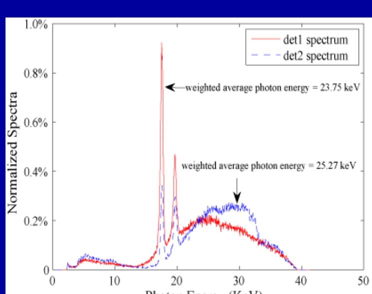
D Zhang, X Wu, H Liu, Phys. Med. Biol., vol.53, 2008

NEQ Curves of the Two Detectors



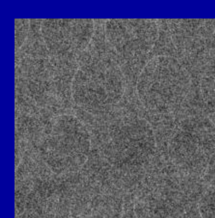
- ❖ NEQ curve of the system with respect to detector-1 and detector-2.
- ❖ The curves were obtained with a 40kV, 12.5mAs, and filtered by a 4cm-thick BR-12 phantom.

Incident Spectra of the Two Detectors



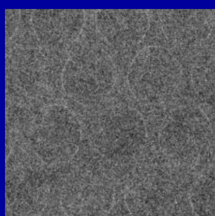
- ❖ Obtained at 40kV,
- ❖ With additional filtration of a 4cm BR-12 phantom

Imaging Experiments: Polyethylene Air-Bubble Wrap



40 kVp, SID = 1.75m, M =1, 7µm focal spot
140 µm pixel-pitch

Attenuation and Phase Contrast Images



M = 1
Attenuation image

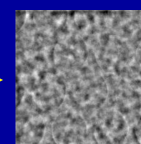
M = 2.8
Phase contrast image

Transport of Intensity Equation (TIE)-Based Phase Retrieval: Bubble Wrap

Phase contrast image

"&"

Attenuation image



Noise spoiled phase retrieval

- TIE-based phase retrieval method is the most commonly used method in literature.

K. Nugent et al, Phys. Rev. Lett. 77, (1996)

Why TIE-Based Method Failed in Phase Retrievals for Clinical Applications

- TIE-based phase retrieval method:

$$\varphi(\vec{r}) = -(2\pi M/\lambda R_2)\,A \times \nabla^{-2}\left\{\nabla\cdot\left[\frac{1}{A_o^2}\nabla\left(\nabla^{-2}\left(\frac{M^2 I}{I_{in}} - A_o^2\right)\right)\right]\right\}$$

∇^{-2} is singular for near-zero frequencies so that it amplifies the low frequency noises

Phase-Retrieval Robustness

- The limited radiation doses make clinical images much noisier than synchrotron based imaging.
- The phase-retrieval robustness against noise is of critical importance for medical imaging
- Attenuation Partition (AP) based iterative phase retrieval method is therefore developed

Attenuation Partition (AP) Based Iterative Phase Retrieval

- Attenuation partition: partition tissue attenuation as

$$A_o^2(\vec{r}) = A_{KN}^2(\vec{r}) \cdot A_{pe,coh}^2(\vec{r})$$

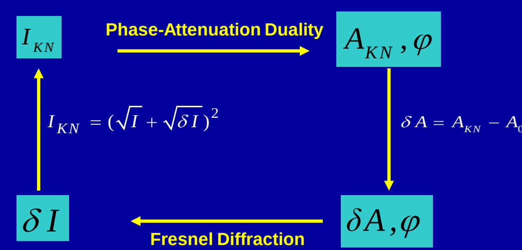
$A_{KN}^2(\vec{r})$ Attenuation from x-ray Compton scattering

$A_{pe,coh}^2(\vec{r})$ Attenuation from photoelectric absorption and coherent scattering

- Physics-motivated regularization:

The AP-based method utilizes the correlations (Phase-Attenuation Duality) between tissue attenuation and their phase shifts to get rid of the singularity and associated noise amplification.

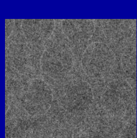
Attenuation Partition Based Iterative Phase Retrieval



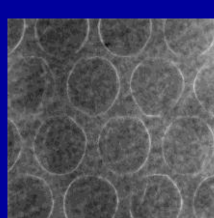
A. Yan, X. Wu, H. Liu, Optics Express, 16, 2008
A. Yan, X. Wu, H. Liu, Optics Express, 18, 2010

Attenuation Partition Based Iterative Phase Retrieval

Phase contrast image

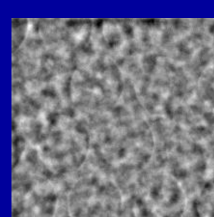


Attenuation image

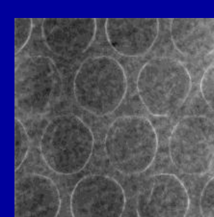


Retrieved phase map

Phase Retrieval: TIE-Based vs. AP-Based Methods

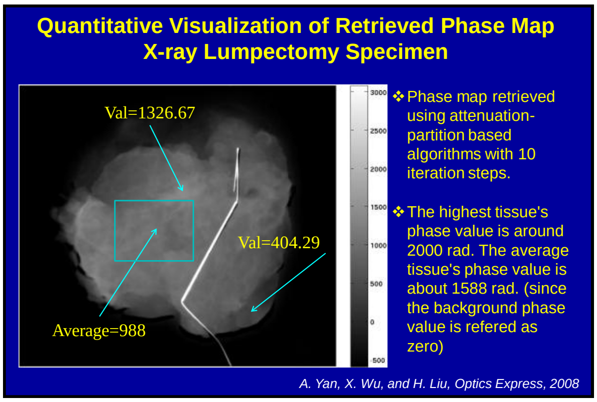


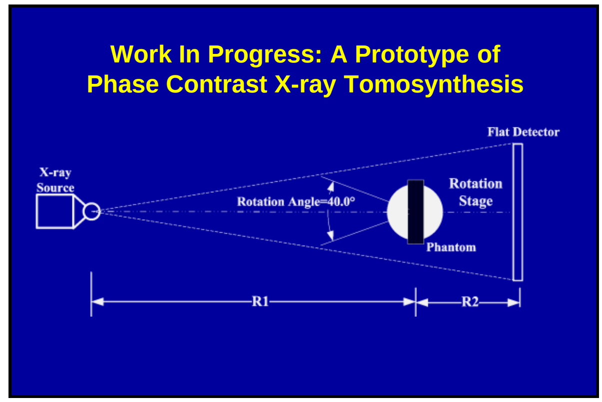
TIE-based method

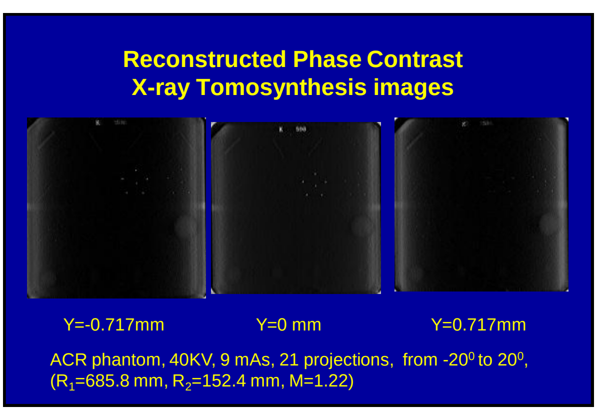


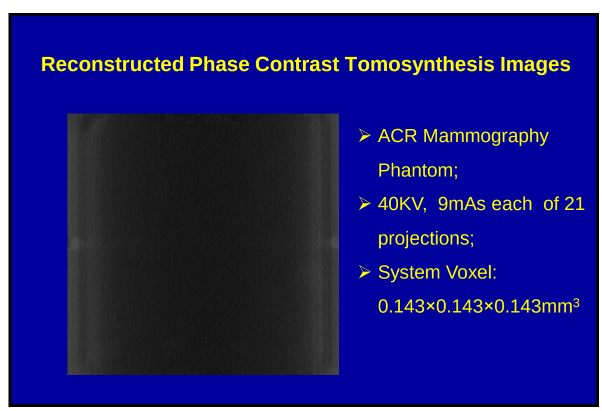
AP-based method

A. Yan, X. Wu and H. Liu, Med. Phys. In press (2011)

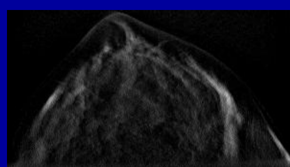

Quantitative Visualization of Retrieved Phase Map
X-ray Lumpectomy Specimen
Val=1326.67
Val=404.29
Average=988
❖ Phase map retrieved using attenuation-partition based algorithms with 10 iteration steps.
❖ The highest tissue's phase value is around 2000 rad. The average tissue's phase value is about 1588 rad. (since the background phase value is refered as zero)
A. Yan, X. Wu, and H. Liu, Optics Express, 2008


Work In Progress: A Prototype of
Phase Contrast X-ray Tomosynthesis
Flat Detector
X-ray Source
Rotation Angle=40.0°
Rotation Stage
Phantom
R1
R2


Reconstructed Phase Contrast
X-ray Tomosynthesis images
Y=-0.717mm
Y=0 mm
Y=0.717mm
ACR phantom, 40KV, 9 mAs, 21 projections, from -20⁰ to 20⁰,
(R1=685.8 mm, R2=152.4 mm, M=1.22)


Reconstructed Phase Contrast Tomosynthesis Images
➢ ACR Mammography Phantom;
➢ 40KV, 9mAs each of 21 projections;
➢ System Voxel: 0.143×0.143×0.143mm³

Reconstructed Phase Contrast Tomosynthesis Images



Anthropomorphic Breast Phantom, 50mm thick, 40KV, 15mAs each of 21 projections; 0.35×0.35×0.35mm^3 Voxel (R_1=508mm, R_2=1016mm, M=2)

Important Contributions Made by Other Investigators Using In-line Methods

Wilkins' group in Australia

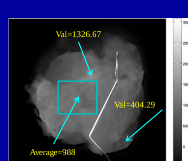
Price's group at Vanderbilt

Anastasio's group at Washington University in collaboration with X. Pan's group in Chicago

Knor's group at Syracuse

And many others all over the world.

Conclusions



- From anatomy based radiography to quantitative phase map to molecular signals
- Combines powers of image acquisition, phase retrieval and quantitative visualization, to improve diagnostic accuracy.

Acknowledgements

- Collaborators, associates and students
  - Drs. Laurie Fajardo , John Rong, George Mardrosian, Larry Knight, Zhengxue Jing, Susan Edwards, …
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