Refraction Corrected Transmission Ultrasound Computed Tomography for Application in Breast Imaging

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Universidade de São Paulo BRASIL — Marcel Jackowski

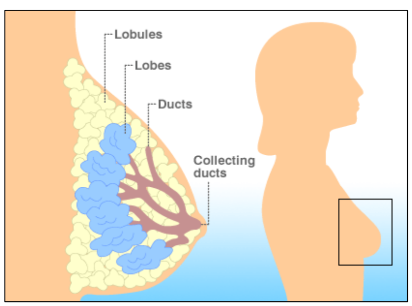
Ultrasound Detection Systems, LLC — Donald Dione

Yale — Lawrence Staib

Motivation

Breast cancer is the dominant cancer in women

- in 2007 1.2 million women world-wide had breast cancer
- 30% mortality (465,000)

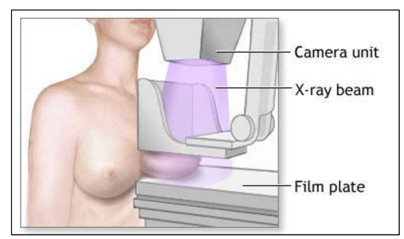


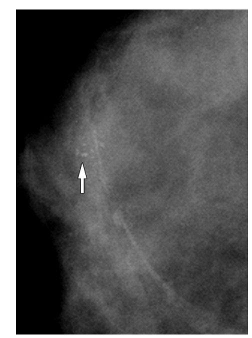
- cancer most common in the ducts (ductal carcinoma)
- cancer also frequent in the lobes or lobules (lobular carcinoma)
- cancer least frequent in the nipple, lymphatic vessels or skin

Early Detection: X-Ray Mammography

Most dominant screening method

- projection of a spread-out breast





ductal carcinoma

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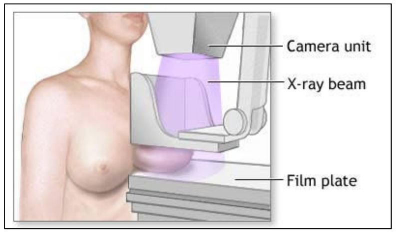
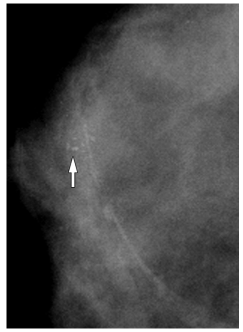




ductal carcinoma

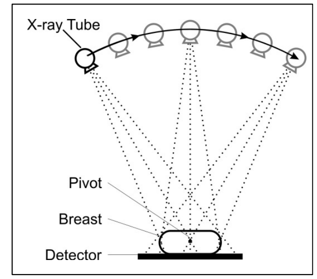
Shortcomings:

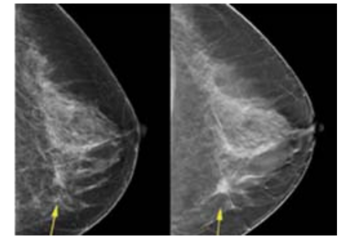
- radiation 2-4 times annual natural background radiation
- high false positive rate → 80% biopsies found benign
- breast compression very inconvenient
- post-compression lesions difficult too localize

Early Detection: 3D X-Ray

Tomosynthesis and 3D cone-beam CT

- both provide a slice-per-slice view





mammo tomo

- much better resolve of small features
- eliminate shortcomings of compression

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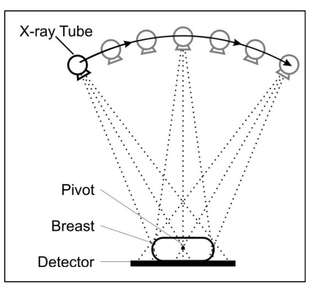
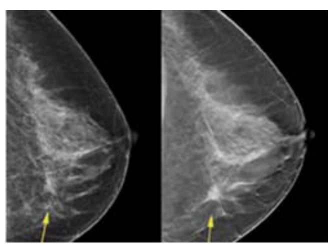




mammo tomo

- much better resolve of small features
- eliminate shortcomings of compression

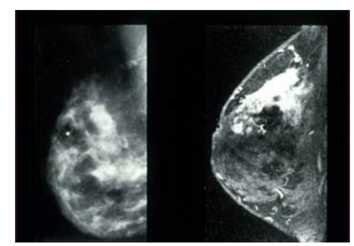
Shortcomings:

- radiation dose still remains

Early Detection: MRI

Most "luxurious" imaging method

- no compression, no radiation



X-ray mammo MRI

- able to detect tumors in even dense breasts (young women)
- able to detect early-stage tumors
  → advisable for women at high risk for breast cancer

Early Detection: MRI

Most "luxurious" imaging method

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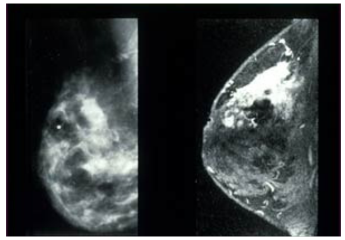

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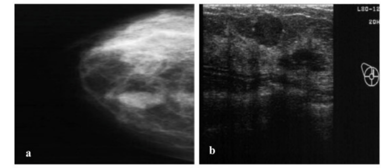
Shortcomings:

- high cost ($1,000 vs. $100)

Early Detection: Ultrasound (Echo)

Promising at first glance:

- no radiation, painless, inexpensive
- in fact, echo (reflective) US routinely used as adjunct modality



X-ray mammo echo US

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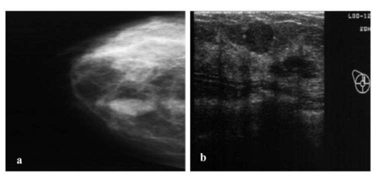


X-ray mammo echo US

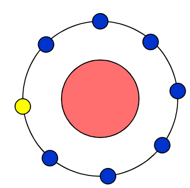
Shortcomings:

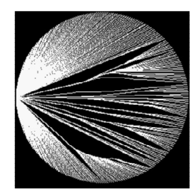
- relatively poor quality
- cannot differentiate malignant from benign masses
  → false positive rate will not improve

Ultrasound: Can We Do Better?

Use *transmission* ultrasound

- insert breast in water bath
- arrange piezo transducers as a ring around the breast
- one piezo fires and the others listen and record





Record at each sensor:

- Time Of Flight (TOF): time of first detected peak
- attenuation: amplitude of first detected peak

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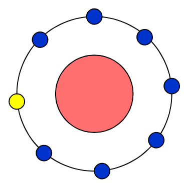

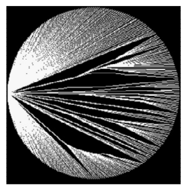

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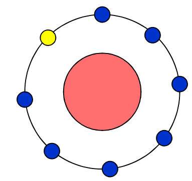

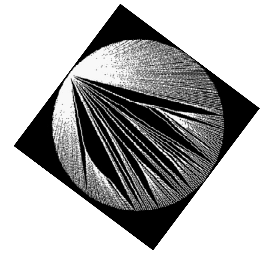

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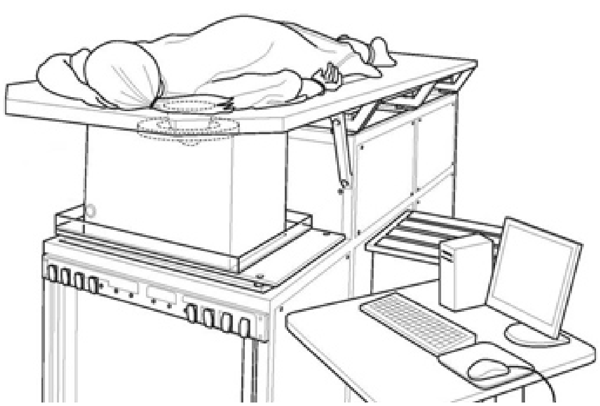
Possible Setup

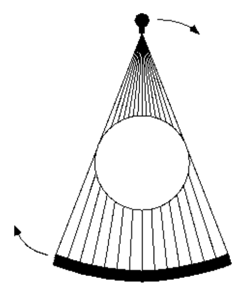


Neb Duric, Karmanos Cancer Institute

CT Reconstruction: A Primer

A quick primer:

- reconstruction is via back-projection
- linear rays are typically assumed
- well developed for X-ray data

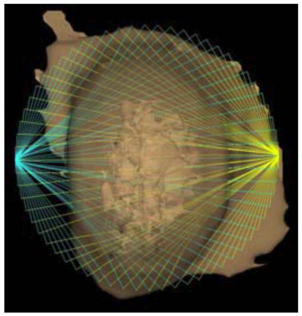


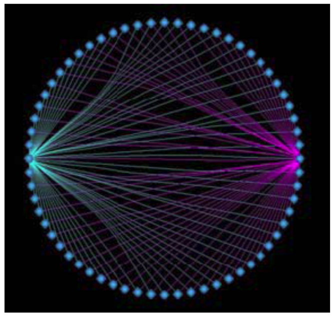
acquisition:
rotating fan beam source

reconstruction:
back-projection of all data

Ultrasound CT: Important Distinctions

In contrast to X-ray CT
- rays are NOT straight

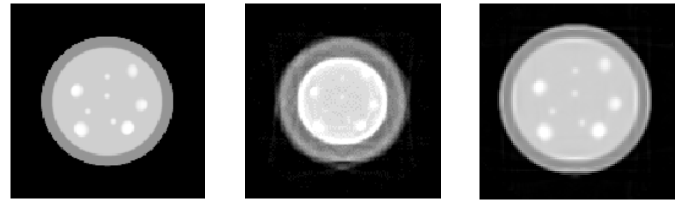




- refraction effects cannot be ignored

The Importance of Refraction

Reconstruction with and without considering refraction effects
- phantom experiment (simulated data)
- TOF reconstruction



original | without refraction | with refraction

- the breast is a heterogeneous medium
  → proper refraction modeling is important for high fidelity
- this has been known for a long time

Energy Propagation Modeling

Ideally one should solve the acoustic wave equation

Obstacles:
- wave solvers are impractical for clinical routine
  → must obtain a reconstruction in 5 minutes tops
- existing methods for refraction modeling are awkward
- noisy ultrasound data require iterative reconstruction schemes
  → cannot afford costly energy propagation schemes

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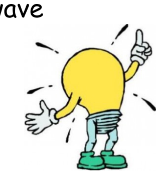
Our key observations
- sensors look for TOF → the front of the acoustic wave
  → wave front tracking approach seems appropriate
- require an efficient wave tracking procedure
  → further accelerate on GPUs



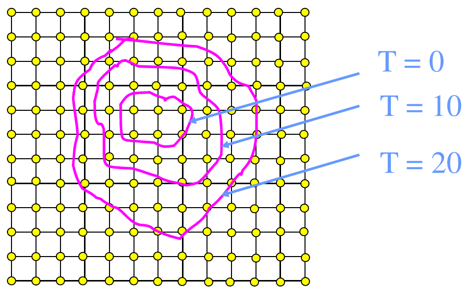
Wave Front Tracking

Propose the use of the Fast Marching Method (FMM)

- well known in computer vision
- also often used for distance transforms

FMM tracks the evolution of the frontier interface

Step 1: move front under velocity V of grid points on frontier
Step 2: record frontier arrival time at each grid point as time field
Repeat



Iterative CT Reconstruction: A Primer

Predictor – Corrector scheme

Start off with an initial estimate of the object

Simulate projections using this estimated object

- important: simulator should be physically accurate
  → *forward projection* step

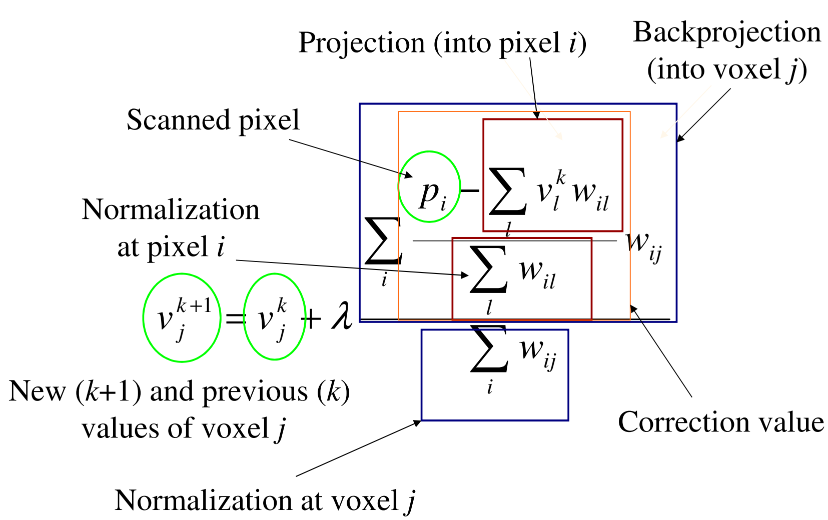
Compute the difference b/w simulated and collected data

Update estimated object by this difference (error)

- spread the corrections across the grid
  → *back-projection* step

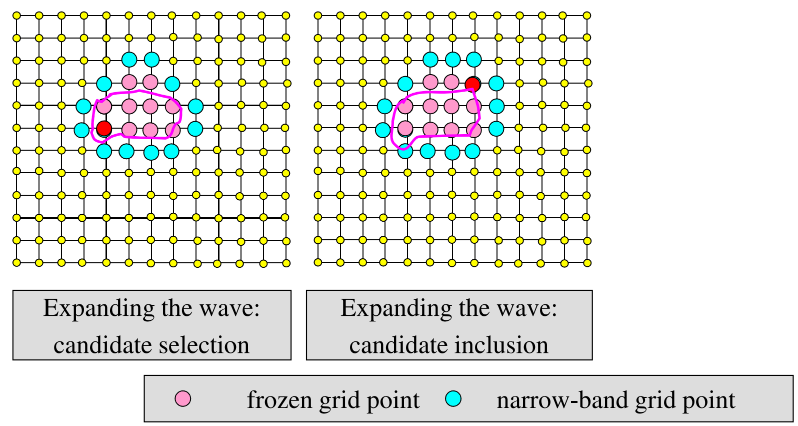
Iterate as long as corrections are significant

More Specifically: SART/SIRT



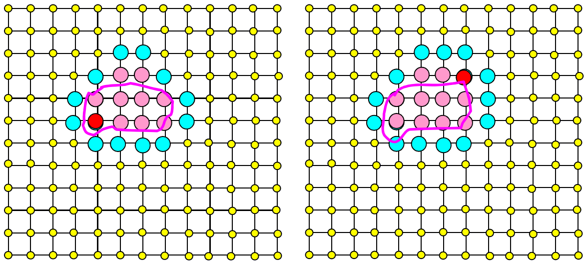
$$v_j^{k+1} = v_j^k + \lambda \frac{\sum_i \frac{p_i - \sum_l v_l^k w_{il}}{\sum_l w_{il}} w_{ij}}{\sum_i w_{ij}}$$

FMM-SART: Forward Projection



Eikonal equation : $(\partial t/\partial x)^2 + (\partial t/\partial y)^2 + (\partial t/\partial z)^2 = 1/ F^2(x, y, z)$

FMM-SART: Forward Projection



Expanding the wave: candidate selection | Expanding the wave: candidate inclusion

frozen grid point — narrow-band grid point

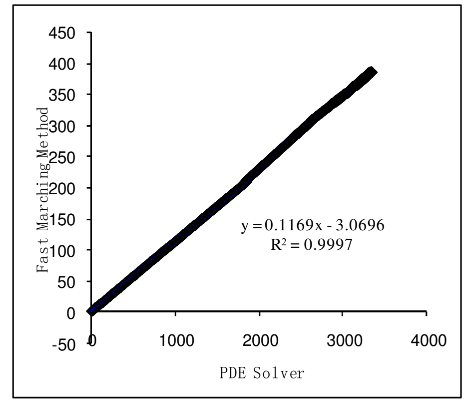
Eikonal equation : $(\partial t/\partial x)^2 + (\partial t/\partial y)^2 + (\partial t/\partial z)^2 = 1/ F^2(x, y, z)$

HAFFM: $\partial t/\partial x = (3t(x, y, z) - 4t(x-1, y, z) + t(x-2, y, z))/2$

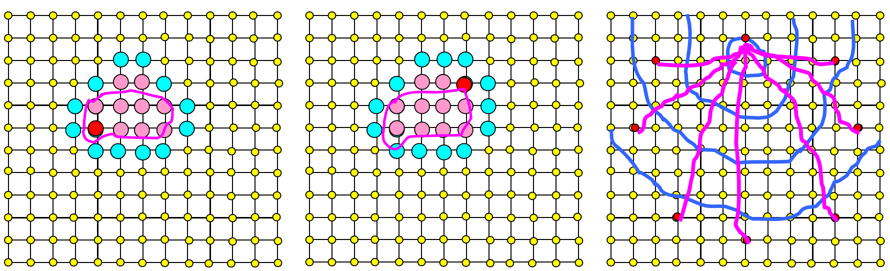
Comparison With Physics Wave Solver

Nearly perfect correlation (F=99%) for TOF simulations

- 95% for attenuation simulations



FMM-SART: Back-Projection



Expanding the wave: candidate selection | Expanding the wave: candidate inclusion | Accurate ray-tracing from source to sensors

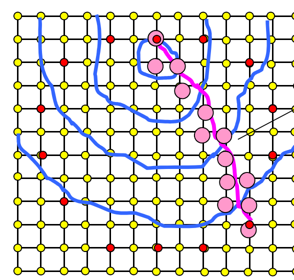
frozen grid point — narrow-band grid point

Eikonal equation : $(\partial t/\partial x)^2 + (\partial t/\partial y)^2 + (\partial t/\partial z)^2 = 1/ F^2(x, y, z)$

HAFFM: $\partial t/\partial x = (3t(x, y, z) - 4t(x-1, y, z) + t(x-2, y, z))/2$

FMM-SART: Complete Algorithm

Track wave front forward



Compute the ray length L

Compute Correction (TOV = Time Of Flight)
ΔTOF = (TOF simulated – TOF collected) / L

Back project along the ray direction
$SV = d / t$

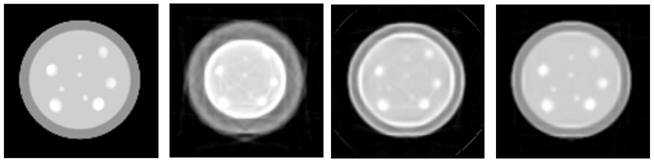
Sound Velocity (*SV*) reconstruction

Process all detector rays

Begin next iteration with near-orthogonal view

Results: Simple Phantom

Sound Speed



Original | Straight rays | FMM | HAFMM

Results: Simple Phantom

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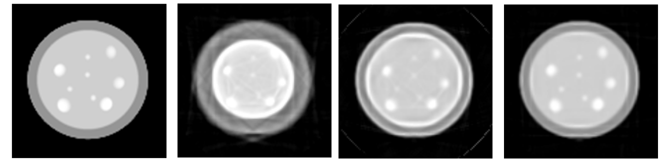
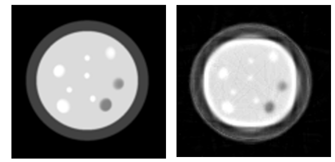


Original | Straight rays | FMM | HAFMM

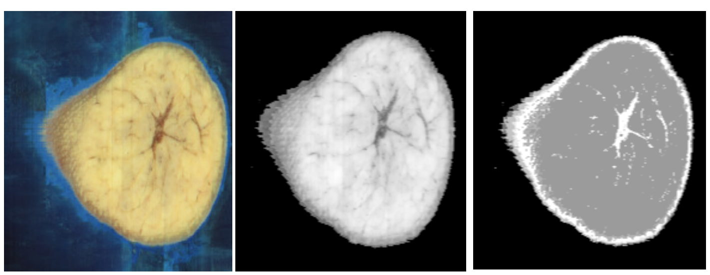
Attenuation



Original | HAFMM

Novel Breast Phantom

Constructed from NIH Visible Woman

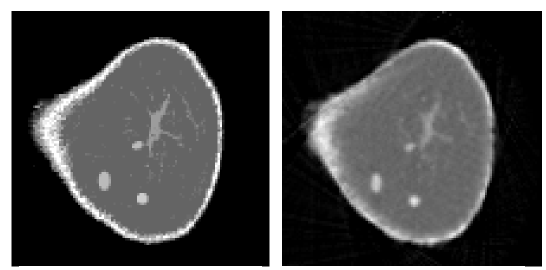


A cryosection RGB slice | *H* value transformed to grey-scale | mapping to acoustic speed

Reconstructed Phantom With 3 Lesions

280 transducers

- realistic tissue properties (sound speed, attenuation)
- lesions 6-9 pixels large with densities from 100 to 250

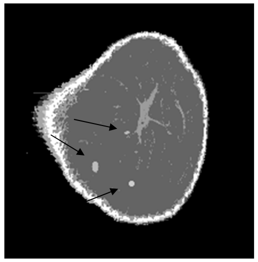


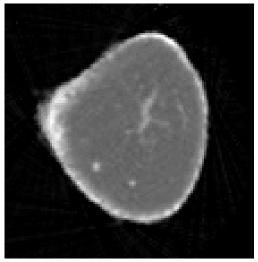
original | reconstructed

Study: Lesion Size

280 transducers

- realistic tissue properties (sound speed, attenuation)
- lesions as small as 2 pixels radius

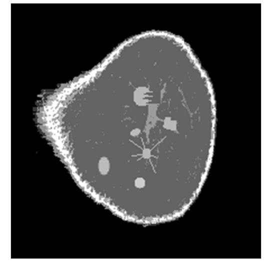

original

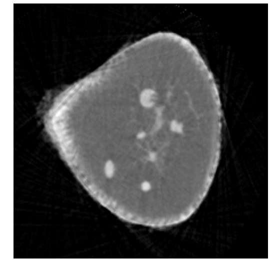

reconstructed

Study: Lesion Shape

280 transducers

- realistic tissue properties (sound speed, attenuation)
- lesion shape: spiculated, lobulated, obscured

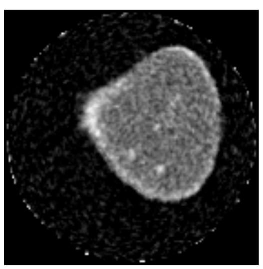

original

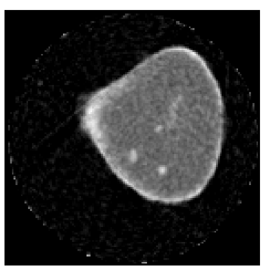

reconstructed

Study: Noise

280 transducers

- realistic tissue properties (sound speed, attenuation)
- noise levels: SNR = 5 and 10


SNR=5


SNR=10

Time Performance

Accelerated a variant of FMM (the FIM) on commodity graphics hardware (GPU)

- achieved an 80-fold speedup over CPU implementation
- clinical reconstruction time (5 min) for realistic dataset

Task	Grid size	FMM	FSM		FIM		
		CPU	CPU	Cluster-8 nodes	CPU	GPU (NVIDIA)	
						8086GTX	Tesla
Projection	128^2	0.025	0.031	0.007	0.038	0.00082	0.00072
Projection	256^2	0.097	0.180	0.039	0.189	0.0023	0.0022
Reconstr.	$128^2 \times 40$	2400	2649	506	3316	37.8	30.9
Reconstr.	$256^2 \times 44$	19200	32732	6393	37221	286.2	225.76

Conclusions and Future Work

Devised a high-accuracy transmission ultrasound framework for breast cancer screening

- clinical reconstruction speed achieved by GPU acceleration

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Preliminary studies have been undertaken using acquired ultrasound data

- more focused efforts underway

Questions?

Funding provided by NIH, NSF