Fast 4D Imaging
Breaking the Speed Limits in MR and CT

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Limitations of Cartesian Acquisitions

For Cartesian acquisition the Nyquist Theorem demands $n^3$ Fourier samples for an $n^3$ image matrix.

This imposes a k-space speed limit that dictates that spatial resolution is directly proportional to imaging time.
Methods for Breaking The k-space Speed Limit

Parallel Imaging
SMASH
SENSE

Undersampled Projection Imaging
SMASH
SiMultaneous Acquisition of Spatial Harmonics

Multiple Coils

Synthesized spatial modulations

Sodickson and Manning
MRM 38:585-590 (1997)
Skipping k-space lines

SMASH
Sodickson and Manning
MRM 38:585-590 (1997)
Image Synthesis

Coil 1  Coil 2  Coil 3

Synthesized Image

SMASH
Sodickson and Manning
MRM 38:585-590 (1997)
SENSitivity Encoding (SENSE)

Pixel in $i$th reduced FOV image from overlapping pixels $j$:

$$P_i = \sum S_{ij} \cdot P_j$$
SENSE Images

Pruessmann et al.
Parallel MRI and Multidetector CT

CT
Multiple image slices at once

MRI
Multiple k-space “slices” at once

DK Sodickson, MD, PhD
Commercially available receiver channels over time
32-element coil arrays: body, cardiac, head...

Zhu et al, MRM 2004; 52: 869

Hardy et al, MRM 2004; 52:878
Possanzini et al, ISMRM 2004, 1609
Spencer et al, ISMRM 2005, 911

Cline et al, ISMRM 2004, 2387
Moeller et al, ISMRM 2004, 2388

Hardy et al
ISMRM 2005, 951

DK Sodickson, MD, PhD

90 element arrays are in the works!
Larry Wald, Graham Wiggins
Massachusetts General Hospital, Boston, MA, USA
ISMRM 2005 #671
Highly Accelerated Coronary MRA

25 sec single breath-hold scan

**NO** localization
60 axial slices
12 cm S-I coverage

8 fold acceleration
(4 x 2 aliasing)

retrospective reformatting

breath-held CAI with whole-heart coverage

T. Niendorf et al, SCMR 2005, #168

DK Sodickson, MD, PhD
Rapid volumetric body screening

Large volume (44 cm x 44 cm x 40 cm) at clinical resolution (1.7 mm x 1.7 mm x 2.2 mm)
12-fold acceleration (4 x 3 aliasing)

4:24
(264 second)
acquisition

÷12

22 second
breath-hold

DK Sodickson, MD, PhD
Acceleration over time

![Graph showing acceleration over time from 1997 to 2004.]
Single Echo Acquisition (SEA) MRI

- Phase encoding is entirely eliminated and replaced by the spatial localization of long and very narrow coils

Single Echo Images- First images

- Standard image on left-
  - 128 acquisitions, 300 msec TR
  - Acq. time: 38 seconds

- Single acquisition image on right-
  - 1 acquisition by 64 elements
  - Acq. time: 20 msec.
Motion imaging

- SEA Imaging is remarkably insensitive to motion artifacts.
  - Each image is created from a single echo.
  - No motion artifacts due to motion in phase encoding gradients

Test phantom
Spin Echo, 256x256 resolution
0 RPM, 100 percent speed

Test phantom
Gradient Echo, 64 x 128 resolution
TR/TE = 8/4 msec.
60 RPM, 80 percent display speed.
Ultra-fast Magnetic Resonance Angiography

How would we do MRA if we could start all over?

Cartesian MRA
Radial Projections

First technique used by Lauterbur

Requires 50% more time than Cartesian to obey Nyquist Theorem
Undersampled
Extension of Undersampled Projection Imaging to 3D

VIPR: Vastly undersampled Isotropic imaging with PRojections

WF Block, AV Barger, TM Grist and CA Mistretta, Radiology 217(P), 311, 2000
Relative VIPR Noise vs Acceleration Factor

Acceleration factors $R$ relative to Cartesian

* Acceleration = ratio $\left(\text{scan speed x voxel resolution x 3D volume}\right)$

A. Barger PhD thesis

256 x 256 x 256
PC VIPR vs. 3D Cartesian PC: Acceleration factor 61 with contrast

**PC VIPR**
- Time: 3:50 (2x)
- S/I Coverage: 18 cm (4.5x)
- Isotropic resolution: $0.63 \times 0.63 \times 0.63$ mm $^3$ (7x)

**Cartesian 3D PC**
- Time: 7:22
- S/I Coverage: 4 cm
- Through-plane resolution: 2 mm
- In Plane resolution: $0.94 \times 0.94$ mm

$= 61$
Navier Stokes Relative Pressure Calculation

\[ \frac{dV}{dy} \]
\[ \frac{dV}{dx} \]
\[ \frac{dV}{dz} \]
\[ \Delta^2 V \]

\[ .63 \times .63 \times .63 = 0.25 \text{ mm}^3 \]

\[ 2.5 \times 2.5 \times 3 = 19 \text{ mm}^3 \]

PC VIPR

3DPC*

In-Vitro Pressure Drop Validation

94% (area) stenosis in 7mm vessel
Pressure relative to input
A New Challenge to The Nyquist Theorem

Candès and Romberg (Cal Tech) and Tao (UCLA) have shown that the number of Fourier samples needed to generate an exact reconstruction of an object is not $N^3$ but instead is about equal to twice the number of occupied pixels in the image.

Iterative reconstruction methods have been used to produce exact reconstructions with angular undersampling factors of $\sim 20$ in 2D for noise-free images. In our experience the addition of noise degrades performance.
Undersampling in $k$-space and Time

In PR TRICKS radial undersampling is performed in $k_x$ and $k_y$ while $k_z$ is sparsely sampled in time, producing an undersampling factor of 18

Vigen KK, et.al.
Recently investigators have developed iterative algorithms that use data from an entire time-resolved acquisition to constrain the reconstruction of individual time frames.


**Highly constrained back Projection**

HYPR
HYPR VIPR Reconstruction Using Highly Constrained Backprojection

\[ S_1 = \frac{w_1}{w_1 + w_2} \quad \text{and} \quad S_2 = \frac{w_2}{w_1 + w_2} \]
Comparison of Conventional Filter Back Projection and HYPR

No. of Projections

<table>
<thead>
<tr>
<th>No. of Projections</th>
<th>FBP</th>
<th>HYPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td><img src="image" alt="FBP 4" /></td>
<td><img src="image" alt="HYPR 4" /></td>
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<td>10</td>
<td><img src="image" alt="FBP 10" /></td>
<td><img src="image" alt="HYPR 10" /></td>
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Anticipated HYPR VIPR Parameters for Velocity and Pressure Measurements

256 x256 x256  30 phases/ cardiac cycle

3 minute scan  undersampling factor = 500
predicted SNR= 1.7 * present VIPR
that undersamples by 50.

Time for equivalent scan obeying the Nyquist Theorem
(k-space speed limit)

23 hour scan
Mistretta, Wieben, et. al., submitted to MRM
Undersampled 3D Projection
MRA
HYPR VIPR

Speed

35,000 mph*

acceleration = 500

*Assuming Nyquist Speed Limit of 70 mph
Multi-Detector CT

Axial Geometry (z-Direction)

Coverage Comparison in 5-Heart Beats

10mm detector
Pitch ~0.25
3cm in 5 sec

20mm detector
Pitch ~0.25
6.2cm in 5 sec

40mm detector
Pitch ~0.25
12.5cm in 5 sec

5-Beat Cardiac™ CT

Courtesy of Jiang Hsieh  GE Healthcare
Flat Panel Cone Beam CT

64 slice CT
4mm coverage
~2000 focal spots/s
ΔT (coronaries)~ 150ms

Flat panel Cone Beam CT
400mm coverage
~30 focal spots/s
Flat-Panel Cone-Beam CT

300 – 600 projections through 360°
(512x512x512) reconstruction

Siewerdsen and Jaffray, Princess Margaret Hospital, University of Toronto
Flat-Panel Cone-Beam CT

Imaging Technique:
110 kVp
1 mAs / proj  (512 × 512 × 384) voxels
$N_{proj} = 300$  $T_{acq} \sim 10$ s – 5 min
$D_0 \sim 0.5$ cGy  $T_{recon} \sim 12$ min

Siewerdsen and Jaffray, Princess Margaret Hospital, University of Toronto
Benchtop platform for advanced applications

Cone-Beam CT

Dual-Energy Imaging

Bone Image  Tissue Image

Siewerdsen and Jaffray, Princess Margaret Hospital, University of Toronto
Flat-Panel Cone-Beam CT

• A promising modality for IG procedures
  - Multi-mode Rad / Fluoro / CBCT
  - Open geometry; Mechanically simple

PerkinElmer RID-1640
Elekta Synergy
Linac Platform for IG Radiation Therapy

Siewertsen and Jaffray, Princess Margaret Hospital, University of Toronto

IGRT of the Prostate:

\[ N_{proj} = 330 \]
\[ T_{acq} = 2 \text{ min} \]
\[ 512^3 \text{ voxels} \]
\[ D_0 = 1.1 \text{ cGy} \]
Flat-Panel Cone-Beam CT

• A promising modality for IG procedures
  - Multi-mode Rad / Fluoro / CBCT
  - Open geometry; Mechanically simple

Varian 4030CB

Siemens PowerMobil

Isocentric C-arm for IG Surgery

Siewerdsen and Jaffray, Princess Margaret Hospital, University of Toronto
Evaluation of interventional procedures using C-arm based tomosynthetic perfusion imaging

Initial CBCT recons

Chen, et al.

One set of synthesized planes per second

Circular tomosynthetic motion
State-of-the-art cone-beam image reconstruction algorithms via filtered backprojection (FBP)

A. Katsevich, SIAM J. APPL. MATH, Vol. 62, 2012-2026 (2002);


E. Sidky, Y. Zou, and X. Pan, Proc. 8th Fully 3D Conference, Salt Lake City, 291-294 (2005);

G.H. Chen, T. Zhuang, B.E. Nett, S. Leng, Proc. 8th Fully 3D Conference, Salt Lake City, 295-299 (2005);

T. Zhuang, B. E. Nett, S. Leng, G. H. Chen, Proc. 8th Fully 3D Conference, Salt Lake City, 337-341 (2005);

State-of-the-art cone-beam image reconstruction algorithms via filtering the backprojection image of differentiated projection data (FBPD)


The Fourier transform of an image object is a weighted sum over the source trajectory of translated Fourier transforms of the $1/r$ weighted backprojection data.

Chen et. Al.
Extension of Undersampled 3D Acquisition to X-Ray CT?
64 slice CT
4mm coverage
~2000 focal spots/s
$\Delta T$ (coronaries)$\sim 150$ms

Flat panel Cone Beam CT
400mm coverage
~30 focal spots/s

Z scan CT 15 sources
400mm coverage
~2000 focal spots/s
$\Delta T$ (coronaries)$\sim 10-15$ms*

Design goal
Z-Scan X-Ray CT

- Detectors
- Rotating gantry
- 1 ms X-ray pulses
- Collimator plates
- X-ray cone
- Detectors (1 2D frame/ms)
“Z-Scan” Simulation Phantom

“Z-Scan” signal = attenuation in 1mm vessel following IV iodine

Focal sphere diameter: 600 mm

Gaussian noise added

Noise unit $\sigma$ = attenuation made by “Z-Scan” feature
Simulated 1mm coronary artery imaged in 10 ms using iv injection and gating.
*Assuming Nyquist Speed Limit of 70 mph

- HYPR VIPR Speed: 35,000 mph*
- Zscan CT Road Under Construction
With thanks for slides and videos from

Guang-Hong Chen
Brian Nett
Jeff Siewerdsen
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Dennis Foley
Willi Kalender