Temporal Fidelity in MRI Time Series

Stephen J. Riederer, Ph.D.
Mayo Clinic
Rochester MN USA

BASP Conference
Villars-sur-Ollon, Switzerland
September 8, 2011

Theme / Outline

- **Fundamental tradeoff in MRI: spatial vs. temporal resolution**
- **Available tools**
  - Dimensionality of acquisition (1D-2D-3D)
  - Ordering of k-space sampling
  - View sharing
  - Parallel acquisition
- **Evaluation Criteria**
- **Results**

Early Example of Time-Resolved MRI

Early 1990s: Cardiac/Coronary MRI

- 3D images required 10^1-10^2 sec of data
- Need to limit acquisition to specific cardiac phase to avoid cardiac motion artifact
- Breathold: short acquisition time caused inadequate spatial resolution
- Extended acquisition times led to respiratory-motion-corrupted images.
- Q: How to extend acquisition time for high spatial resolution but without artifact?

Real-Time Navigator Echoes

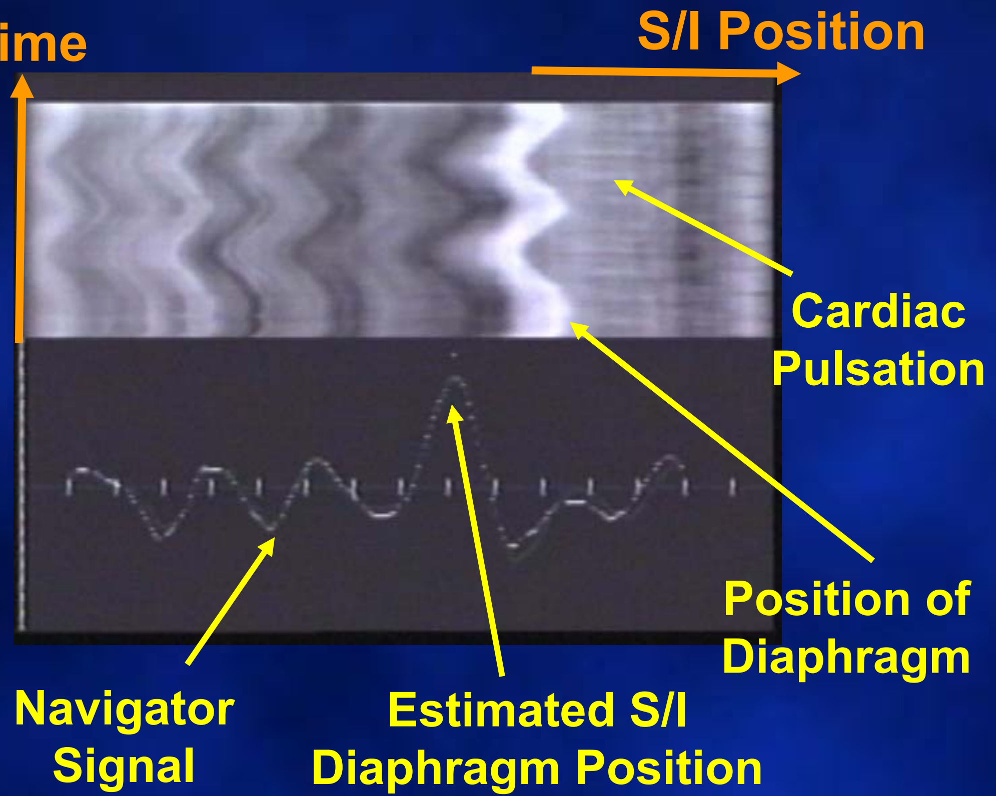
- **Line scan (1D) excitation**
  - Excitation of line (1-2 cm dia column) directed S/I through dome of liver
  - Frequency encode along line
  - Spatial resolution along line ≈ 0.5 mm
  - Temporal resolution = TR ≥ 20 msec
- **Immediate (msec) reconstruction**
- **Use S/I position to guide associated 3D acquisition in some fashion**
  - e.g. gate within specific respiratory phase

Real-Time Navigator Echoes

Respiratory Motion

[Video]

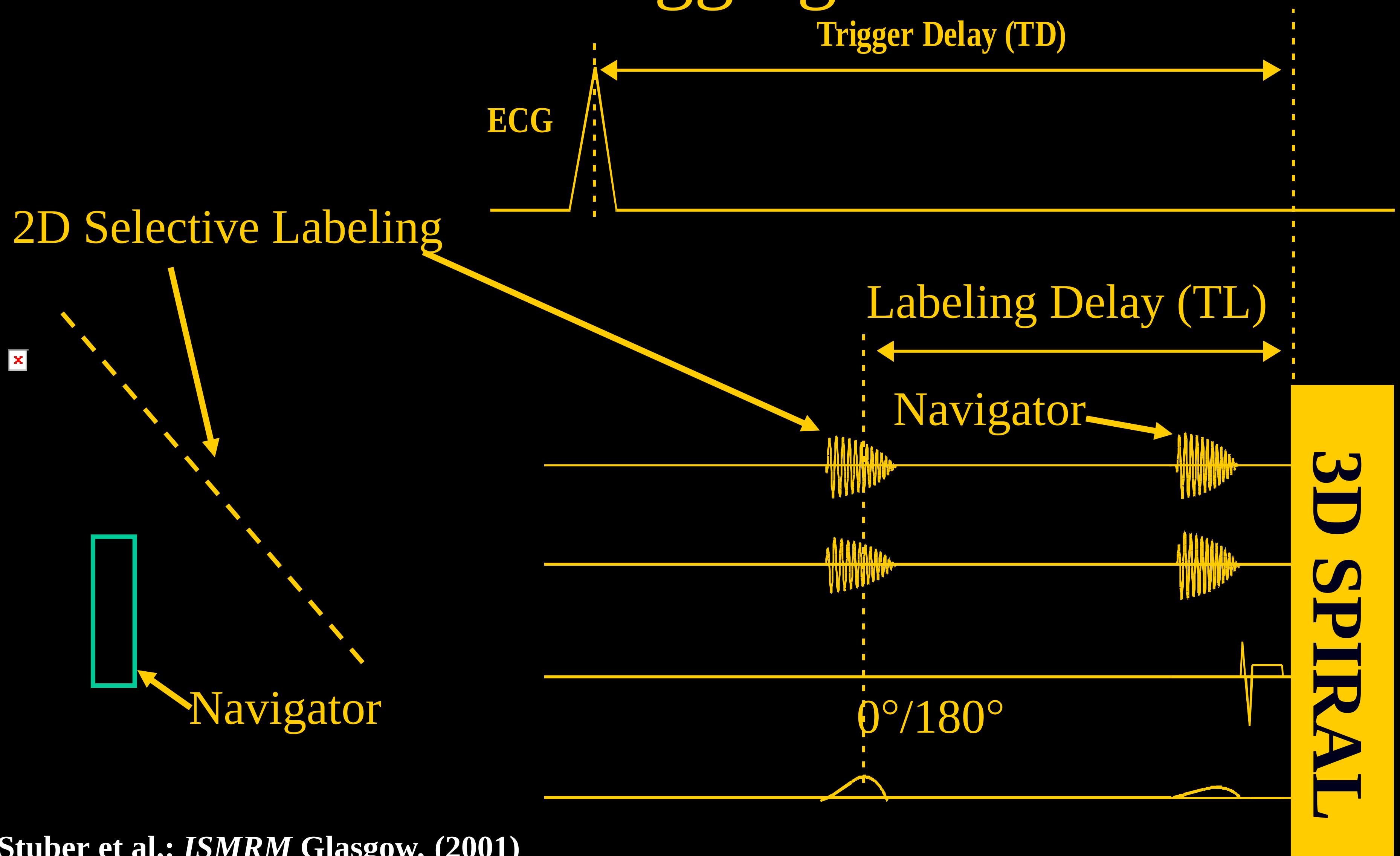
Navigator Echoes



[Video]

Liu and Riederer, MRM 1993

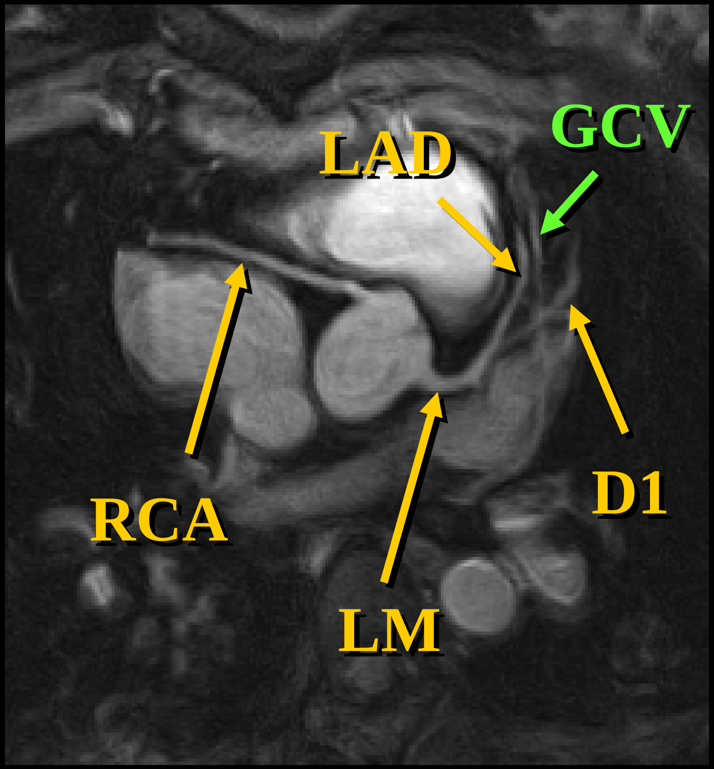
Free Breathing 3D Aortic Spin Tagging



Stuber et al.: *ISMRM* Glasgow, (2001)

Free Breathing 3D Aortic Spin Tagging

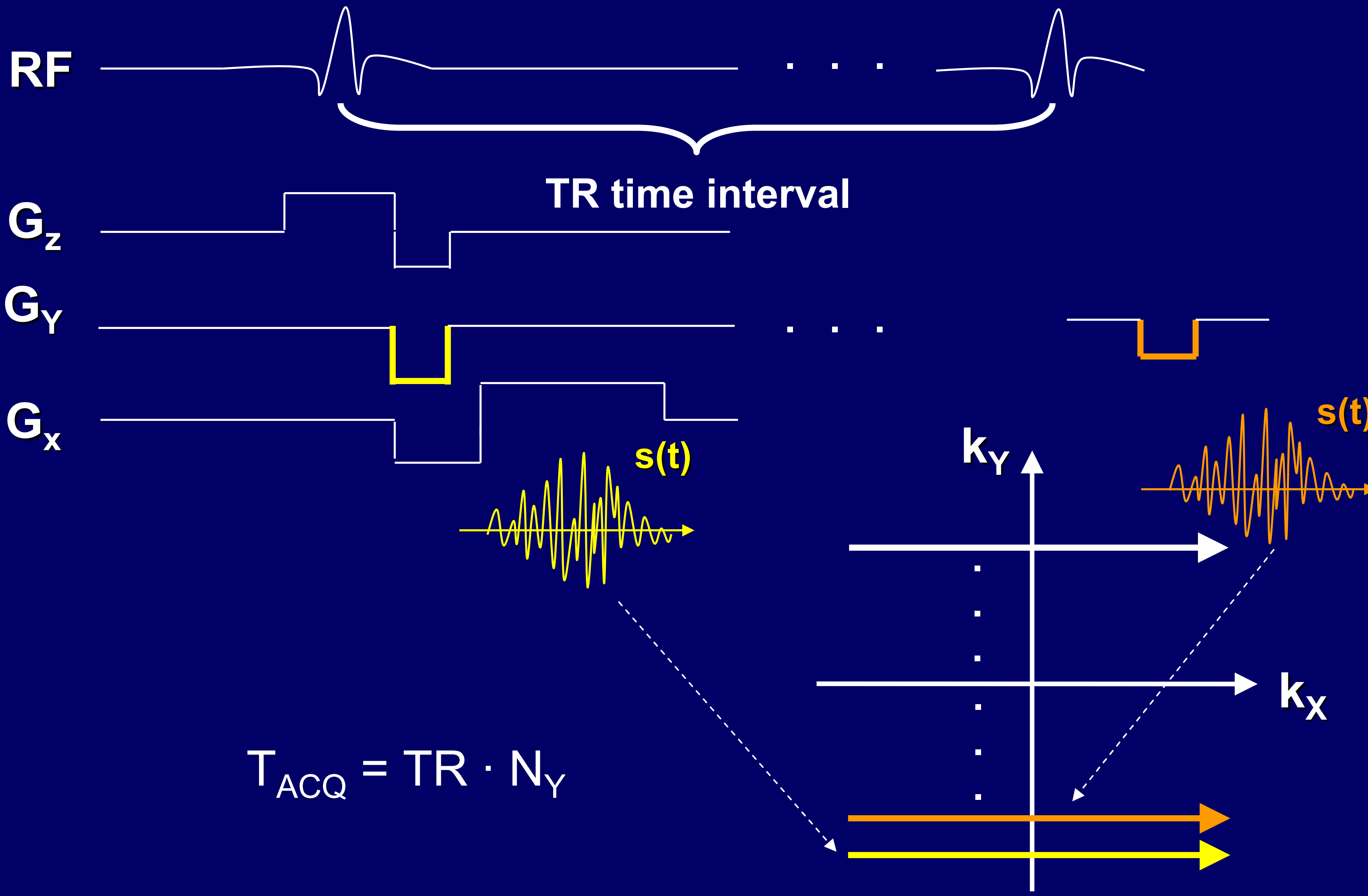
Anatomical Coronary MRA



Aortic Spin Labeling
TL=350ms

Stuber et al.: *ISMRM* Glasgow, (2001)

Data Acquisition and 2D k-Space in MRI



$T_{ACQ} = TR \cdot N_Y$

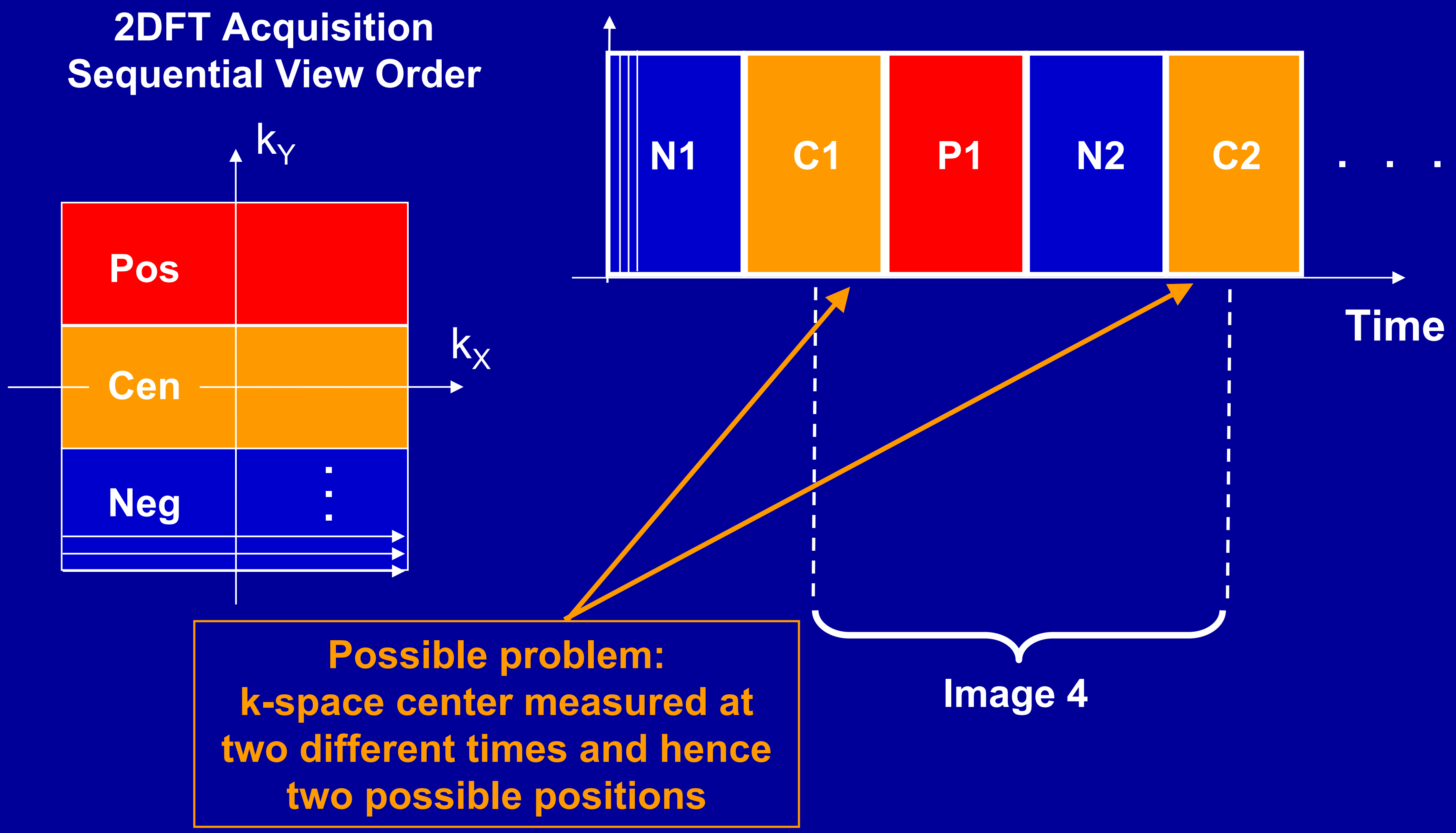
View Sharing

- *Motivation:* provide frame time shorter than intrinsic image acq time of MRI
- Continuous cyclical sampling of k-space using some ordering
- Reconstruct a full image after only partial replacement of the k-space data
- Potential to sample central k-space more frequently than periphery
- Successive images in sequence are correlated:

  frame time ≠ temporal resolution

Riederer et al, MRM 1988

View Sharing Example



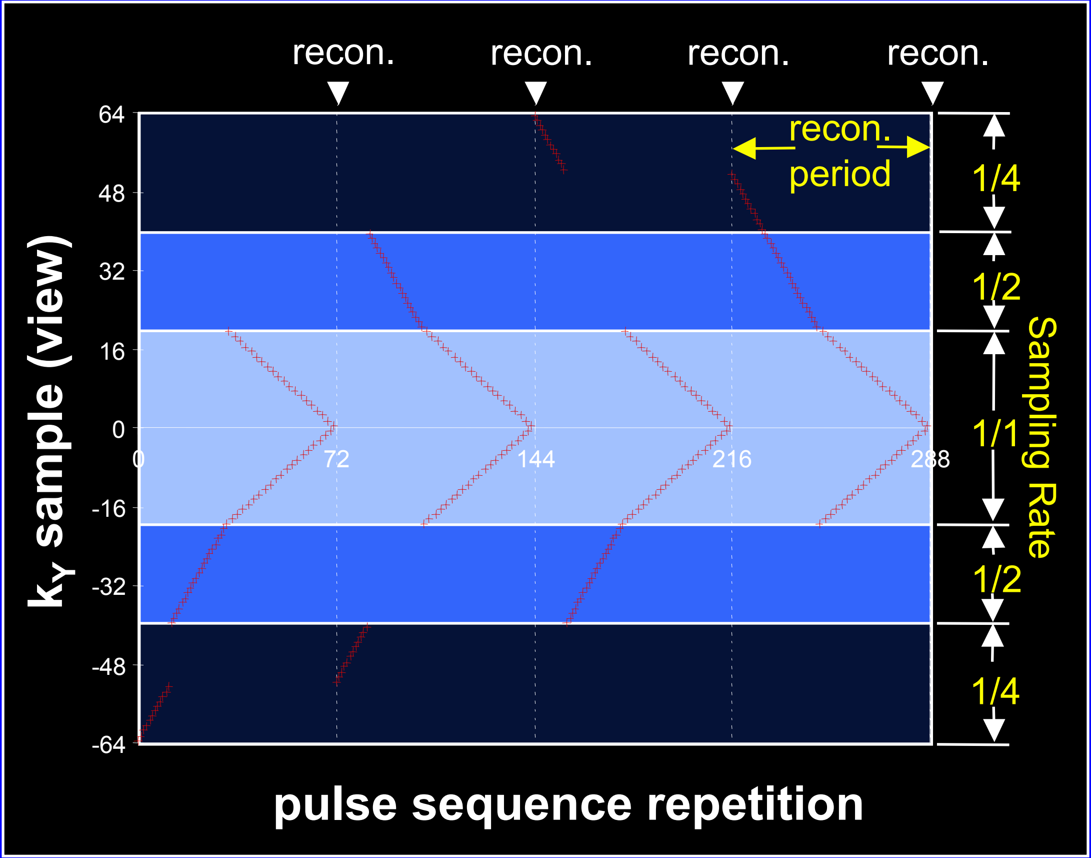
Evaluation of Time-Resolved MRI

Need for criteria beyond those used for static images

- Actual temporal resolution - as opposed to image update rate
- Latency – delay from actual occurrence to display of event
- Artifacts – dispersion of signal; robustness of acquisition to motion
- Consistency – ability to smoothly portray continuous motion

Flexible View Ordering Algorithm

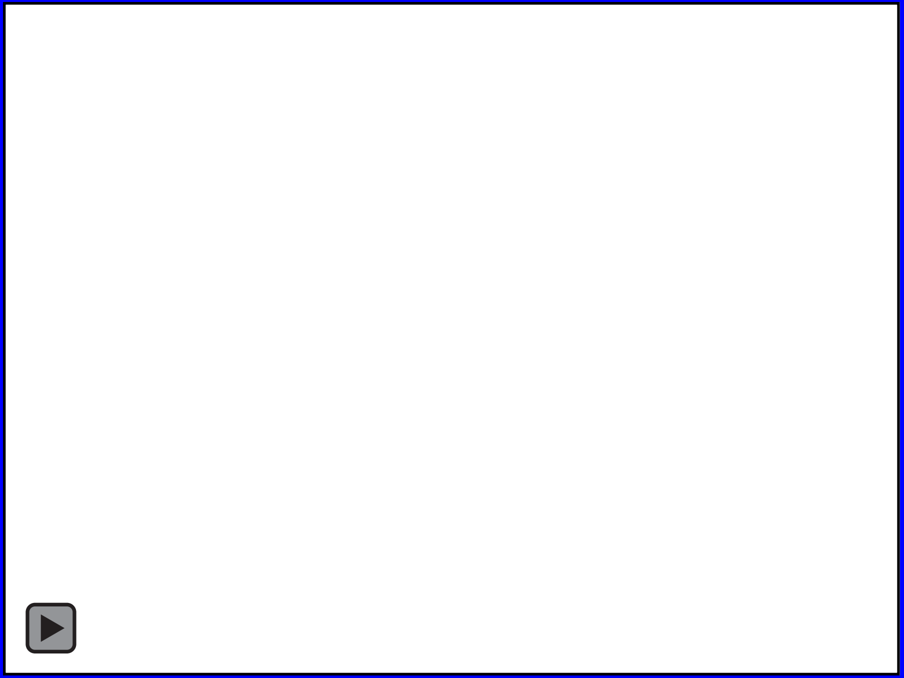
- Reconstruction: sample central k-space at the recon rate
- Latency: sample central k-space just prior to recon (reverse centric)
- Dispersion: sample in large blocks to minimize k-space discontinuities
- Consistency: sample in a consistent pattern w.r.t. reconstruction timepoints

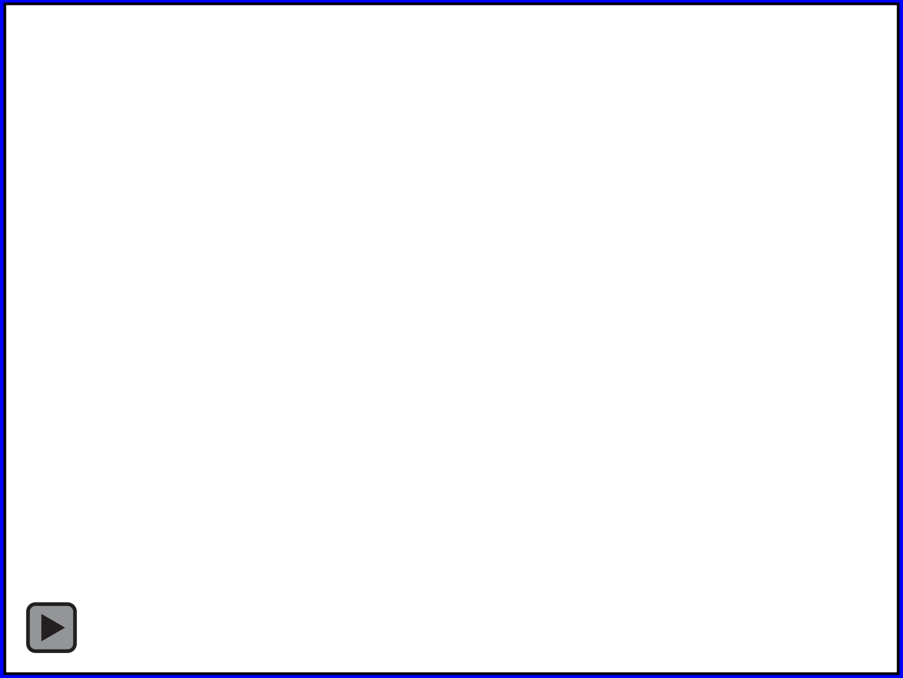


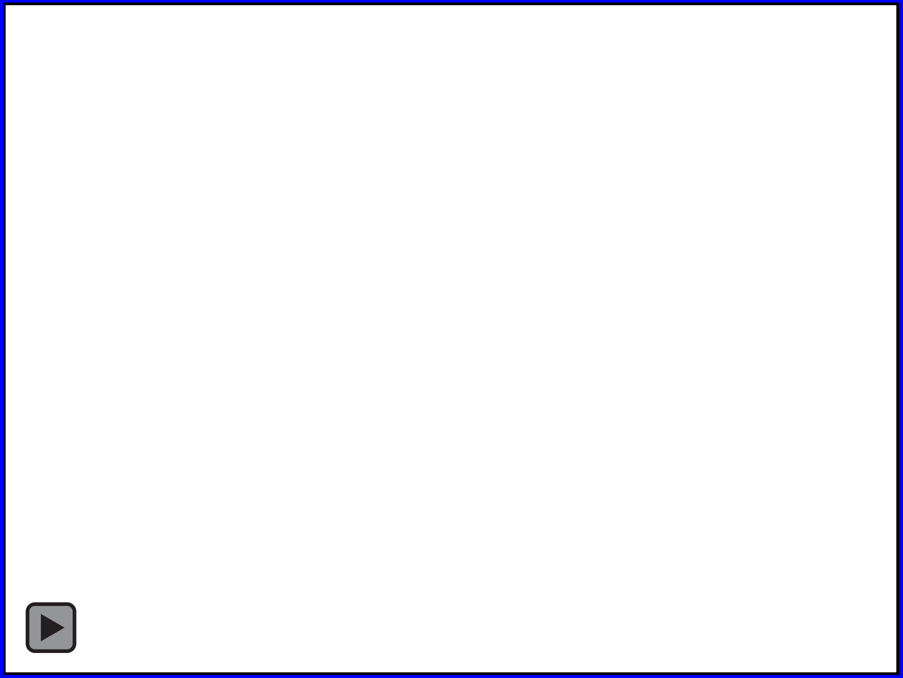
Make view ordering dependent on reconstruction rate

Recon-Dependent View Order

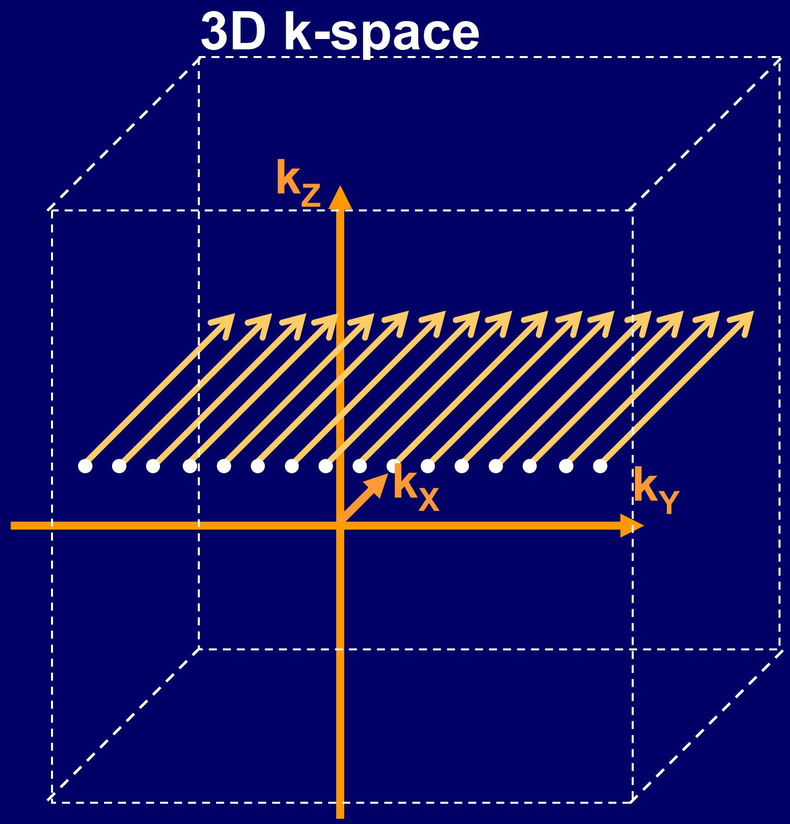
(rotating phantom)





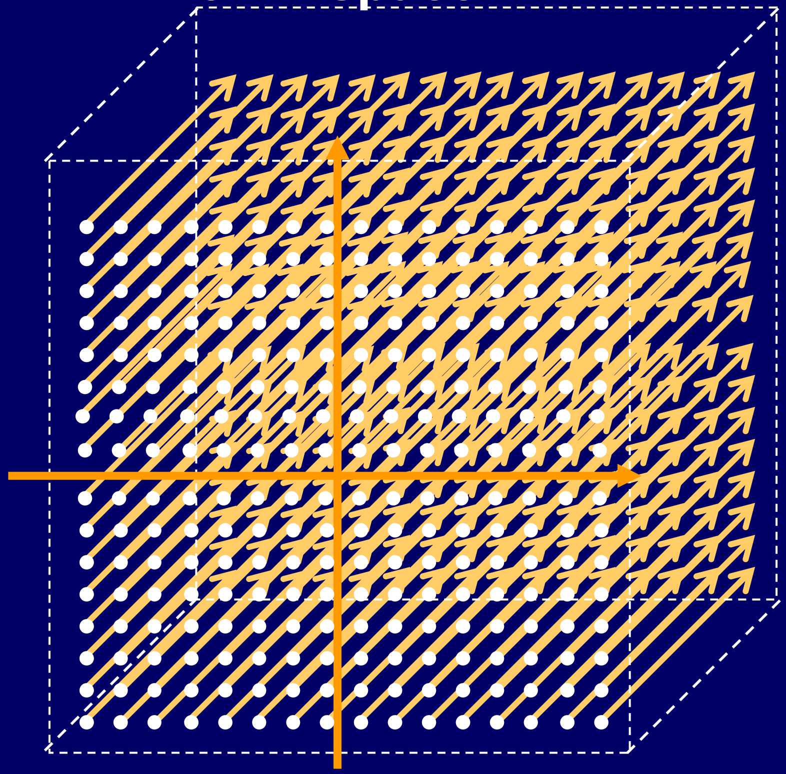


3DFT Imaging



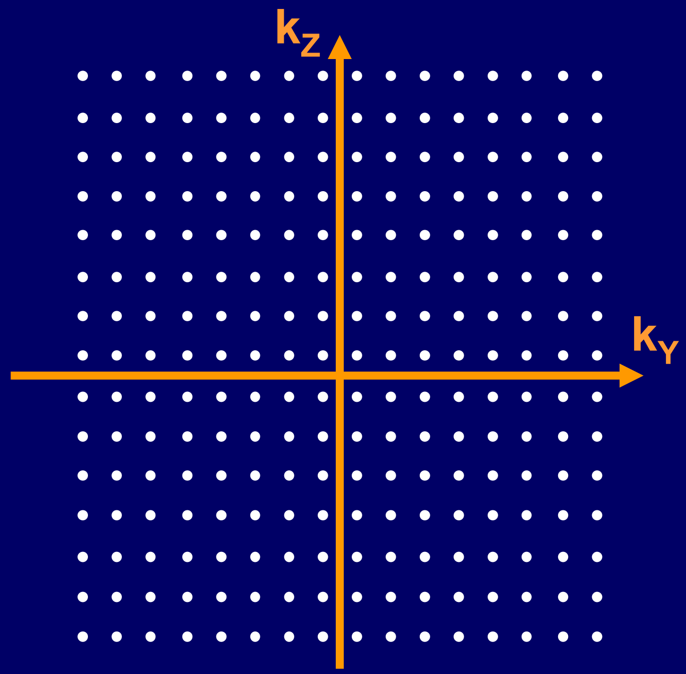
3DFT Imaging

3D k-space



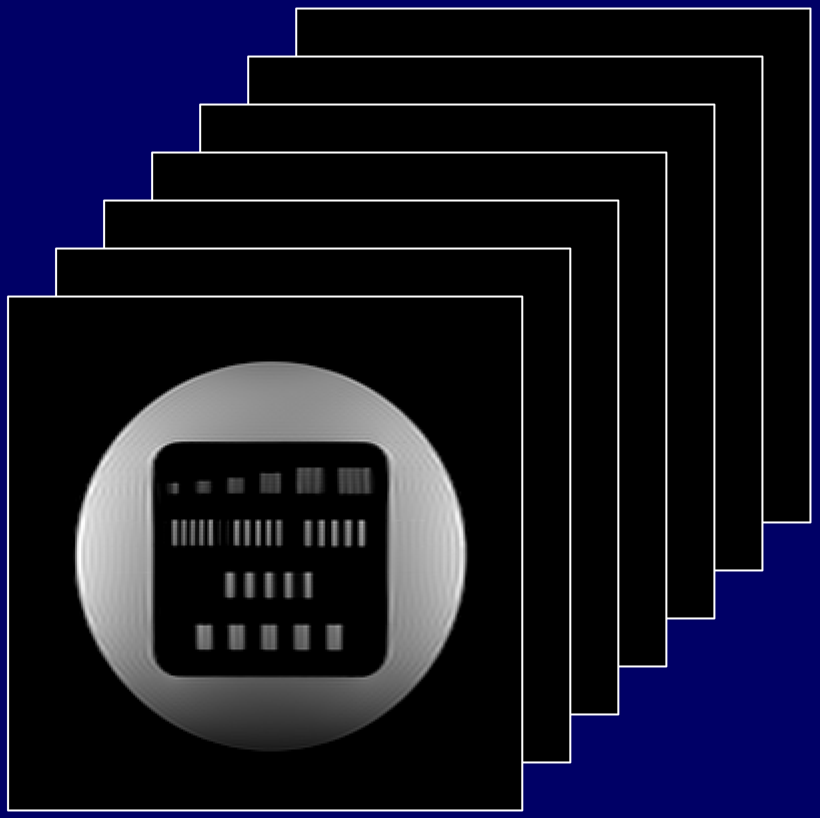
3DFT Imaging

3D k-space



3D FT

3D Image Space

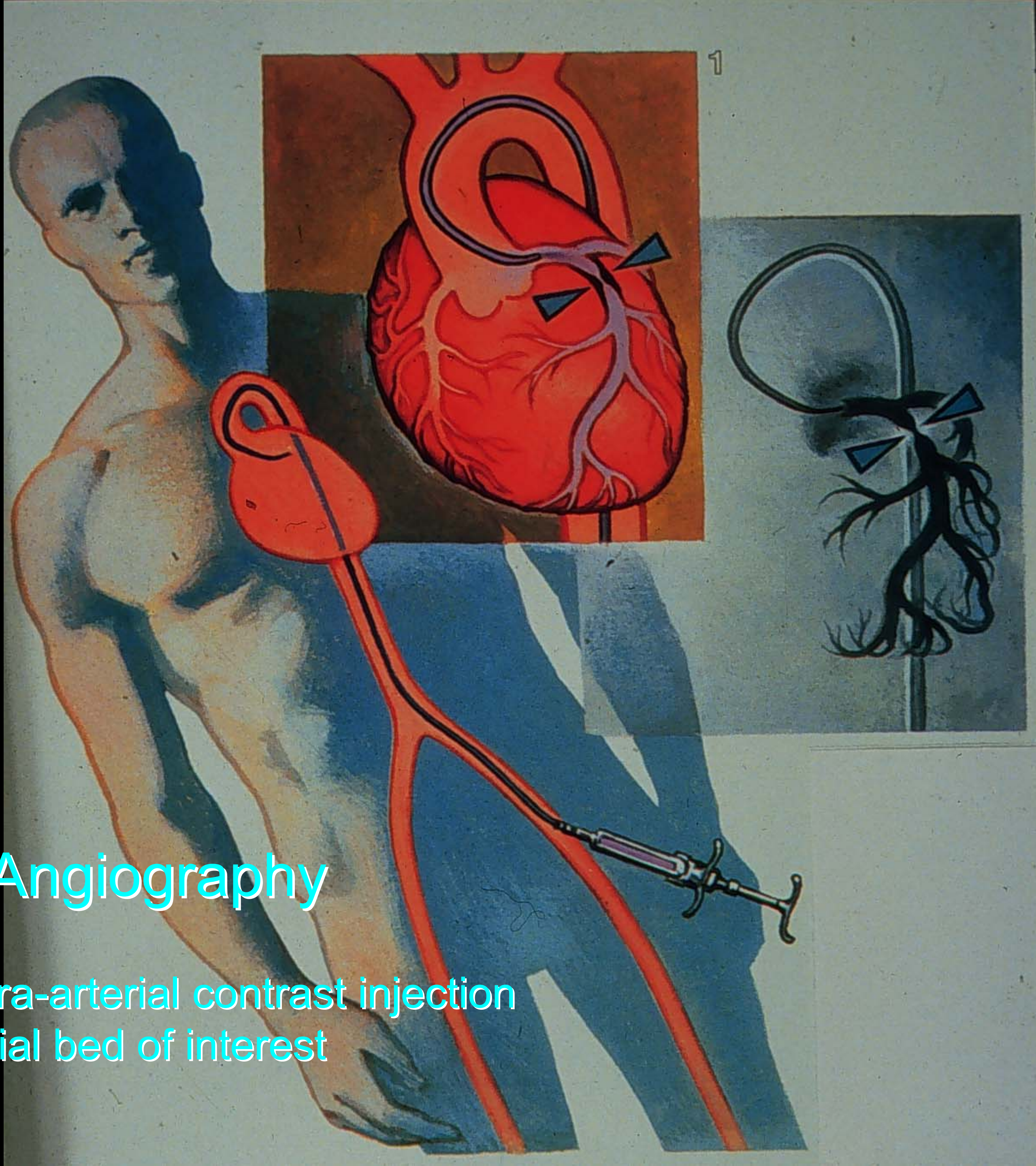


$$T_{ACQ} = TR \cdot N_Y \cdot N_Z$$

$$= 5 \text{ msec} \cdot 128 \cdot 64 = 40 \text{ sec}$$

X-ray Angiography

Direct intra-arterial contrast injection
Into arterial bed of interest



Non-invasive Angiography

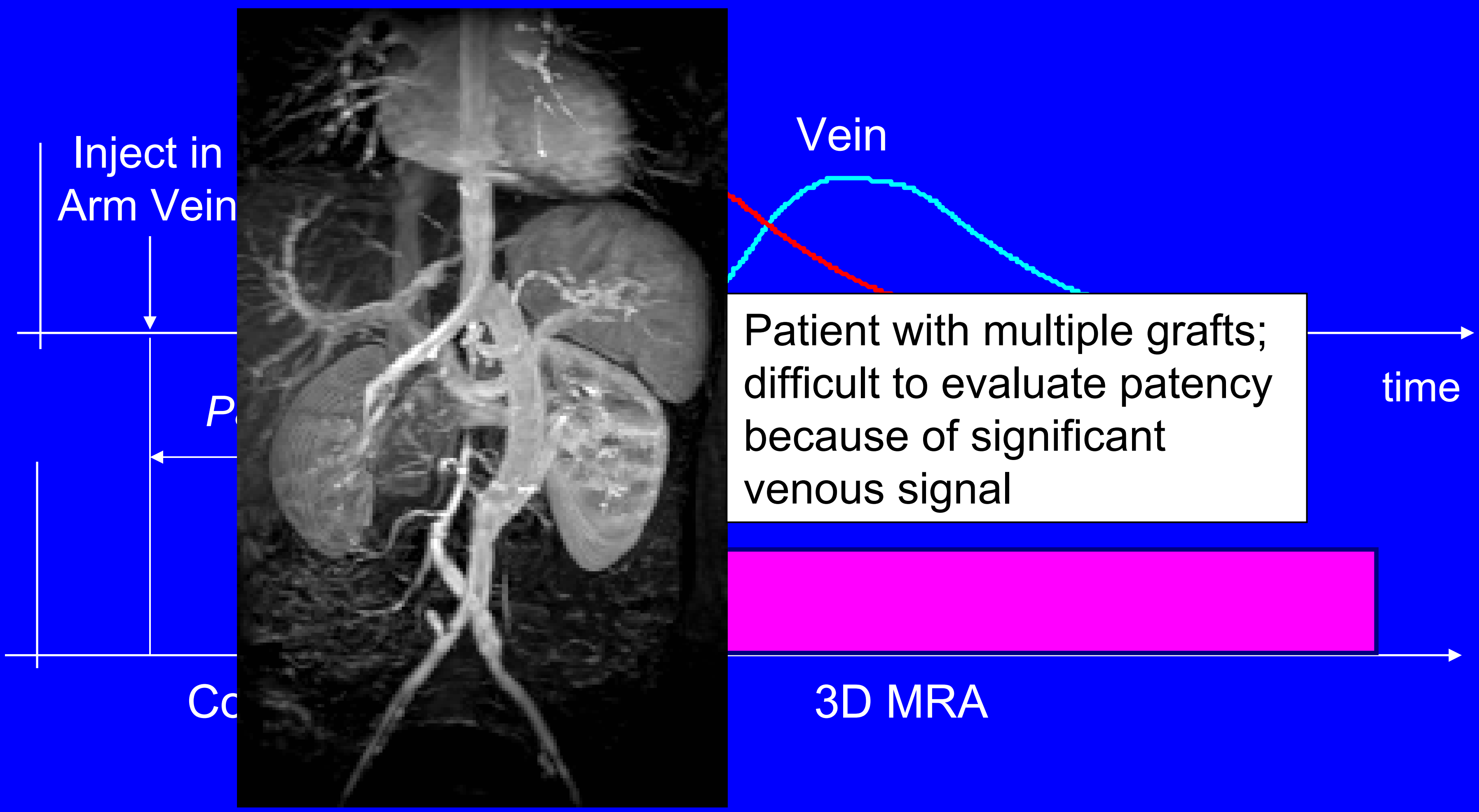
- X-ray angiography uses arterial injection and has an associated risk of complication.
- Contrast-enhanced MR angiography (CE-MRA) offers:
  - Intravenous contrast injection
  - Essentially no risk
  - No ionizing radiation
  - 3D format

Prince, Radiol 1995

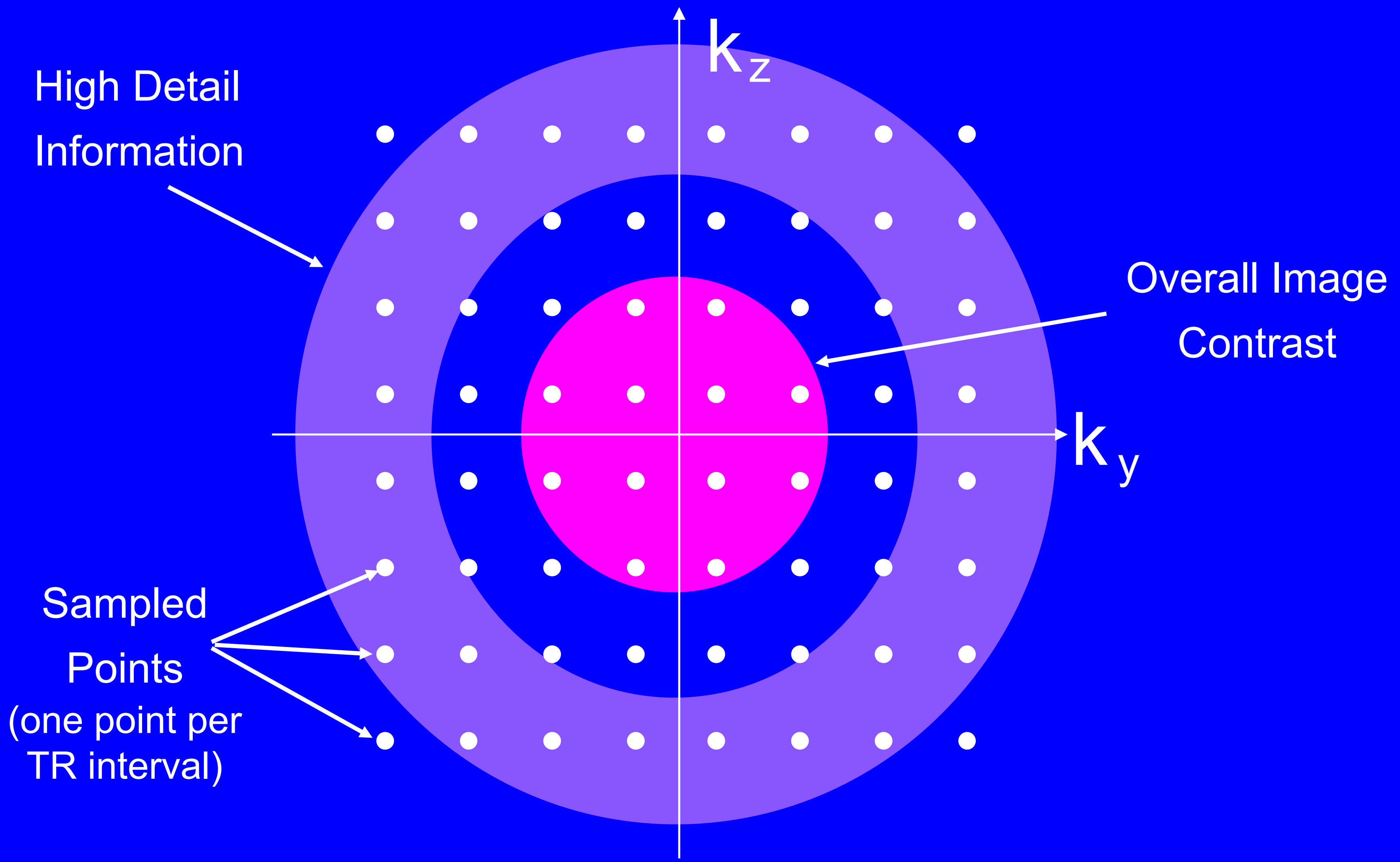
Ordering of k-Space Sampling

- Target application:
  Contrast-enhanced MR angiography
- The limited arterial phase (~ 10 sec or less) of the contrast bolus may limit the spatial resolution.
- Extended acquisition time provides improved spatial resolution but also confounding venous enhancement.
- How to get high resolution arterial phase images?

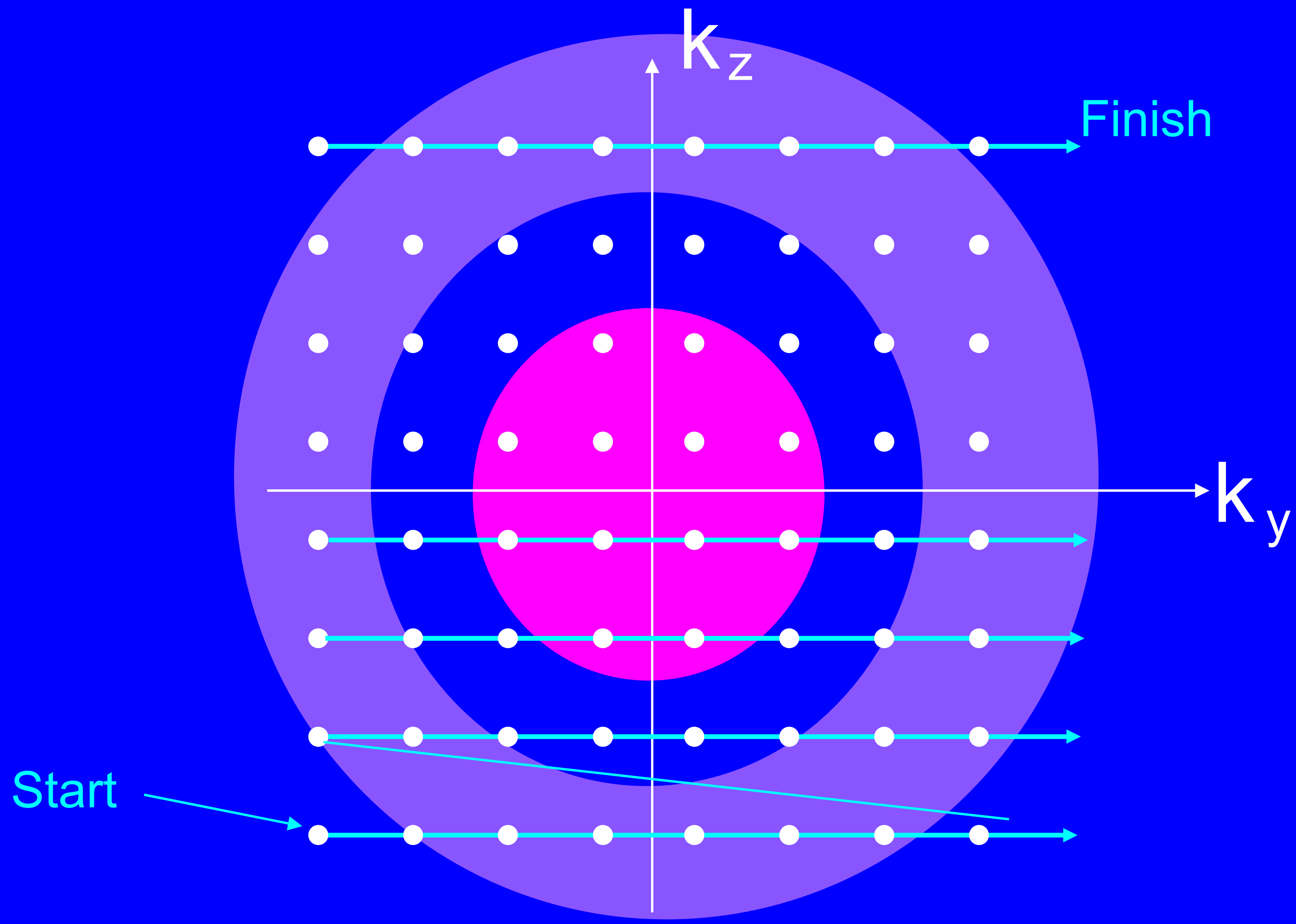
Contrast-Enhanced MRA - Timing



k-Space for 3D Acquisition

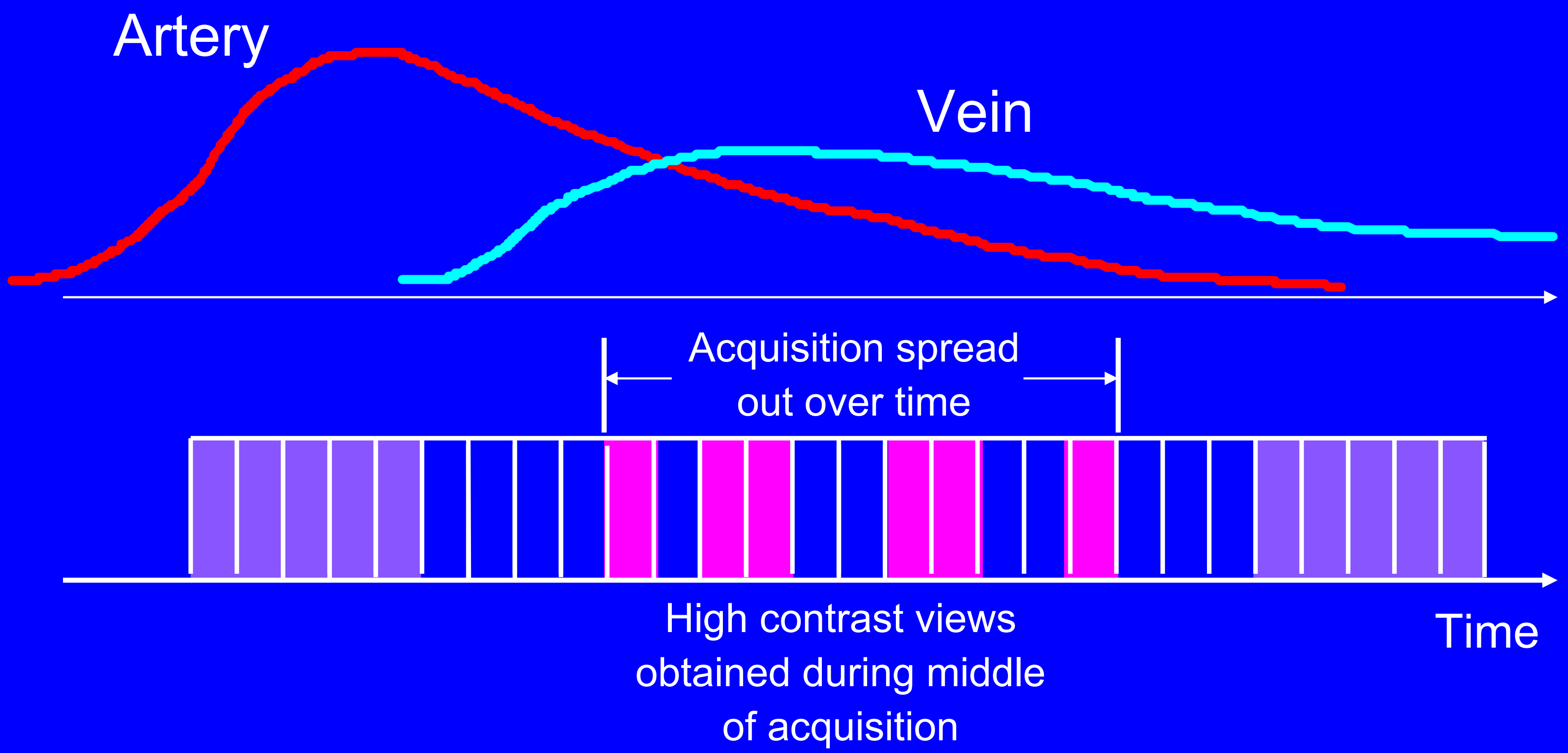


k-Space: Sequential View Order

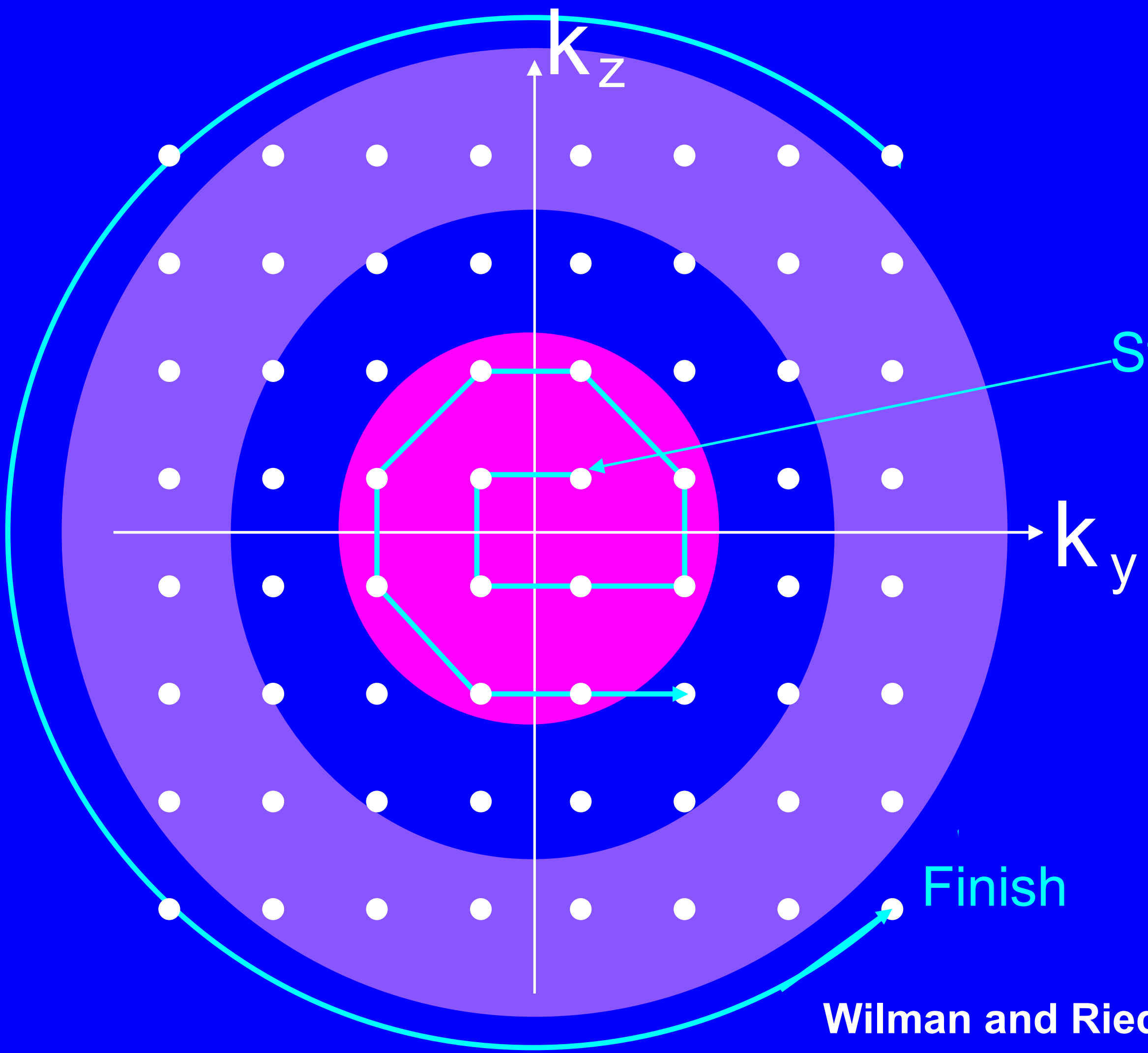


Sequential View Order

Timing with respect to Contrast Bolus



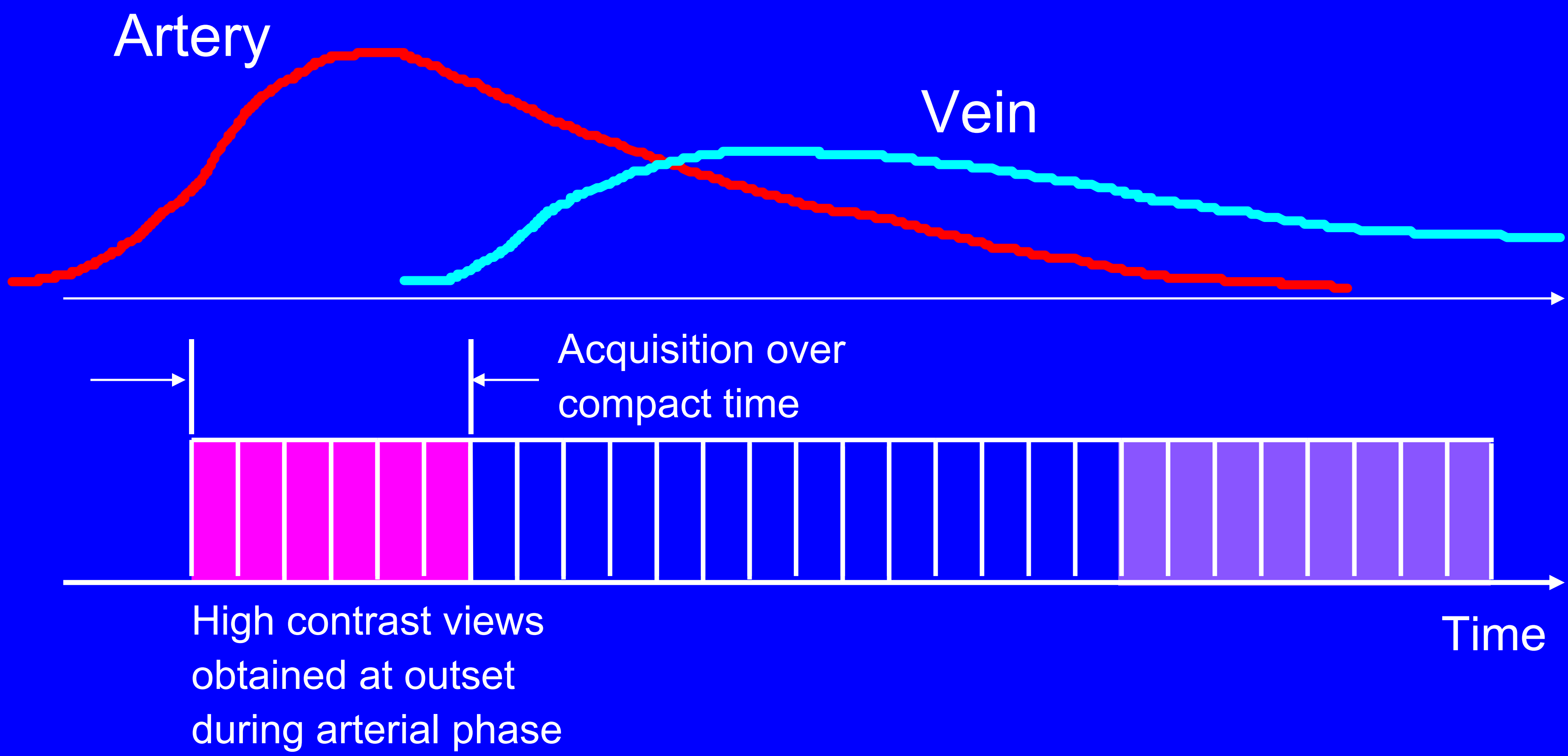
k-Space: Elliptical Centric View Order



Wilman and Riederer, MRM 1997

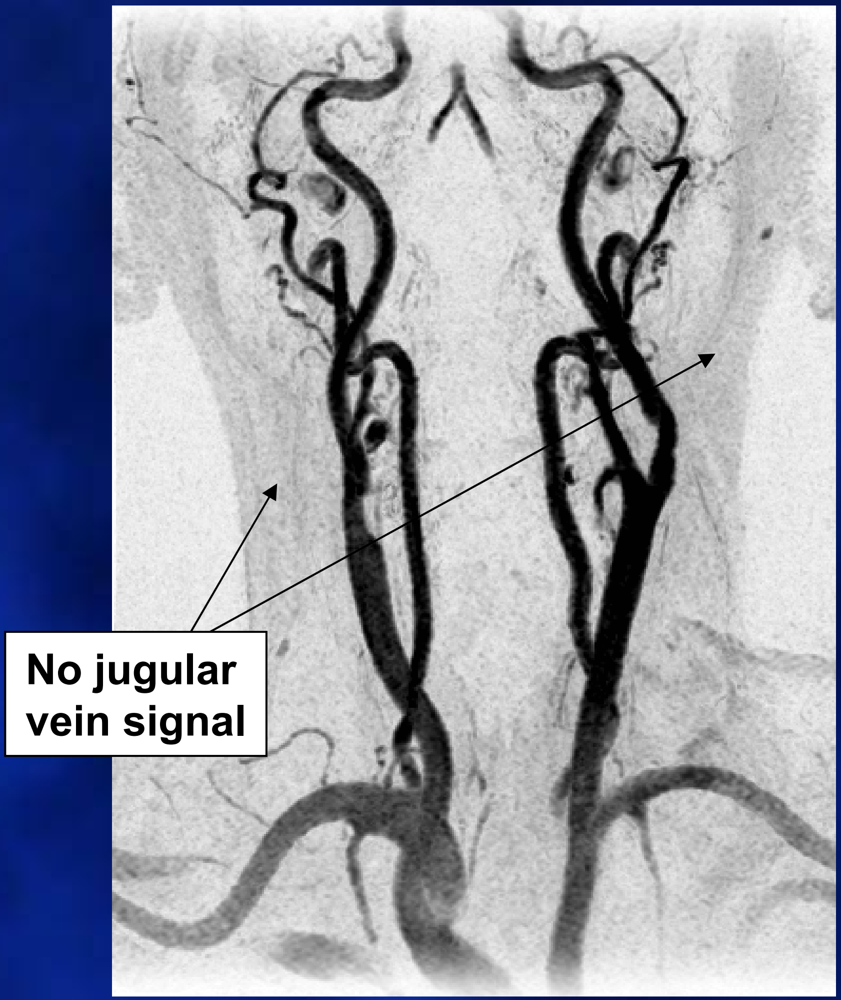
Elliptical Centric View Order

Timing with respect to Contrast Bolus

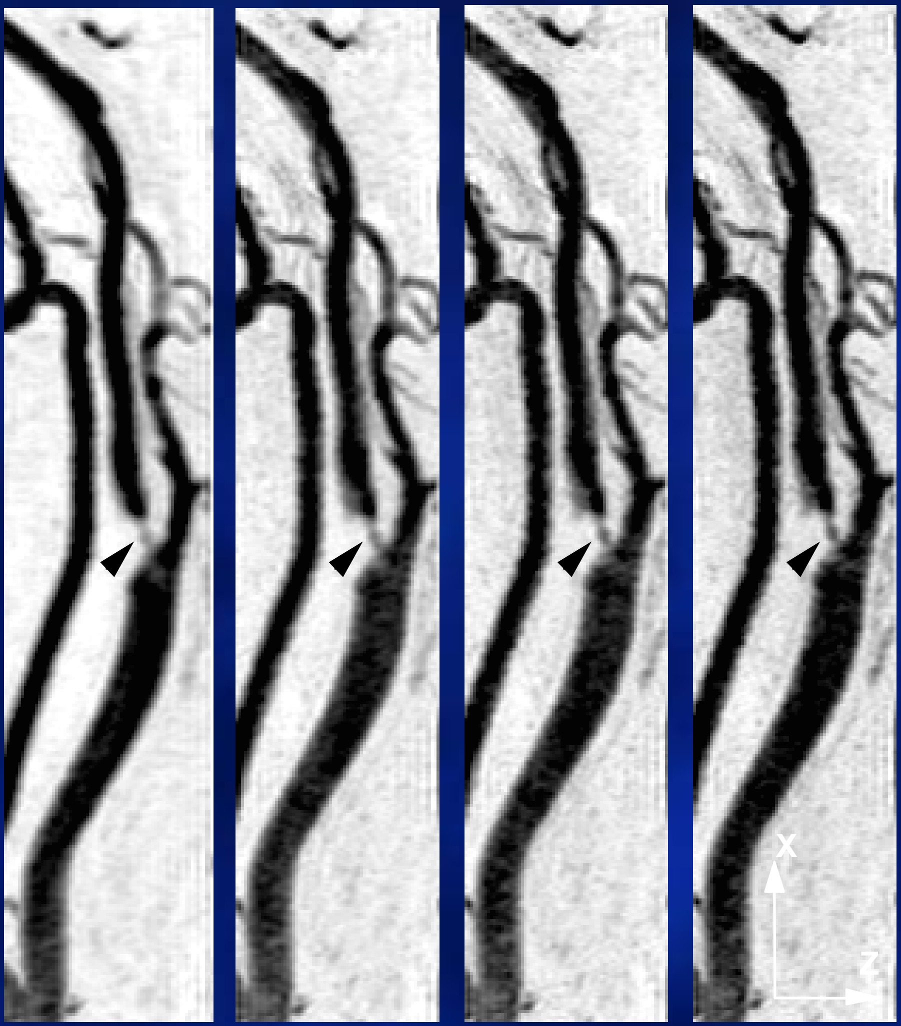


Spatial Resolution in CE MRA

Importance of Acquisition Time – Clinical Example



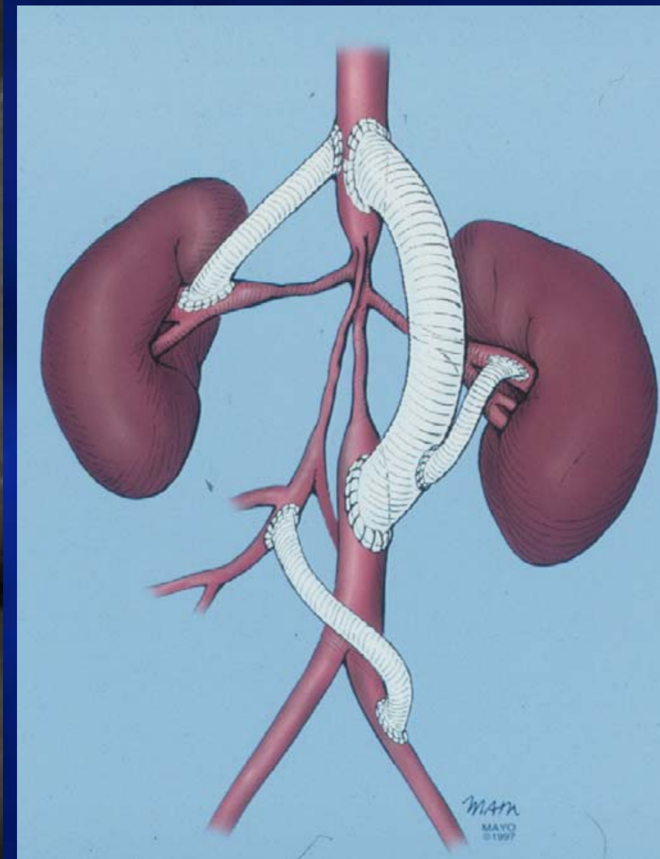
Acquisition Time: **11 sec** **22 sec** **33 sec** **44 sec**



Sequential vs. Elliptical Centric View Order for 3D CE-MRA

Sequential: significant venous contamination

Elliptical centric: primarily arterial phase



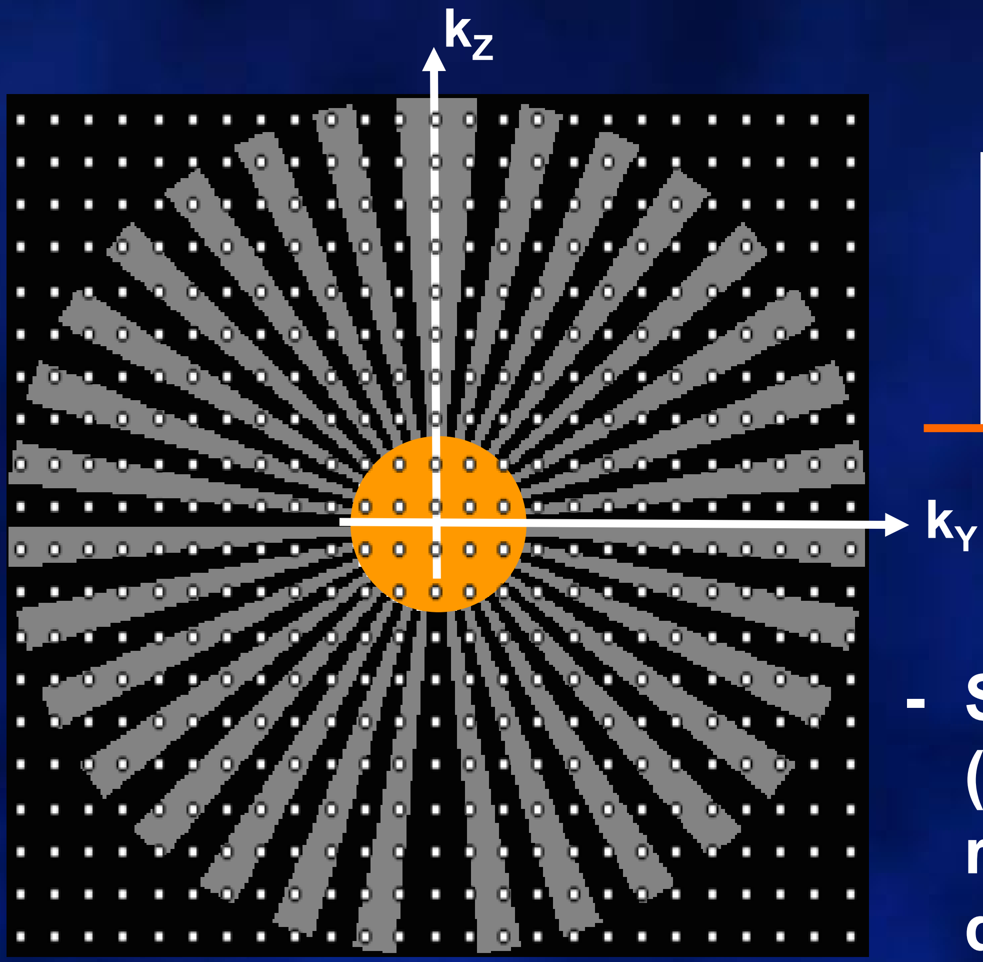
Phase Encoding (PE) View Order

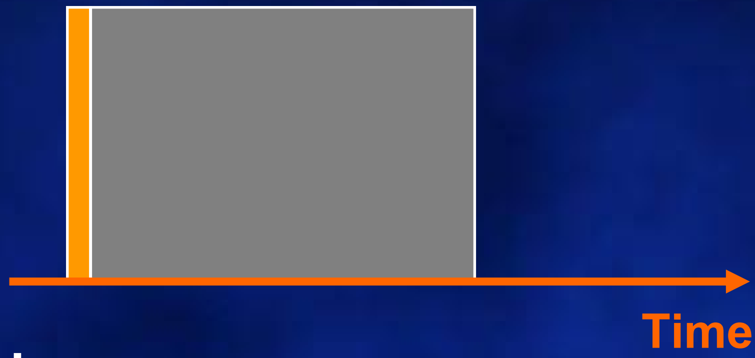
- **The view order can "focus" the acquisition on the status of the object at the time the central views are acquired.**
- **Applicable to**
  - One P.E. direction $\mathbf{k_Y}$, for 2DFT acquisition
  - Two P.E. directions $\mathbf{k_Y}$ and $\mathbf{k_Z}$ (3DFT)
- **View ordering is also the basis for the effective echo time TE in RARE / Fast-spin-echo imaging.**

Conversion to Time-Resolved Acquisition

- **3DFT acquisition**
  - 2D (k_Y-k_Z) phase encoding plane
- **Elliptical centric phase encode order**
- **View sharing**
- **Compatibility with parallel acquisition**

Standard Elliptical Centric Acquisition



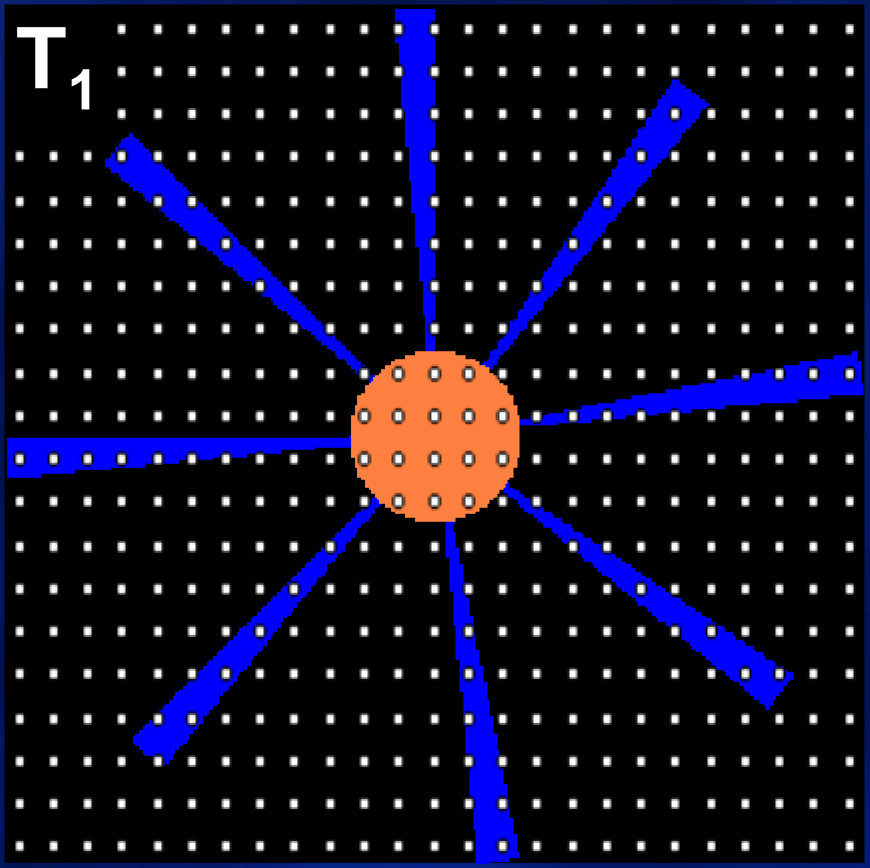


- Start at k-space center (orange region); order of readout is according to distance from center
- Possibly sample only the gray vanes in outer region (partial Fourier)

Cartesian Acquisition with Projection-Reconstruction-like Sampling (CAPR)

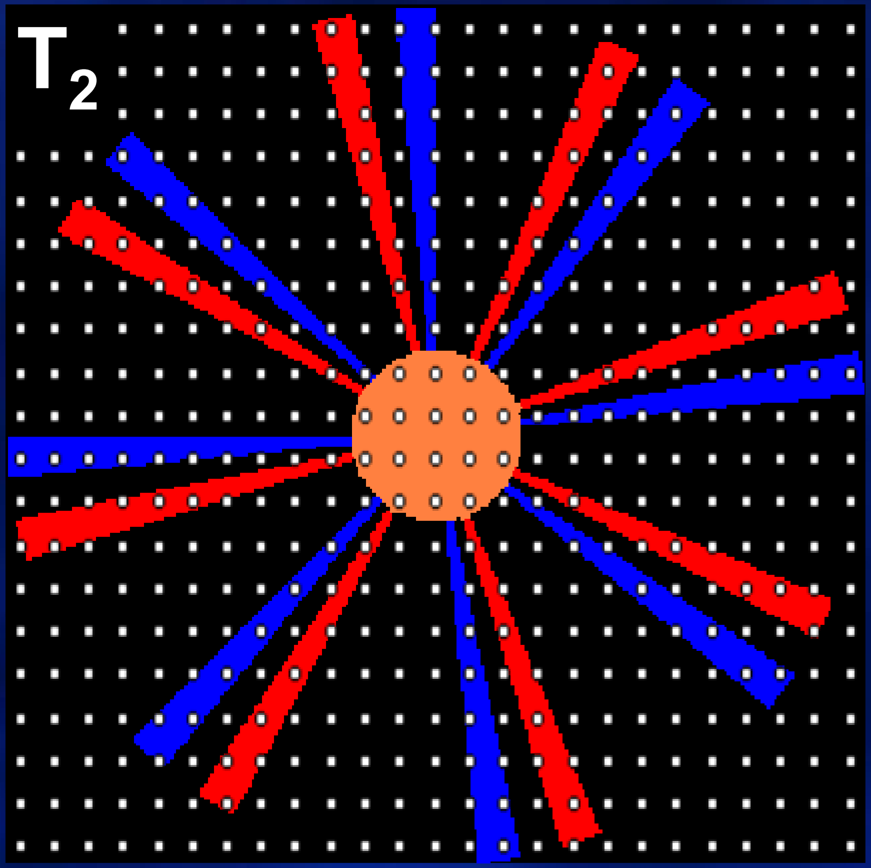
- Subdivide outer vanes into groups (shown subsequently in colors)
- Use view sharing
- Sample k-space center more frequently

CAPR k-Space Sampling Pattern



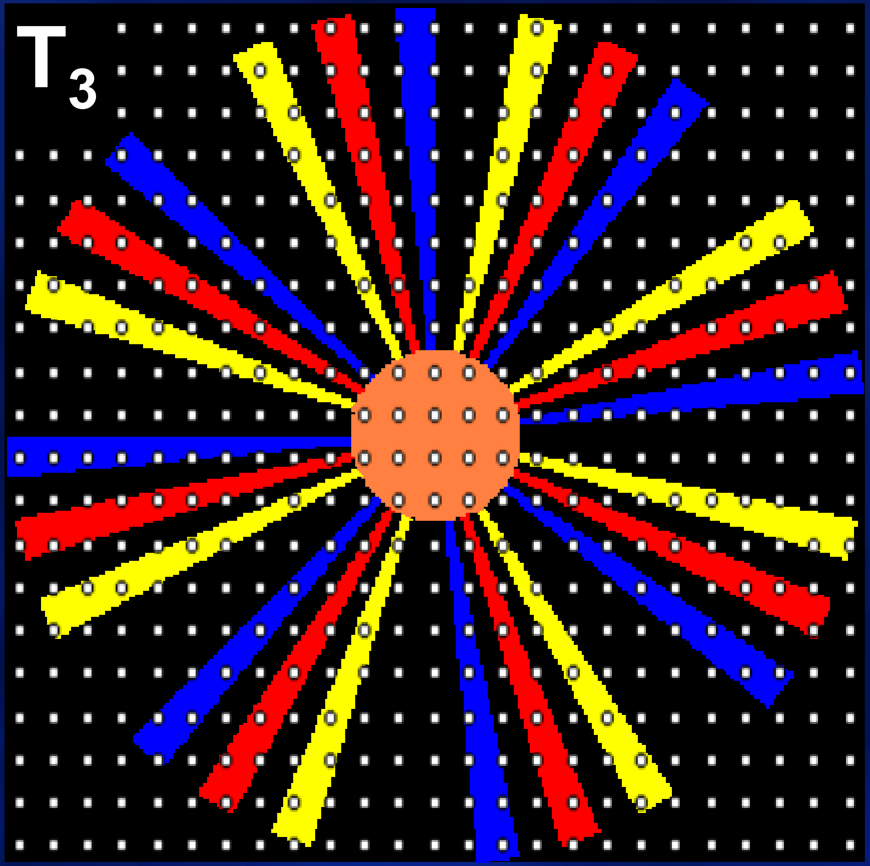
CAPR k-Space Sampling Pattern

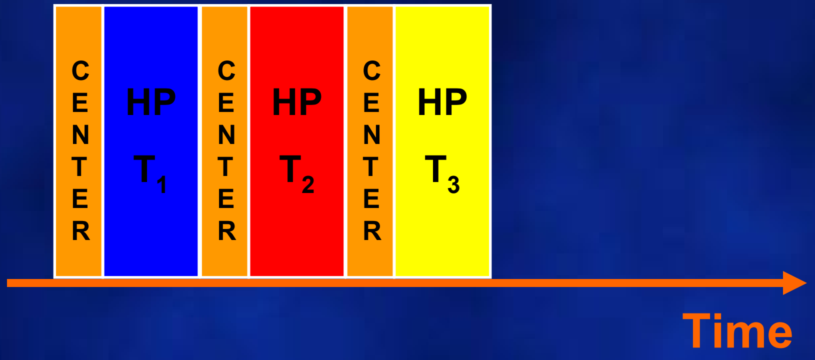
k_y-k_z Plane



CAPR k-Space Sampling Pattern

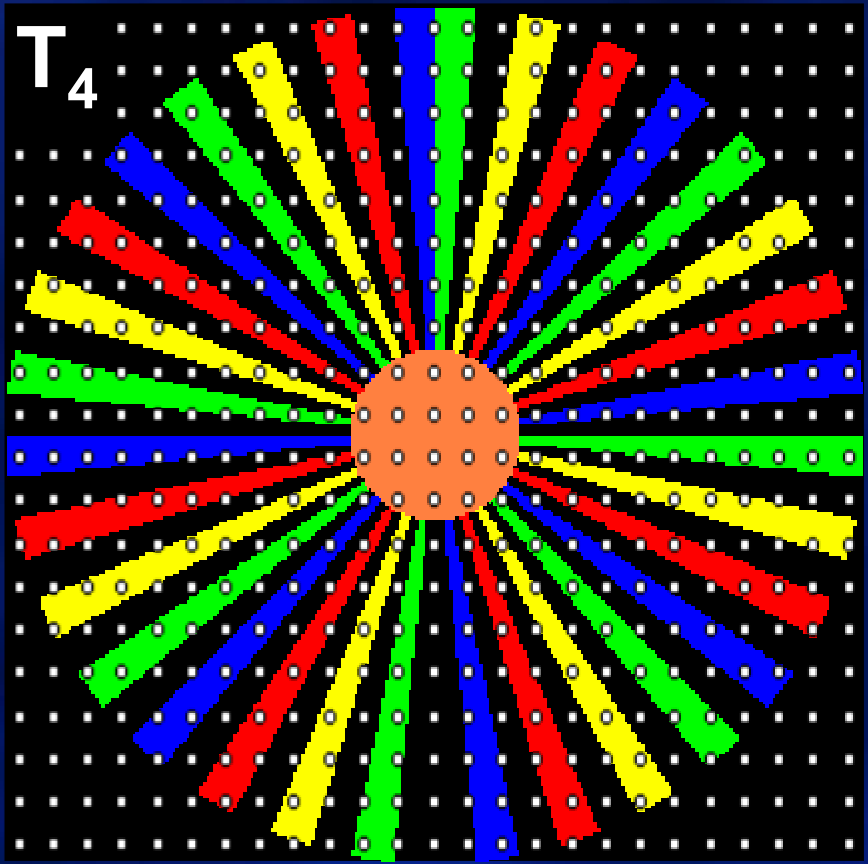
k_y-k_z Plane

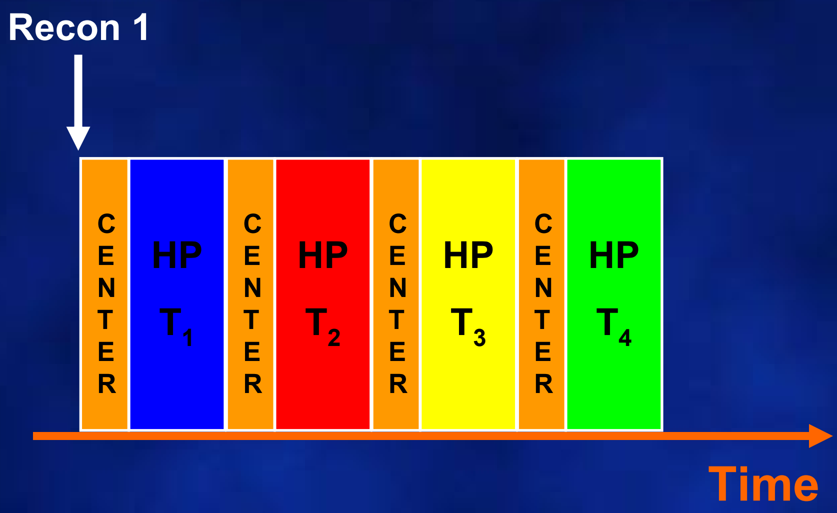




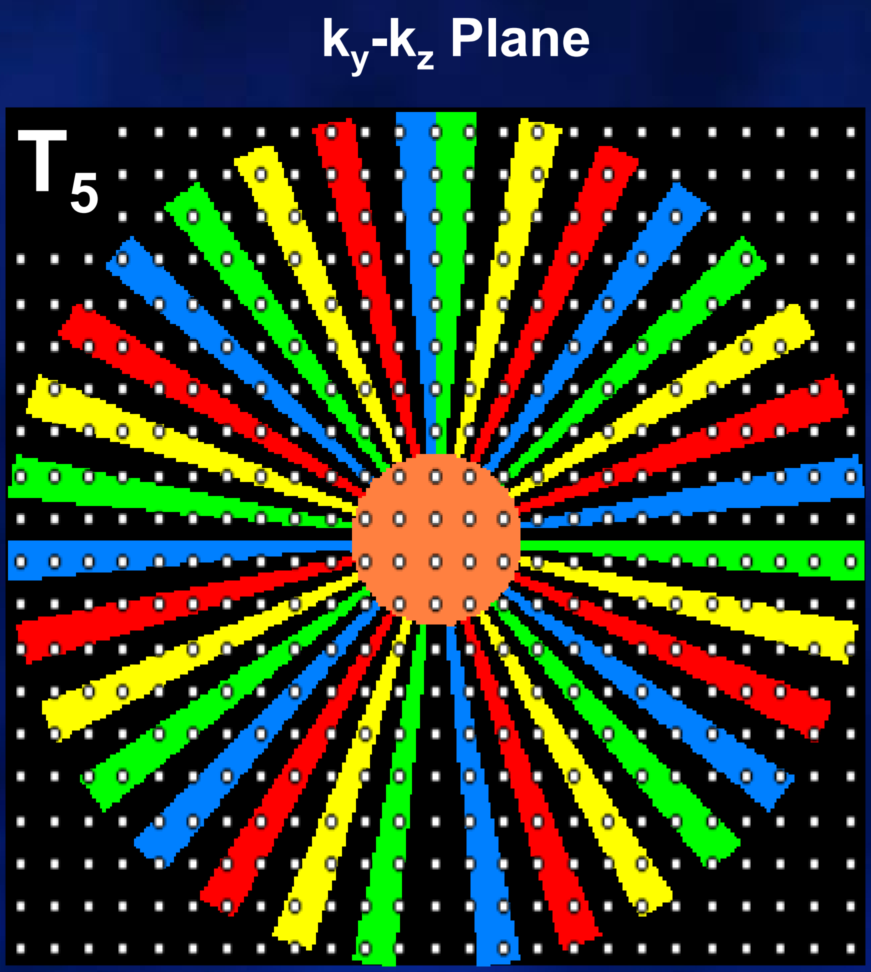
CAPR k-Space Sampling Pattern

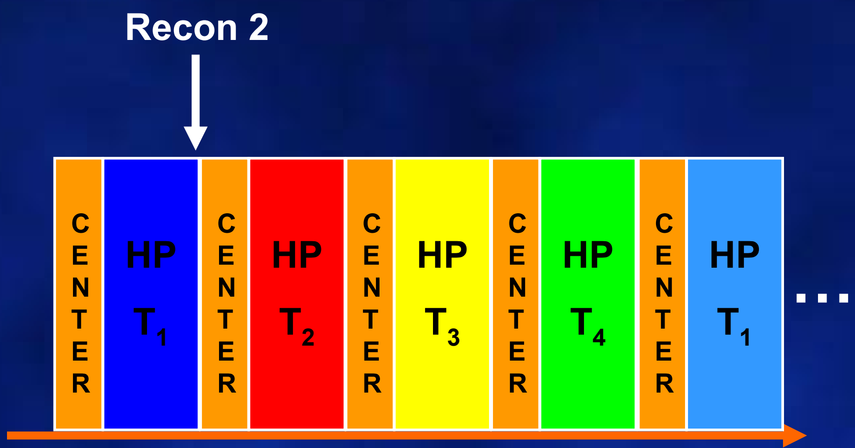
k_y-k_z Plane





CAPR k-Space Sampling Pattern

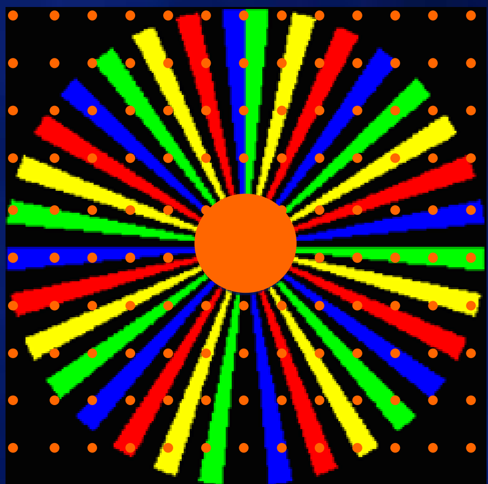


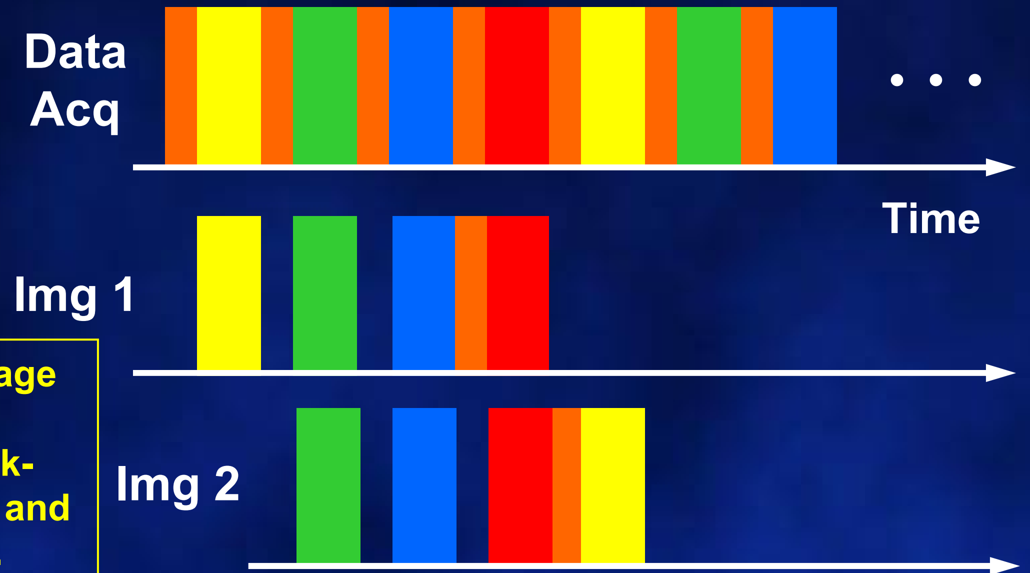


For each new frame the k-space center and one vane set are updated (blue vane set in this example).

Image Formation and Temporal Footprint

k_Y-k_Z space



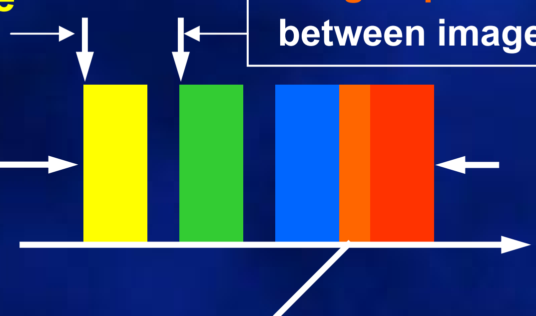


Each new image is formed by updating the k-space center and one vane set.

The Temporal Footprint can be used to characterize any time-resolved technique

Image Update Time: time between images; ≈ 5 sec

Temporal footprint duration: time over which any views used for image formation are acquired ≈ 20 sec



Footprint for all images is identical for consistency

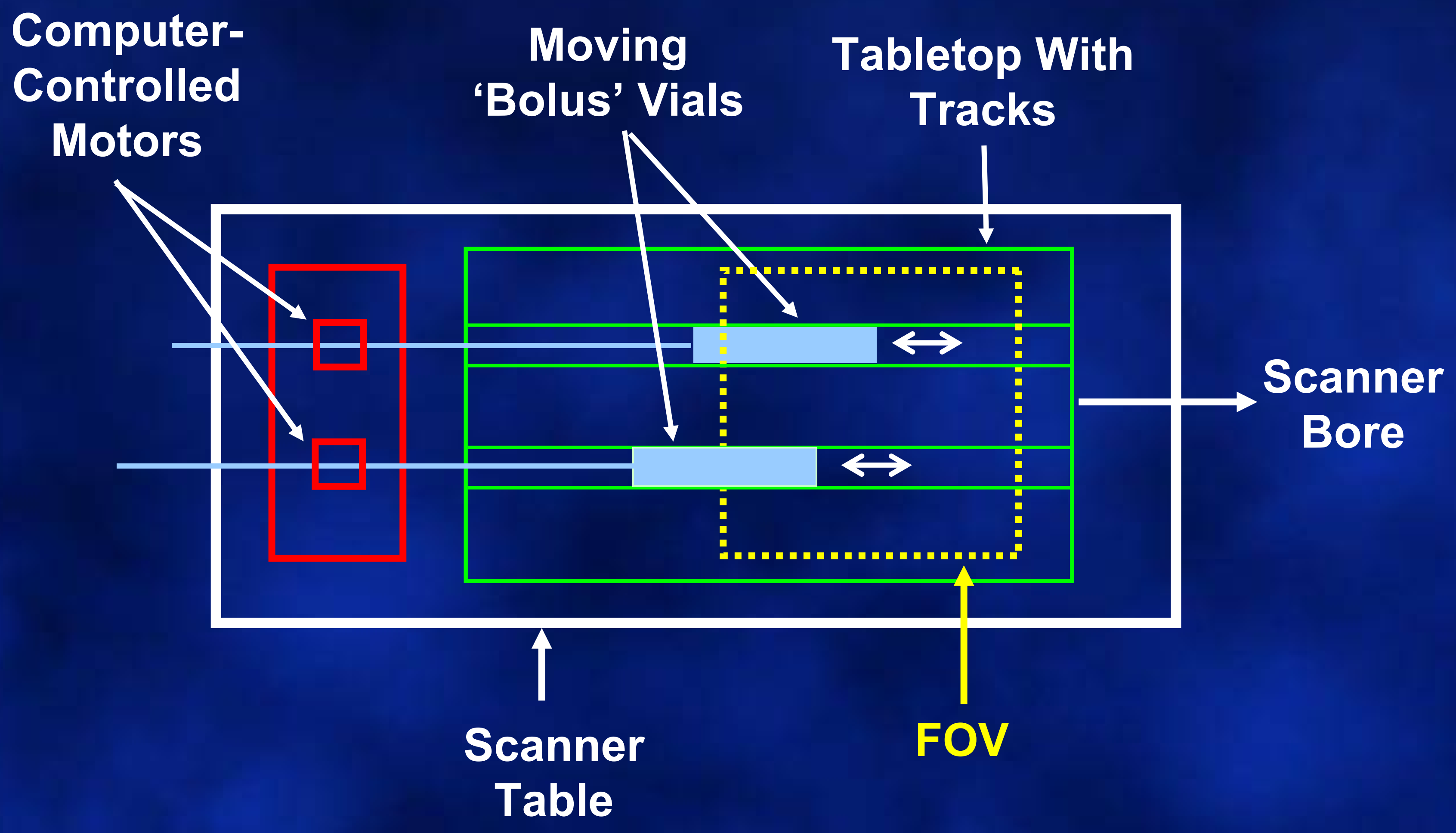
All central views sampled w EC view order, freezing object status; ≈ 2 sec

Fidelity of Image of Contrast Bolus

- **All MR sequences have a finite (non-zero) acquisition time.**
- **Consequently, an image of the contrast bolus at some time deviates from reality.**
- **Ideally a time-resolved MRA sequence:**
  - Accurately portrays bolus edge **position**
  - Provides **minimal blur** of the bolus edge
  - Accurately portrays bolus **velocity**
  - Has **negligible artifact**

Phantom Study Design

Study of Simulated Moving Contrast Bolus



Mostardi and Riederer, MRM 2009

Image Results

3.8 mm/sec

Frame 1

Image Results

3.8 mm/sec

Frame 1

Image Results

3.8 mm/sec

Frame 2

Image Results

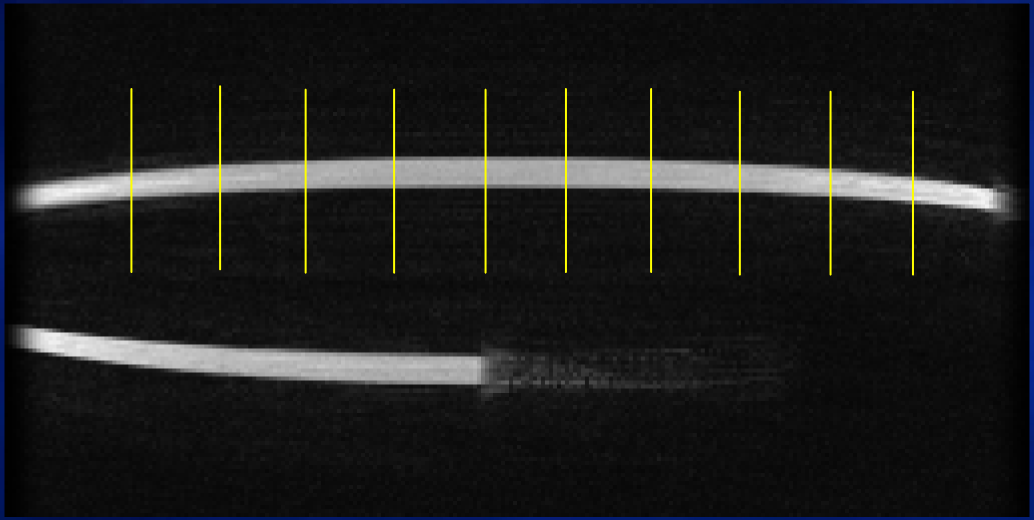
3.8 mm/sec

Frame 2

Image Results

3.8 mm/sec

Frame 11



Because all frames have the same k-space weighting, velocities are depicted accurately

Consistent frame-to-frame k-space sampling

In Vivo Example

Resolution:
1.0 x 2.0 x 2.0 mm^3

FOV:
256 x 256 x 128 mm^3

2D SENSE:
2.67 x 2 = 5.33

Update Time:
1 sec

Footprint:
3 sec

T = 1 sec

In Vivo Example

Resolution:
1.0 x 2.0 x 2.0 mm^3

FOV:
256 x 256 x 128 mm^3

2D SENSE:
2.67 x 2 = 5.33

Update Time:
1 sec

Footprint:
3 sec

T = 2 sec

In Vivo Example

Resolution:
1.0 x 2.0 x 2.0 mm^3

FOV:
256 x 256 x 128 mm^3

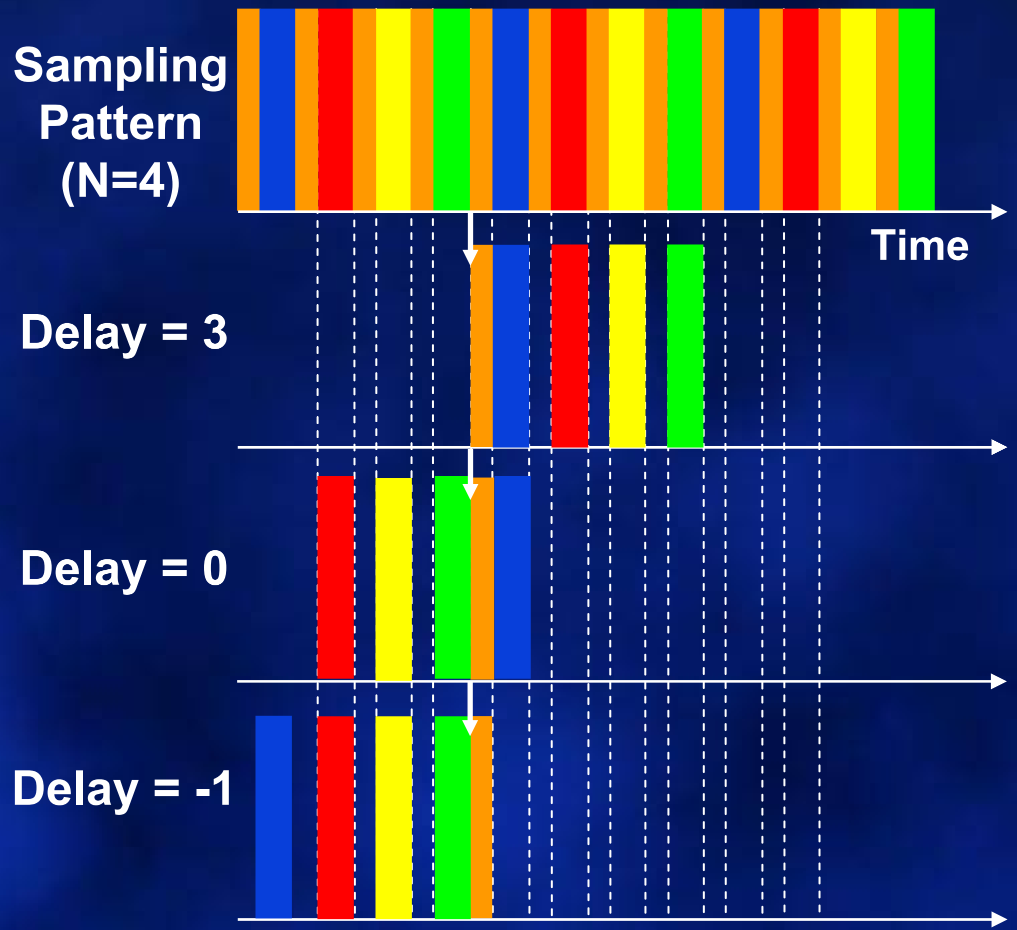
2D SENSE:
2.67 x 2 = 5.33

Update Time:
1 sec

Footprint:
3 sec

T = 3 sec

Data Sorting for Reconstruction



Define "**Reconstruction Delay**" as the number of central samplings acquired after the k-space center used for a given reconstruction

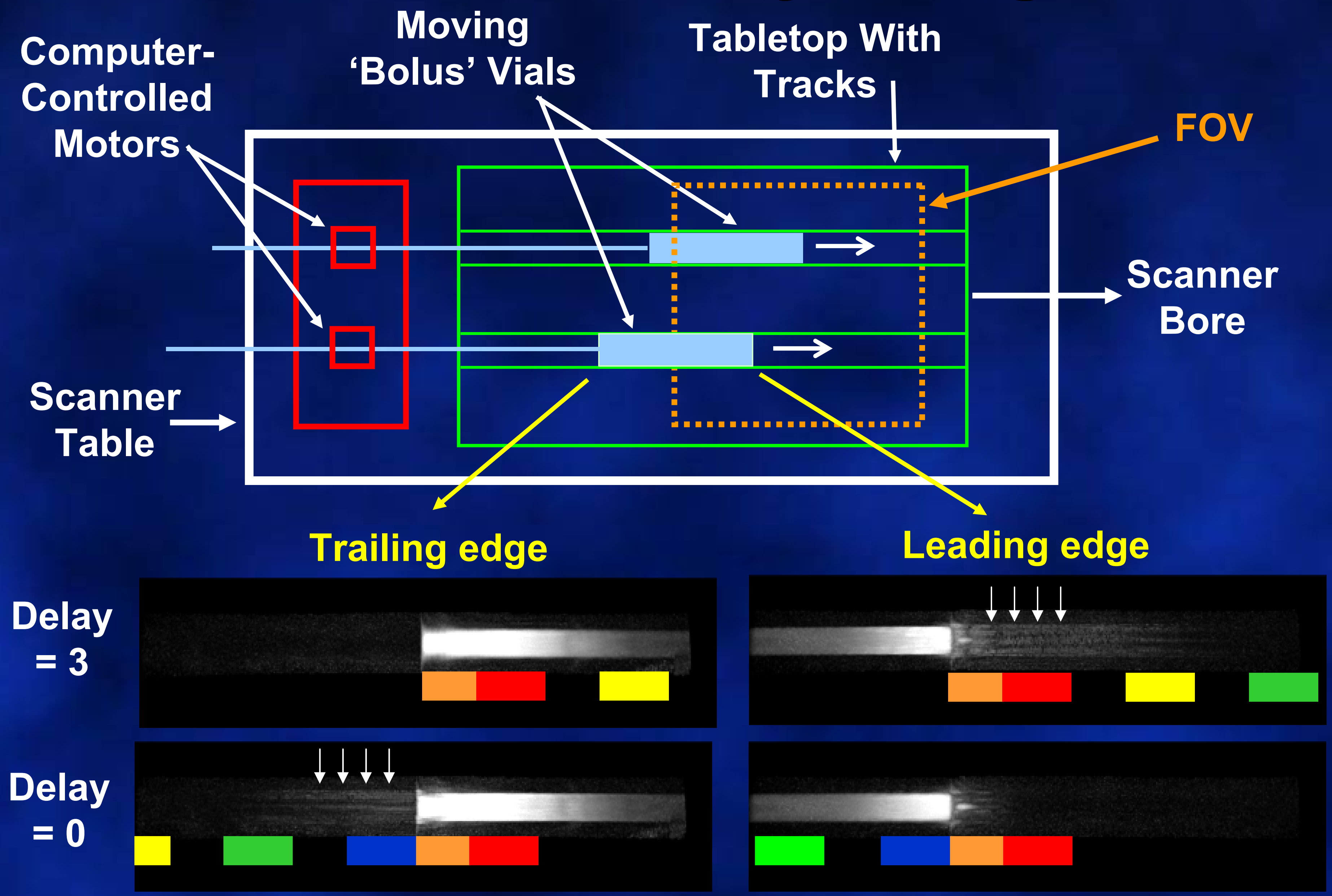
Delay 3 uses the earliest acquired center

Delay 0 uses the most recently acquired center

Delay -1 uses most recently acquired center but not its corresponding high spatial frequency vane set

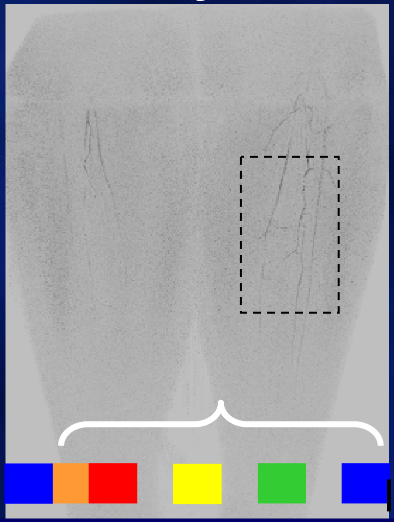
For the next image in the time series, the center and one peripheral vane set are updated; the other three vane sets are maintained or view-shared.

Phantom Study Design

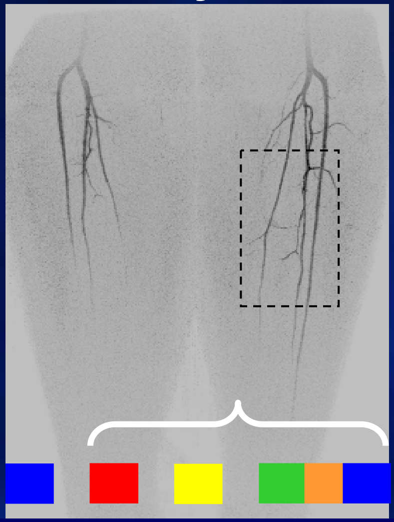


In Vivo Results: Overlapping Footprints

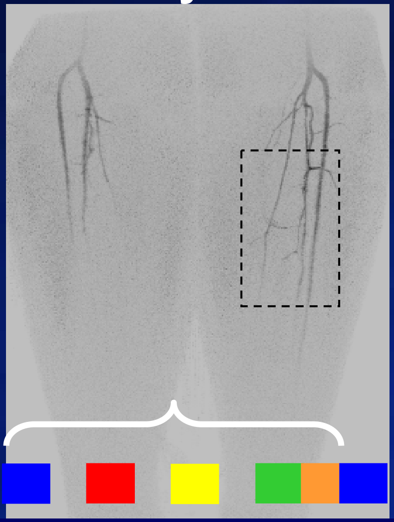
Delay = 3



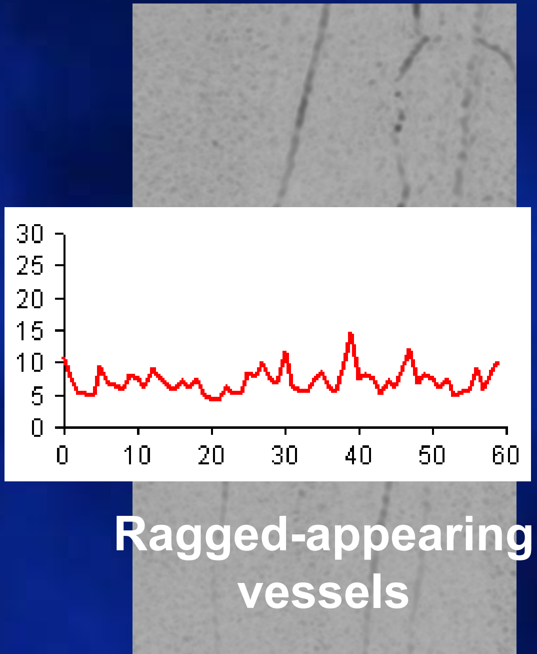
Delay = 0



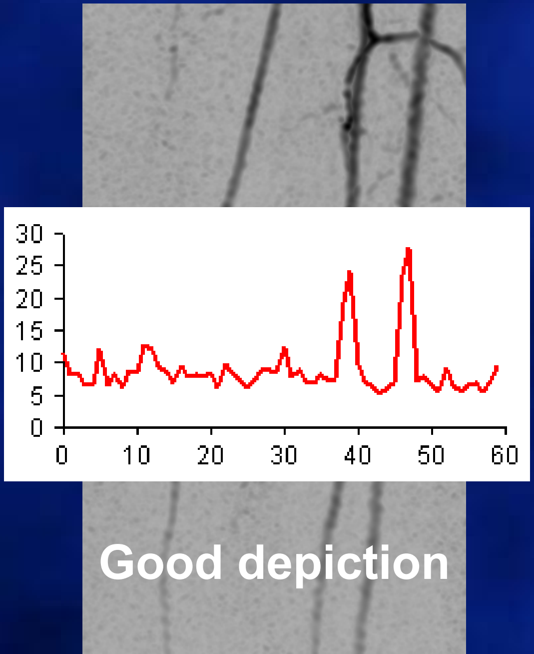
Delay = -1



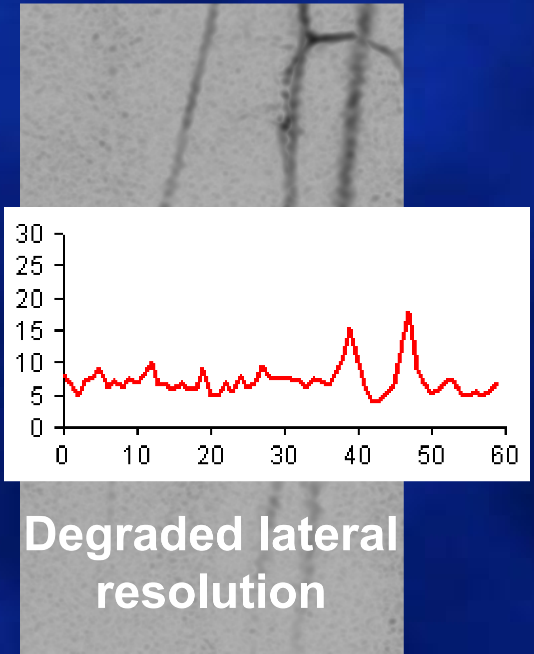
Enlargements of ROI:



Ragged-appearing vessels



Good depiction

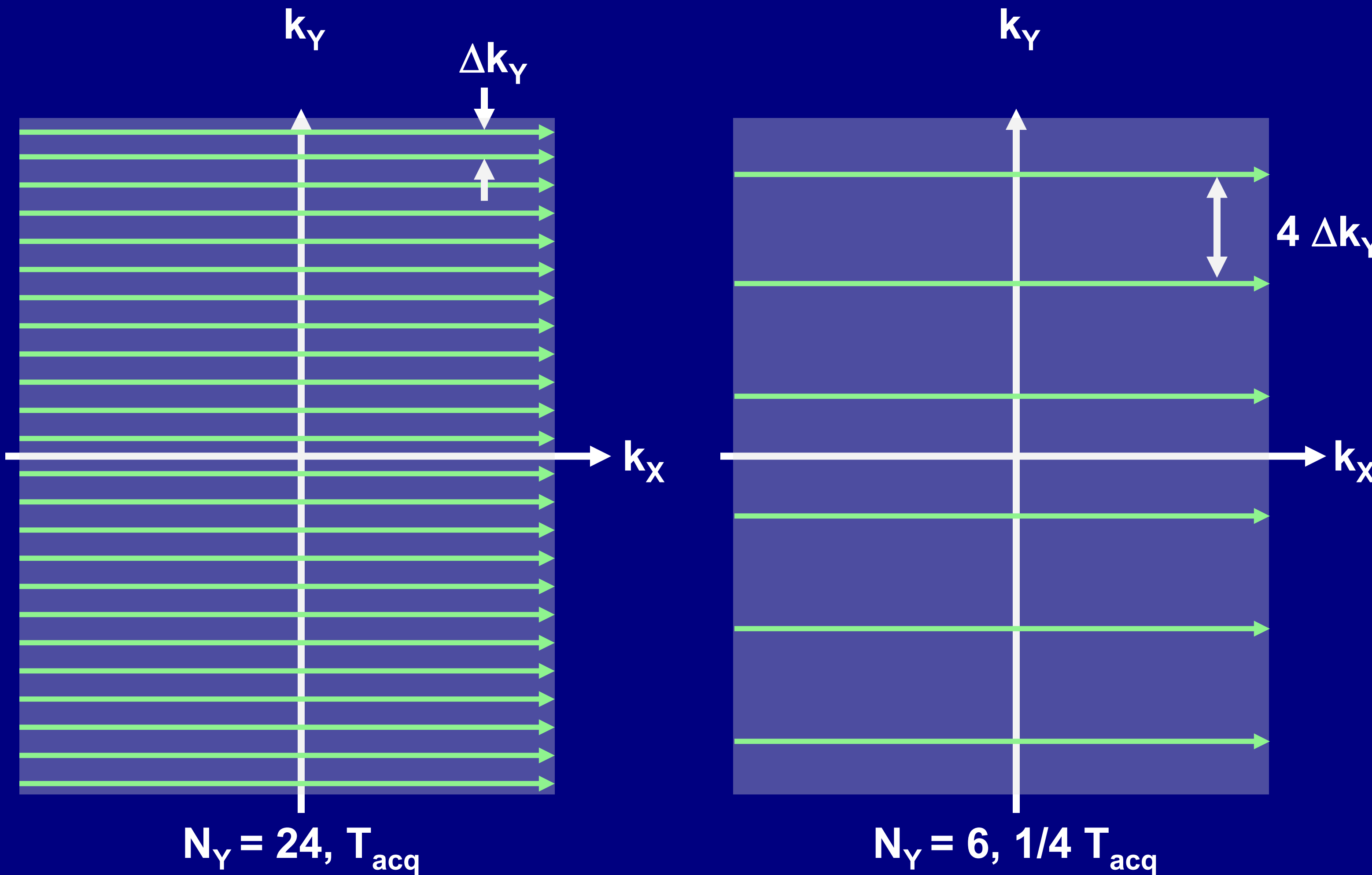


Degraded lateral resolution

Parallel Acquisition

- $T_{ACQ} = N_Y \cdot N_Z \cdot TR$ for a 3D volume
- Is there some way to reduce the number of repetitions of data acquisition?
- 1990s: extensive development of receiver coils. Perhaps this can be further used?

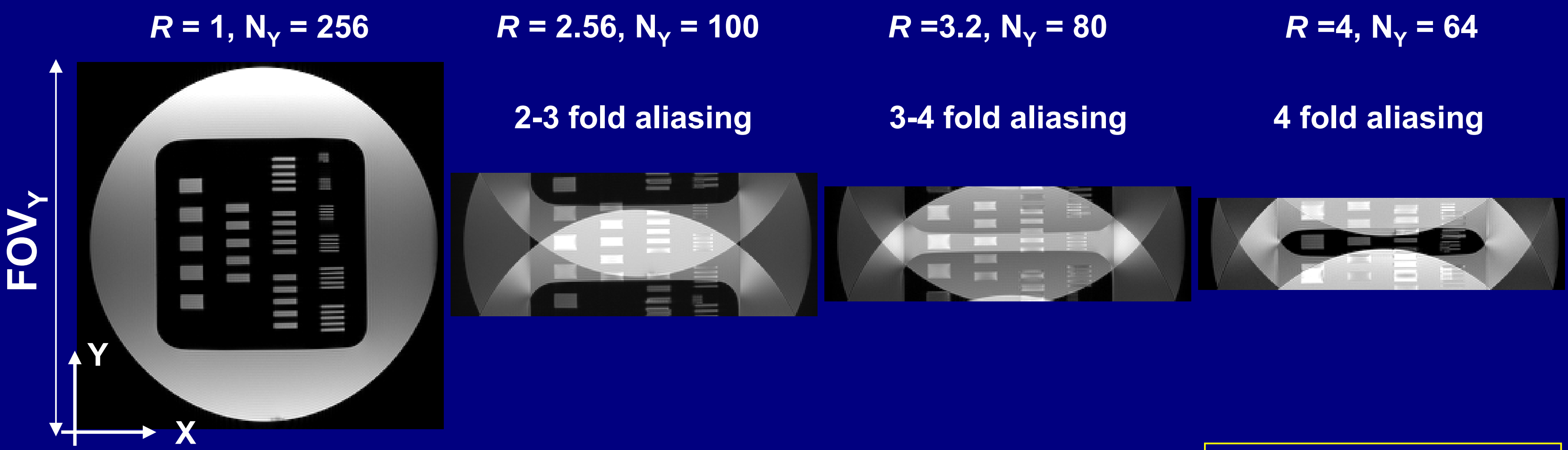
Suppose N_Y is reduced? Any consequence?



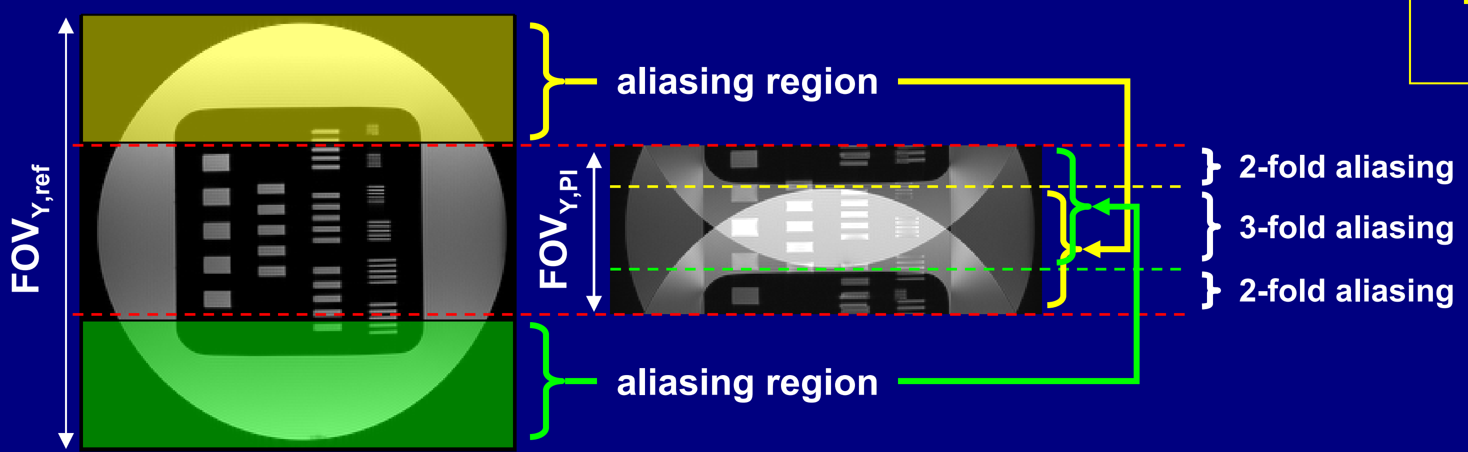
Spacing along k_Y is the inverse of the Y field of view.

Consequences of FOV Reduction: Foldover or "Aliasing"

$\Delta k_Y = 1/FOV_Y$; if $\Delta k_Y\uparrow$, then $FOV_Y\downarrow$



Images are not interpretable



Solution: acquired images from multiple coils

Image from Coil 1

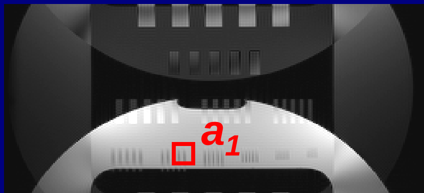
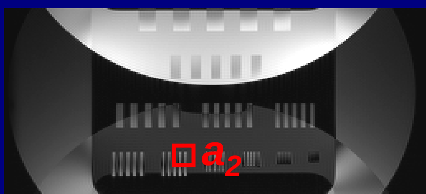
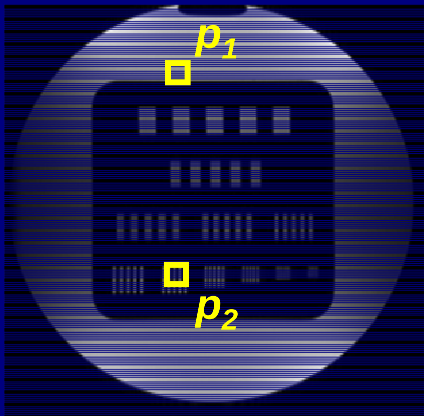


Image from Coil 2



Unaliased object



The aliasing is exactly predictable.

The net signal at a point in an aliased image is the superposition of the signals from two known points in the desired image.

Expression from coil 1:

$$a_1 = S_{1,m} \cdot p_m + S_{1,n} \cdot p_n$$

where S describes the relative coil sensitivity.

The signal for the second coil is identical except with different coil sensitivity.

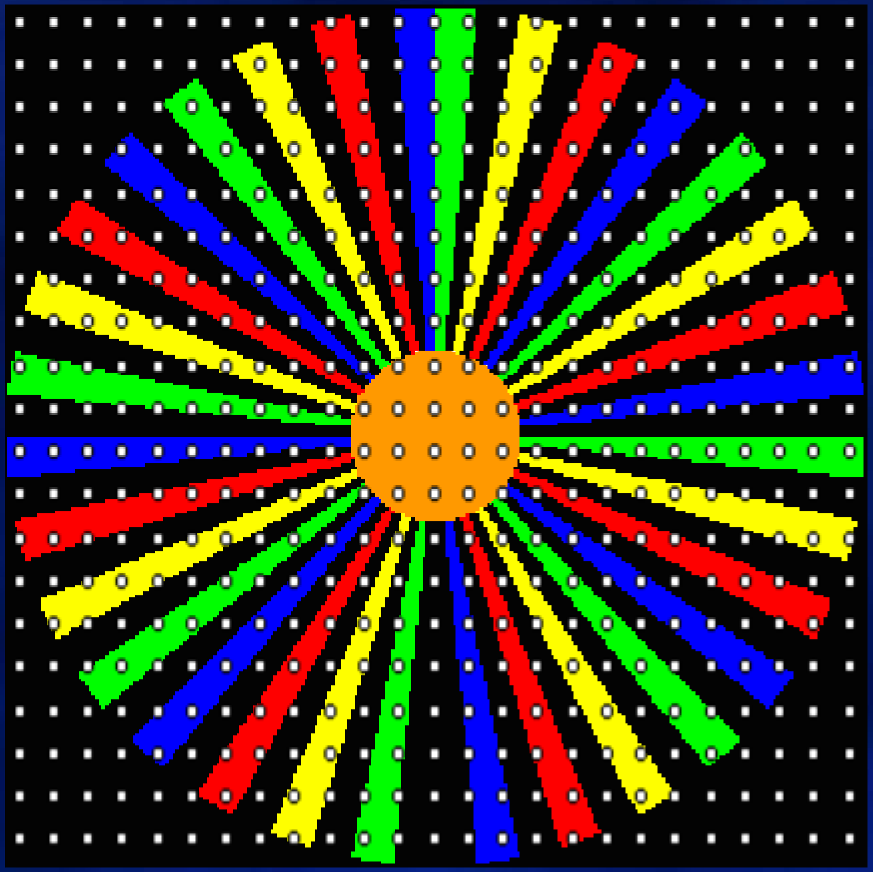
Expression from coil 2:

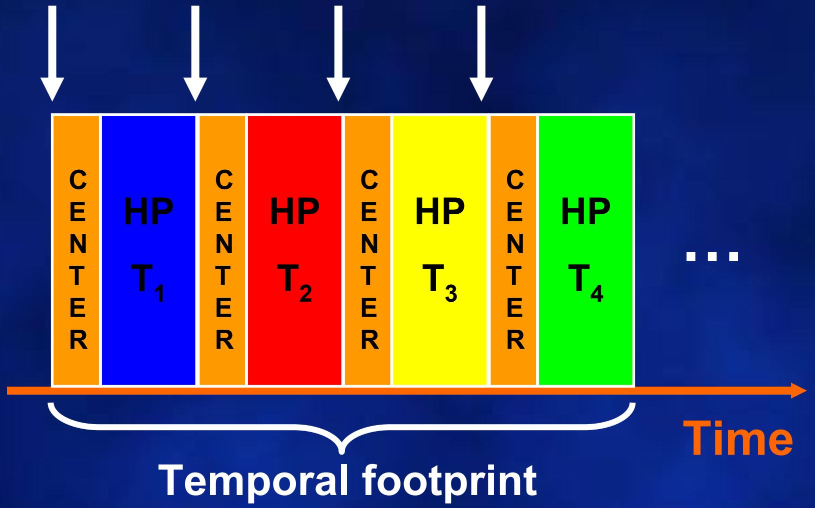
$$a_2 = S_{2,m} \cdot p_m + S_{2,n} \cdot p_n$$

Two equations in two unknowns! Solve algebraically to recover the unaliased image.

Pruessmann, MRM 1999

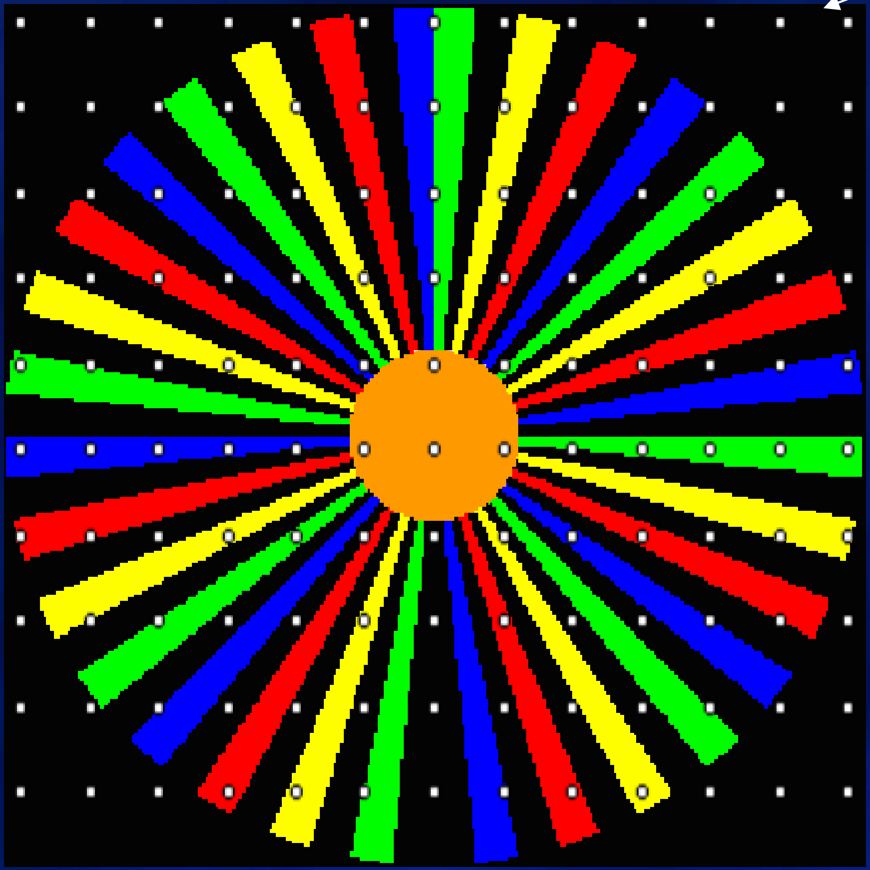
CAPR


k_y-k_z Plane

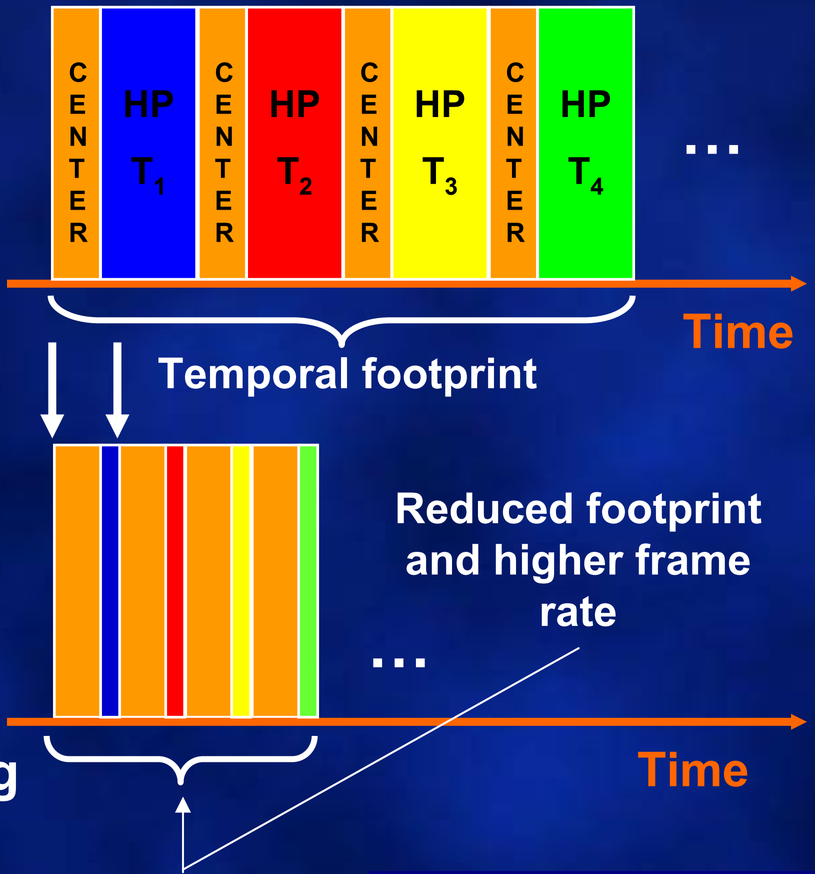

CENTER
HP T_1
CENTER
HP T_2
CENTER
HP T_3
CENTER
HP T_4
...
Time
Temporal footprint

From CAPR to CAPR with 2D SENSE

k_y-k_z Plane



SENSE allows coarser sampling in the k_y-k_z plane, reducing the acquisition time



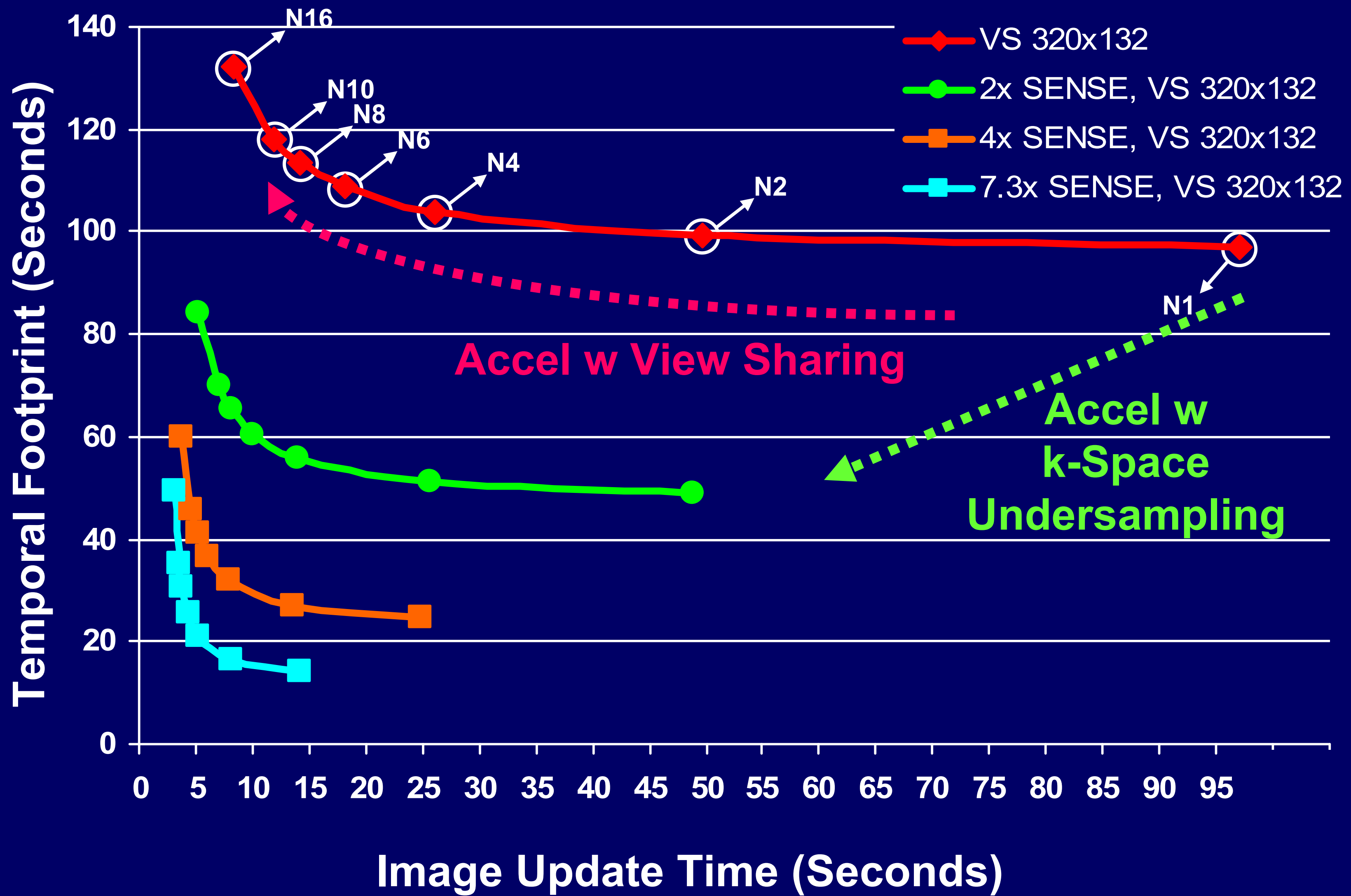
R = accel due to k-space undersampling

$= R_{SENSE} \times R_{HD}$

$= (4 \text{ to } 12) \times 1.8 = 7.2 \text{ to } 21$

Weiger, Magma 2002

Methodology: Time-resolved 3D CE-MRA CAPR Fixed Spatial Resolution



MAYO CLINIC
College of Medicine

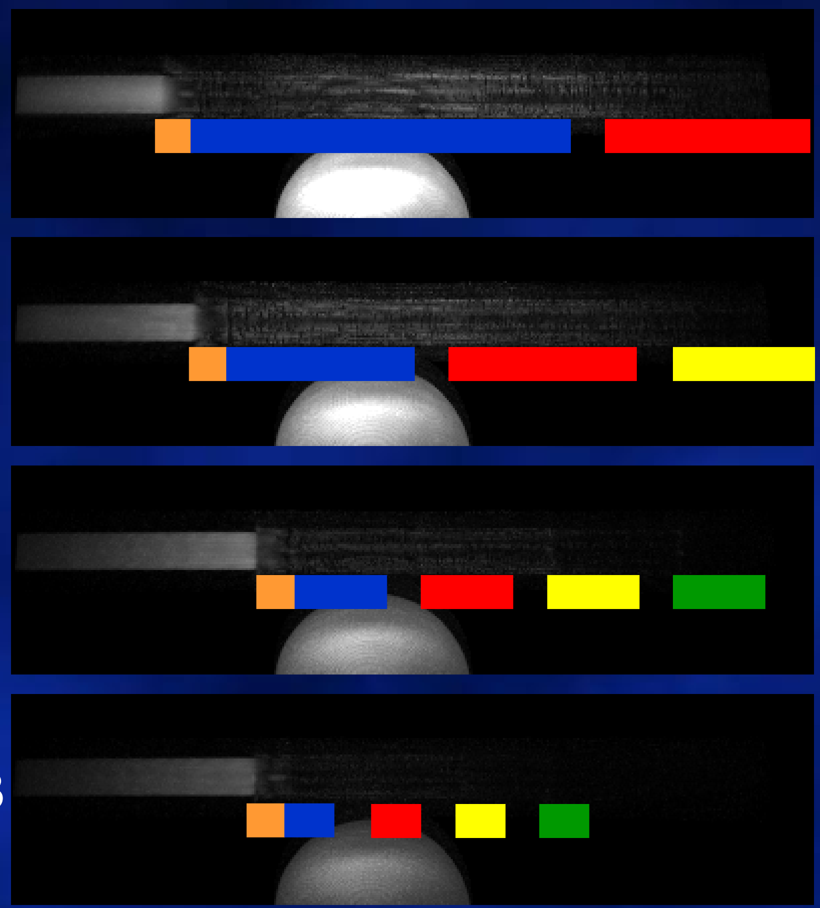
Application of 2D SENSE

R = 1

R = 2

R = 4

R = 7.3



Direction of motion

Resolution:
1.0 x 1.0 x 1.0 mm^3

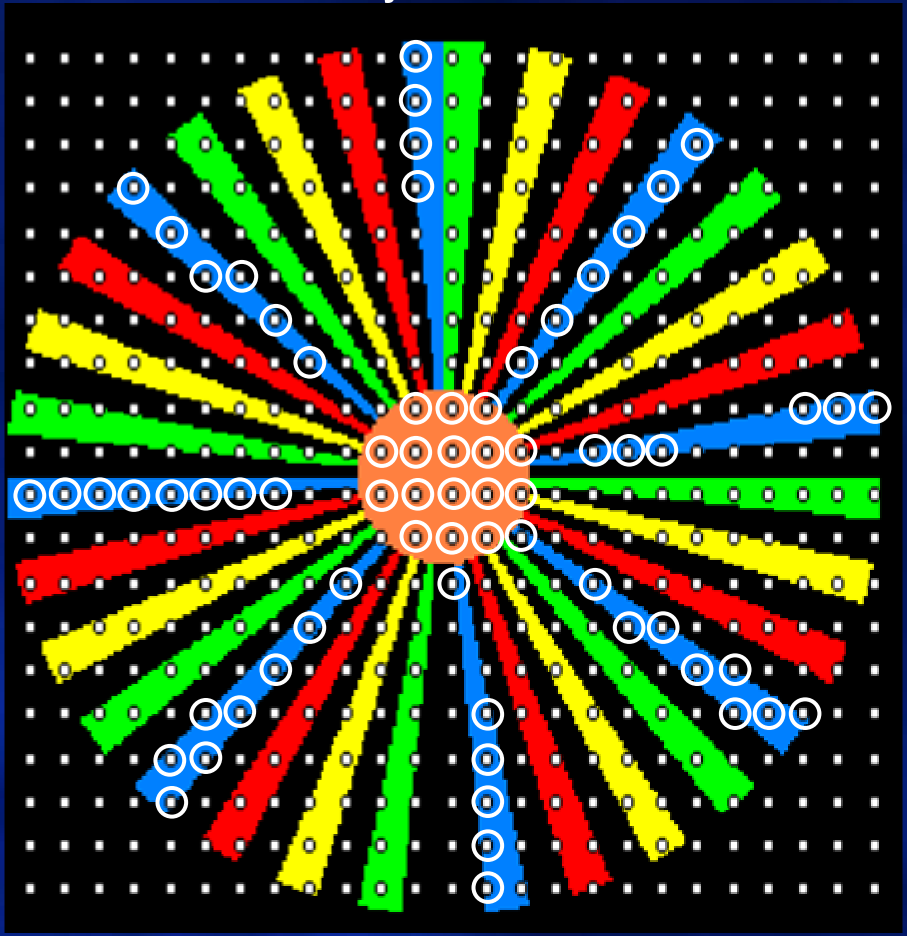
FOV:
400 x 320 x 132 mm^3

Bolus Velocity:
8 mm/sec

Random CAPR Sampling

Standard EC CAPR Sampling

k_y-k_z Plane



Random CAPR Sampling

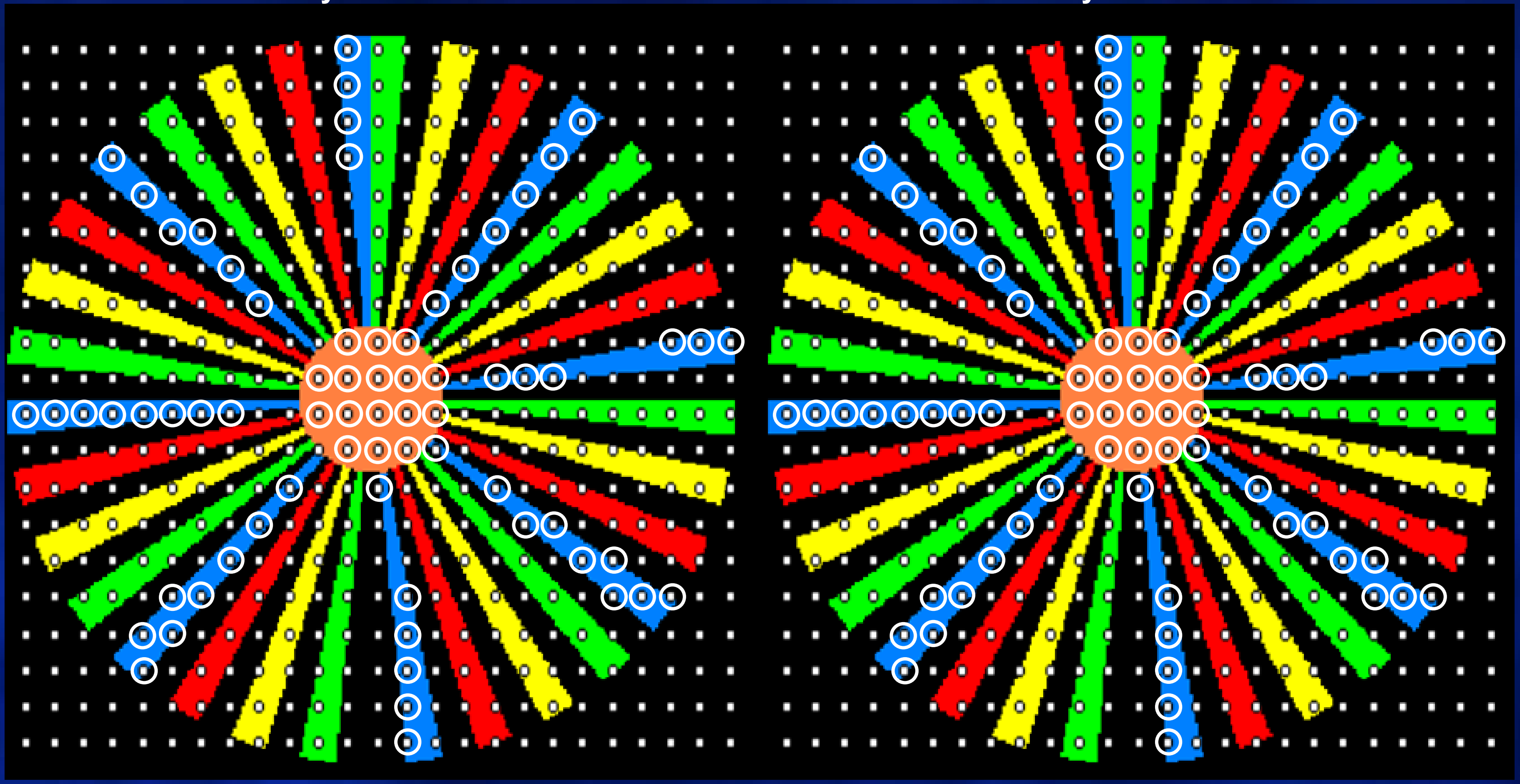
k_y-k_z Plane

MAYO CLINIC

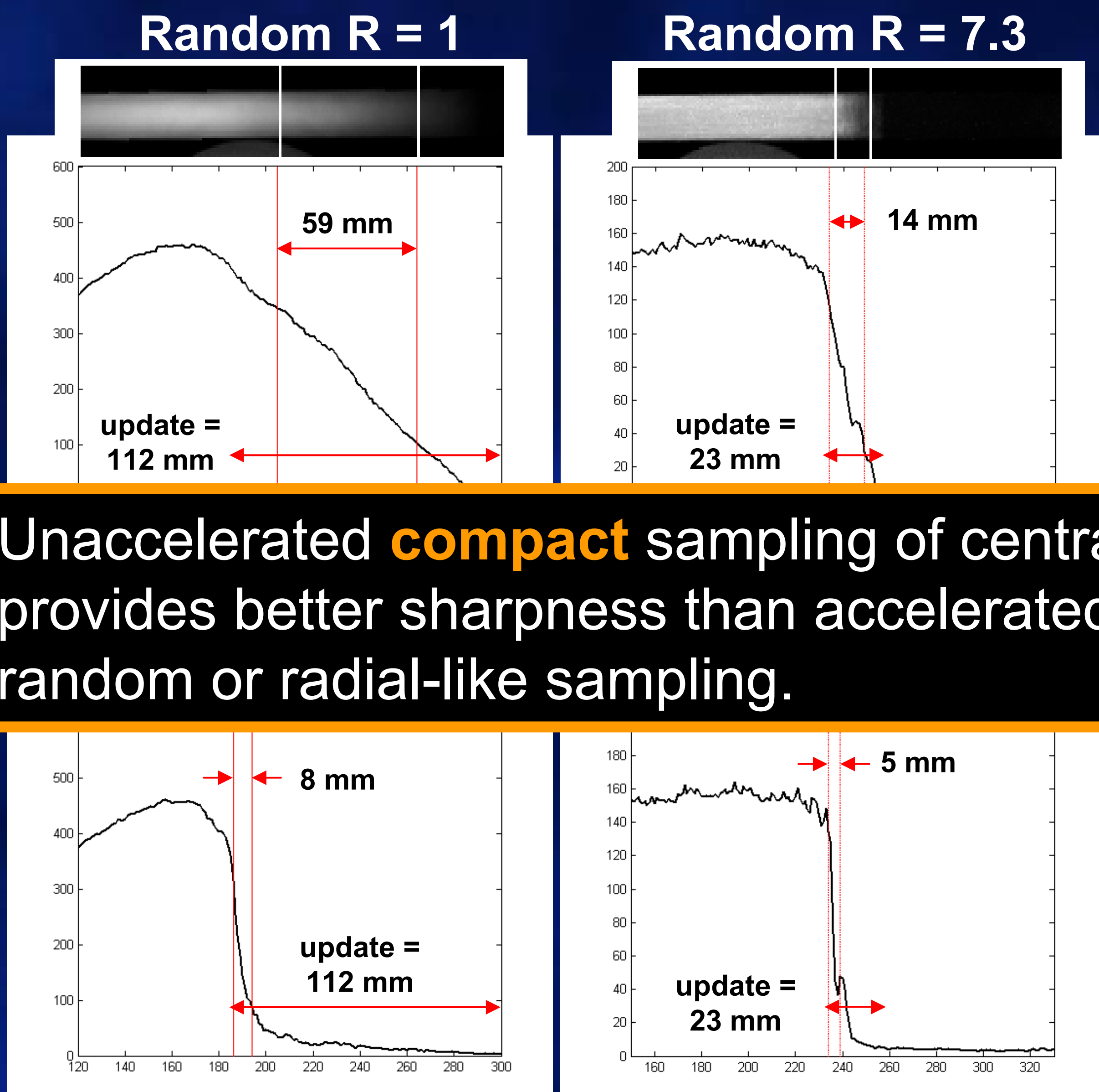
Random CAPR Sampling

Standard EC CAPR Sampling | **Random CAPR Sampling**

k_y-k_z Plane | k_y-k_z Plane



Random vs. Standard CAPR Sampling



Resolution:
1.0 x 1.0 x 1.0 mm^3

FOV:
400 x 320 x 132 mm^3

2D SENSE:
3.65 x 2 = 7.3

22.78 sec

Bolus Velocity:
4 mm/sec

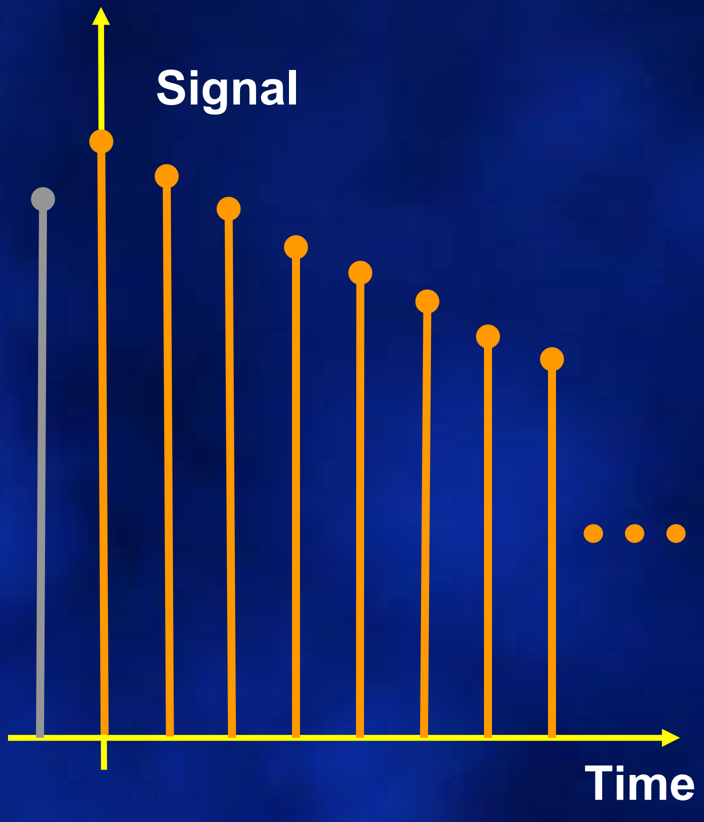
Unaccelerated **compact** sampling of central k-space provides better sharpness than accelerated (R=7.3) random or radial-like sampling.

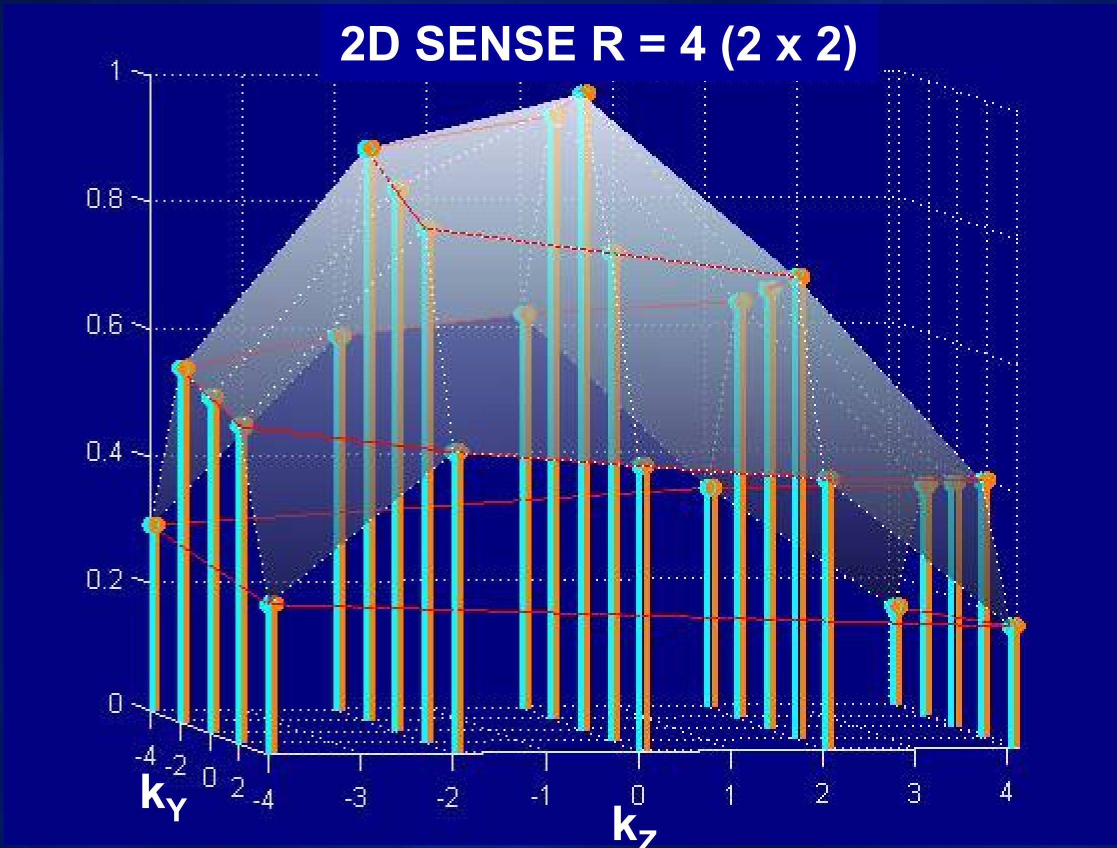
Parallel Imaging of Transient Magnetization

- **For many MRI techniques the signal is not constant for all repetitions**
  - Fast-spin-echo
  - Magnetization-prepped gradient echo
  - Contrast-enhanced MRA
  - Fat suppression
- **What is the effect of this when parallel imaging techniques are applied?**

Extend to Two Phase Encode Directions
3D CE-MRA

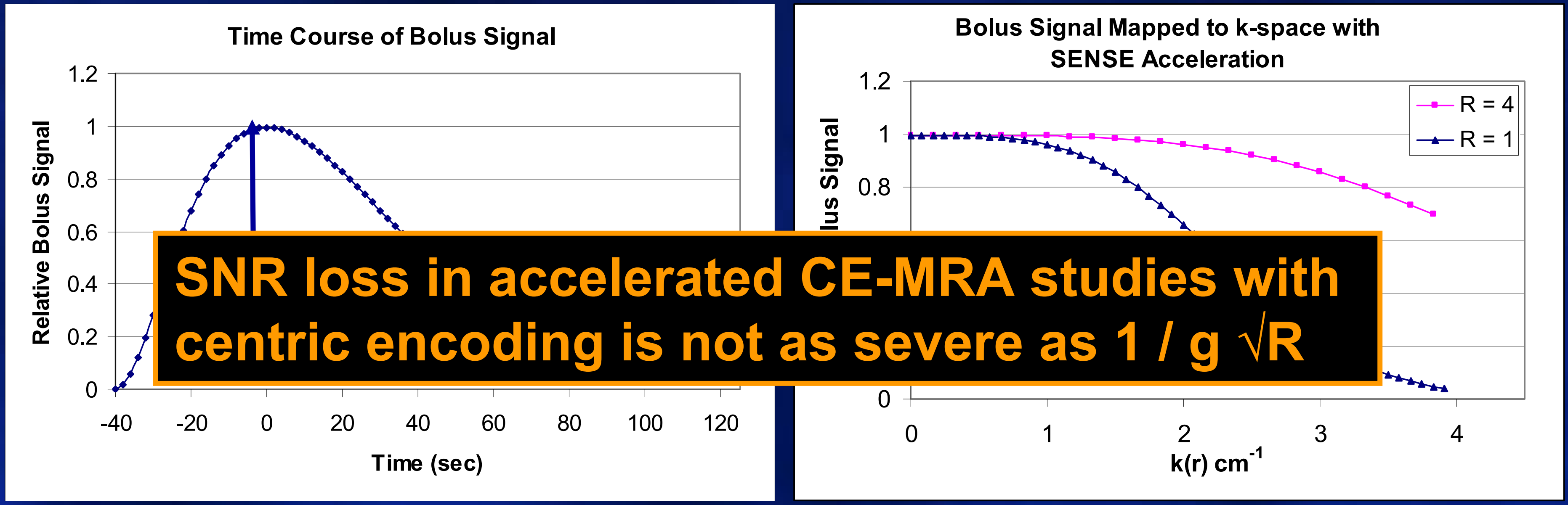
- The contrast bolus typically decays with time
- The EC maps the waning signal to progressively larger radial k





Example of 2D SENSE (R=4)

Hypothetical Bolus Profile



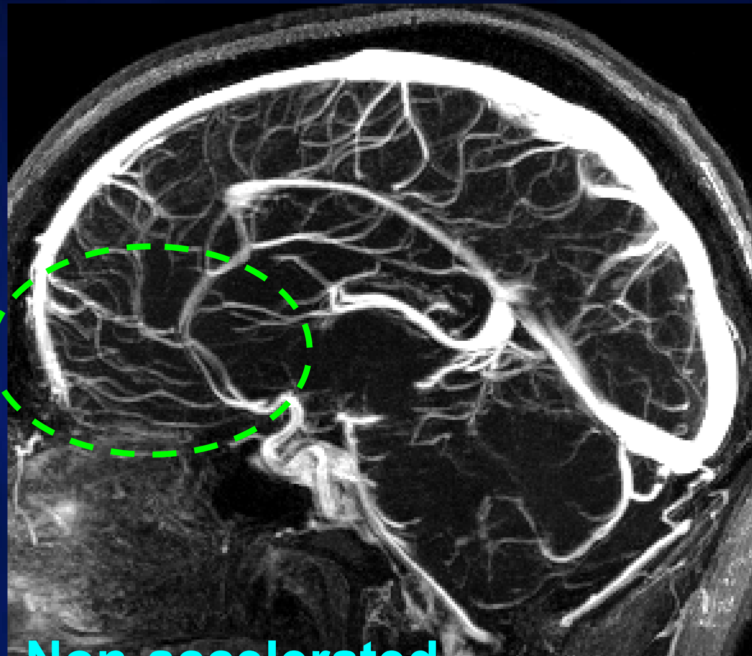
SNR loss in accelerated CE-MRA studies with centric encoding is not as severe as 1 / g √R

SENSE scales the k-space signal modulation

Reduced signal decay for SENSE leads to:

- narrower PSF (improved spatial resolution)
- larger overall signal level

Vol #10

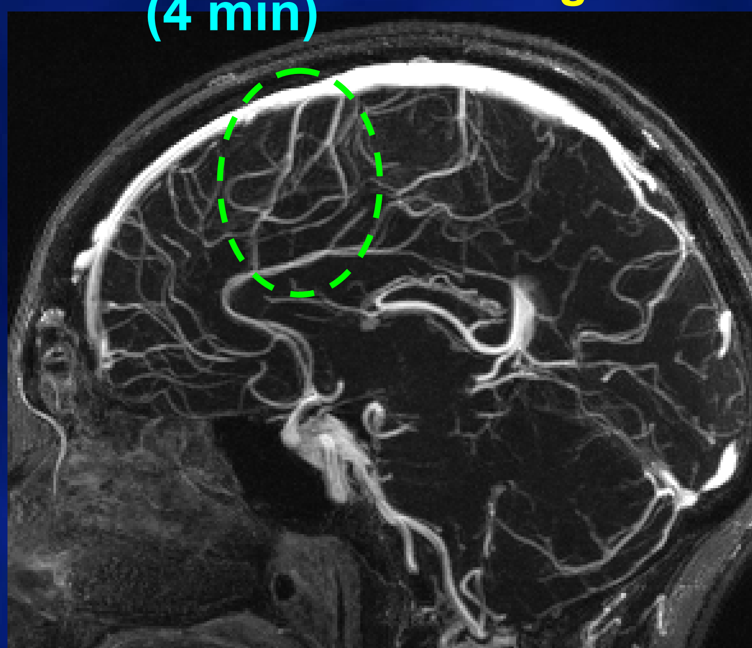


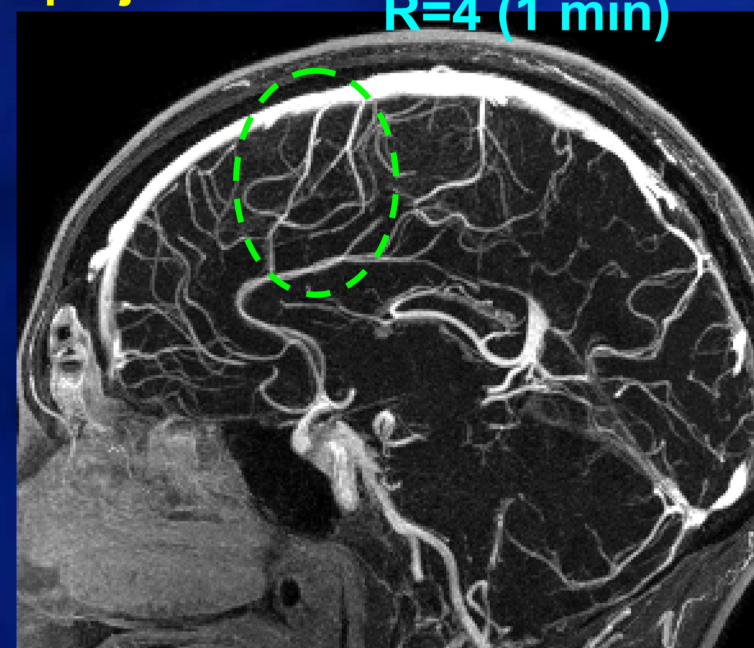
Non-accelerated
(4 min)

targeted ~2 cm projections

2D-SENSE
R=4 (1 min)

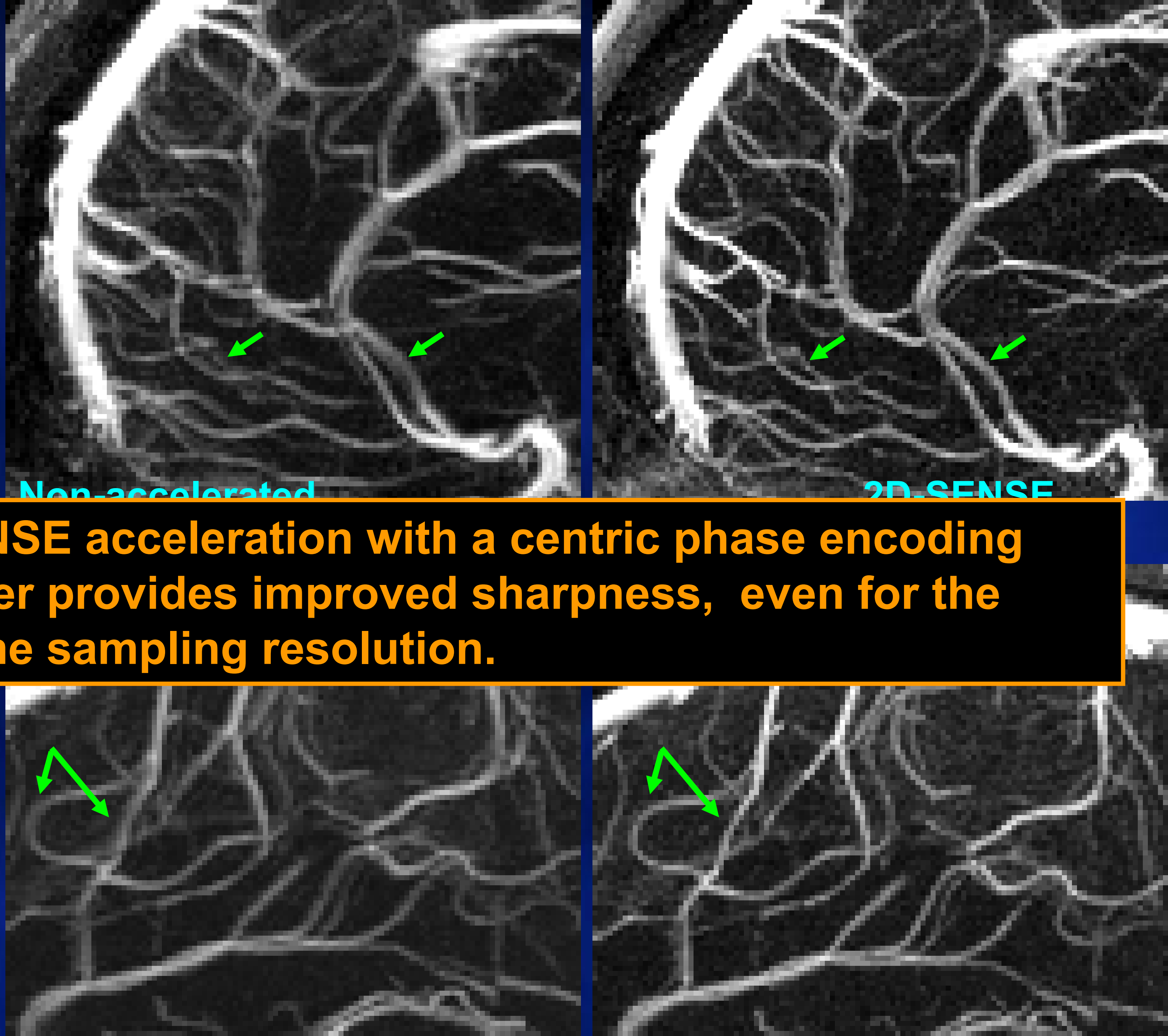
Vol #12





Vol #10

Vol #12



SENSE acceleration with a centric phase encoding order provides improved sharpness, even for the same sampling resolution.

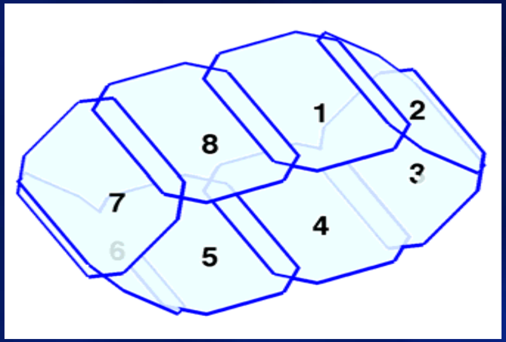
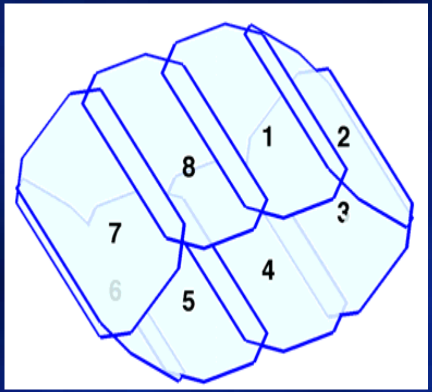
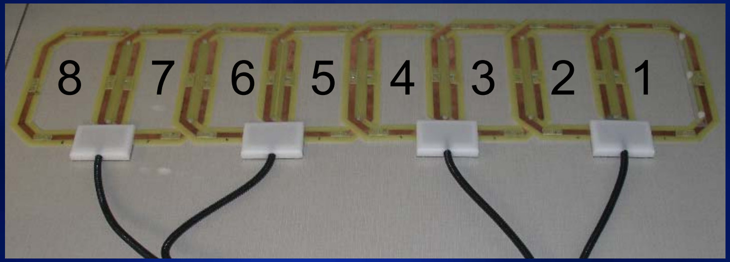
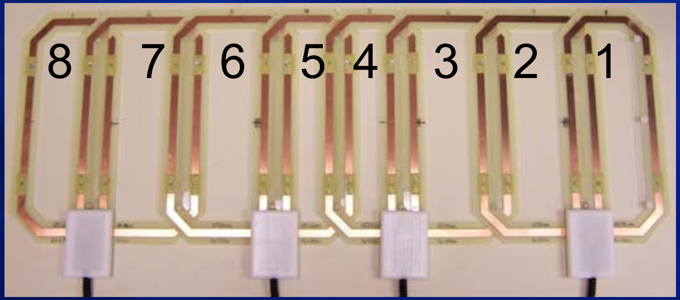
Example of Coil Development

CE-MRA of the Calves (1 mm isotropic resolution)

Img. Acq. Parameter:
7.3x 2D SENSE R_{net} = 14.56 (2D SENSE + HD)
Image Update Time: 4.9 sec Temporal Footprint: 19.6 sec

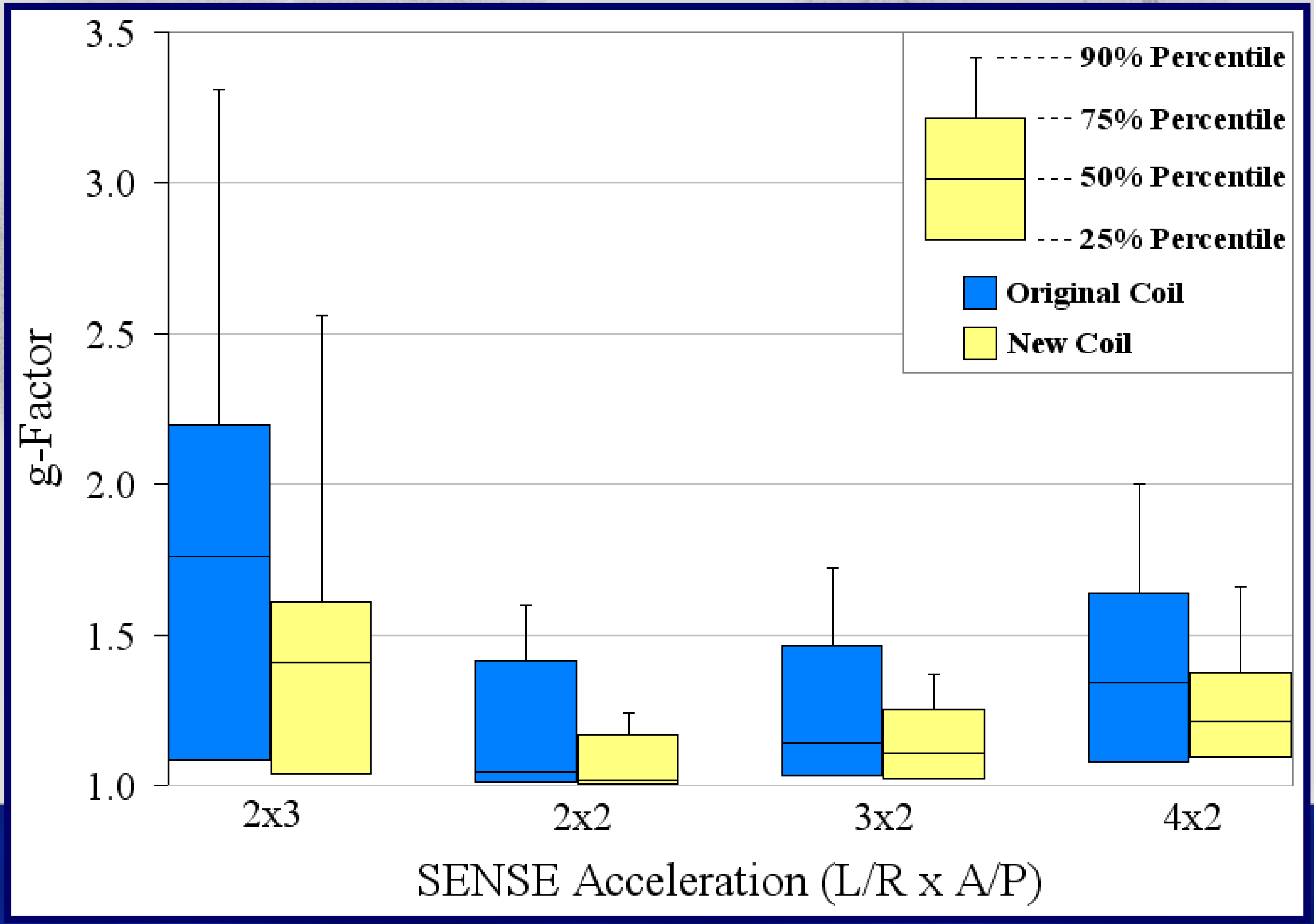
Receiver coils
- Limited S/I coverage
- Large circumference
- Too far A/P falloff

Comparison of Coils

Original Eight-Element Array	Modified Eight-Element Array
	
	
All elements: 21.5 x 14.3 cm^2	AP elements: 27.1 x 10.5 cm^2 LR elements: 27.1 x 14.4 cm^2

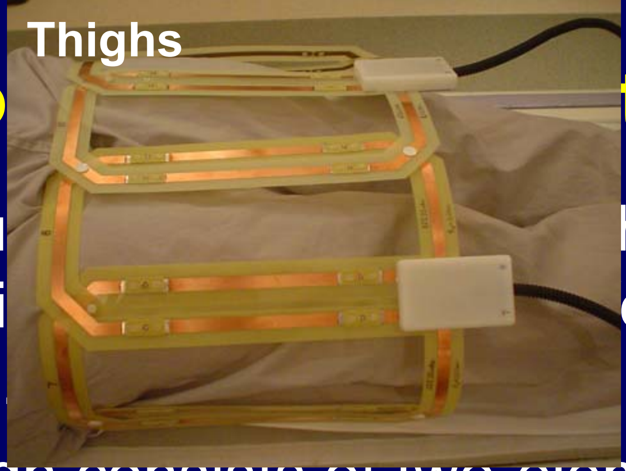
Results: Comparison of Original and Modified Calf Arrays

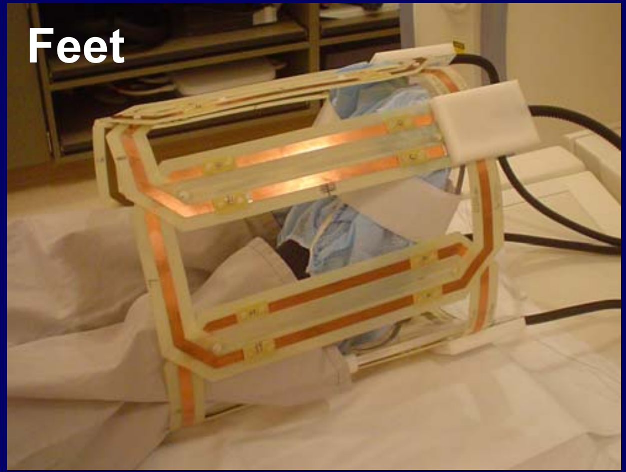
Original Array; R = 7.3 | **Modified Array, R = 7.3**



Co… t… on

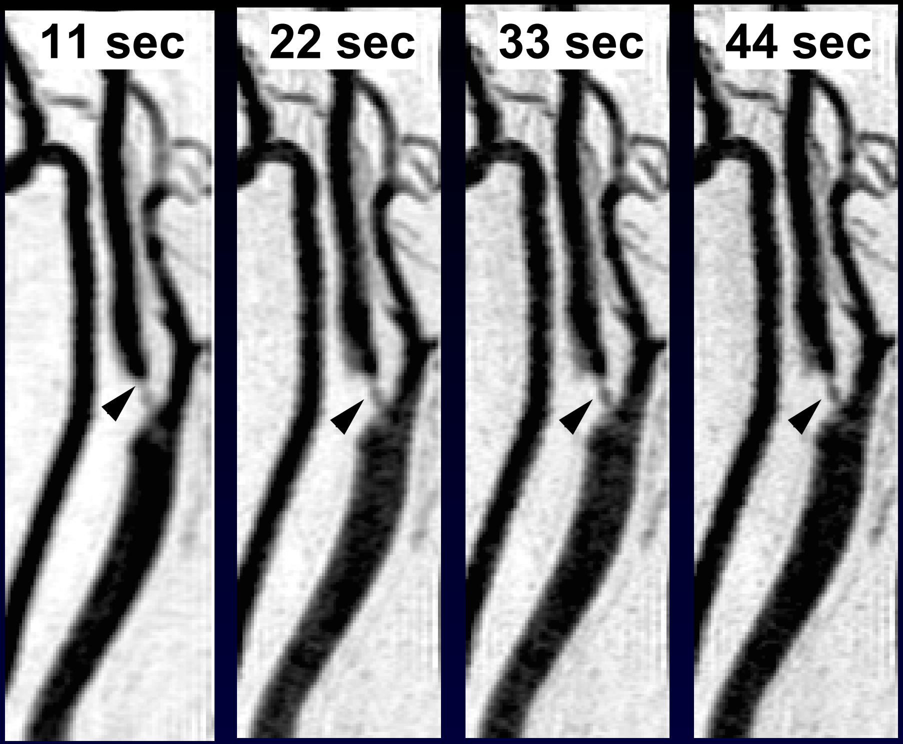
- Circu… h
  speci… e… and
  brain.
- Design consists of two-element modules which can be
  linked … d
- 2D SI… n… R ≥ 8
  are ro… g





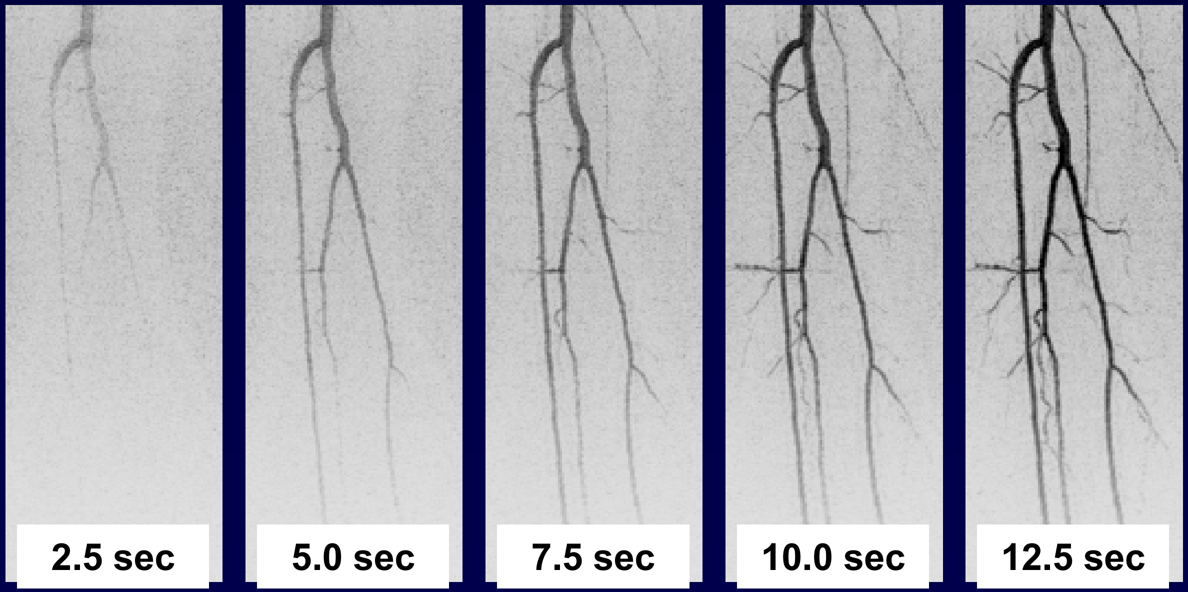
Comparison of Buildup of Spatial Resolution

2000



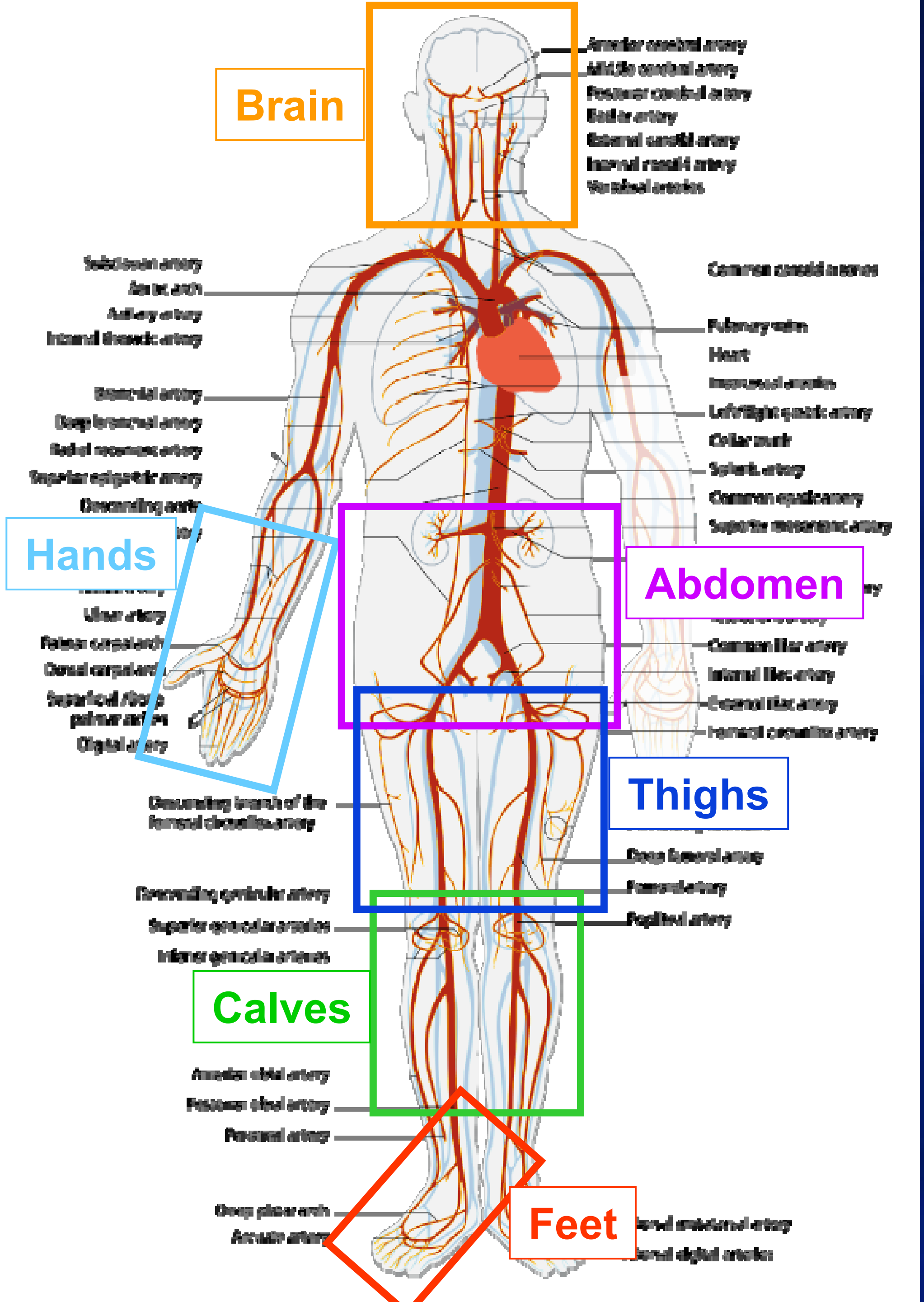
2011

Buildup of higher spatial resolution over a shorter time



Applications to Cardiovascular System

The accelerated CAPR technique using modular circumferential receiver coils has been applied to multiple vascular regions



In Vivo Results

8x 2D SENSE (R_{net}=14.6), IUT = 4.9 sec, TF = 19.6 sec

Note clearly demarcated bolus leading edge

In Vivo Results

8x 2D SENSE (R_{net}=14.6), IUT = 4.9 sec, TF = 19.6 sec

In Vivo Results

8x 2D SENSE (R_{net}=14.6), IUT = 4.9 sec, TF = 19.6 sec

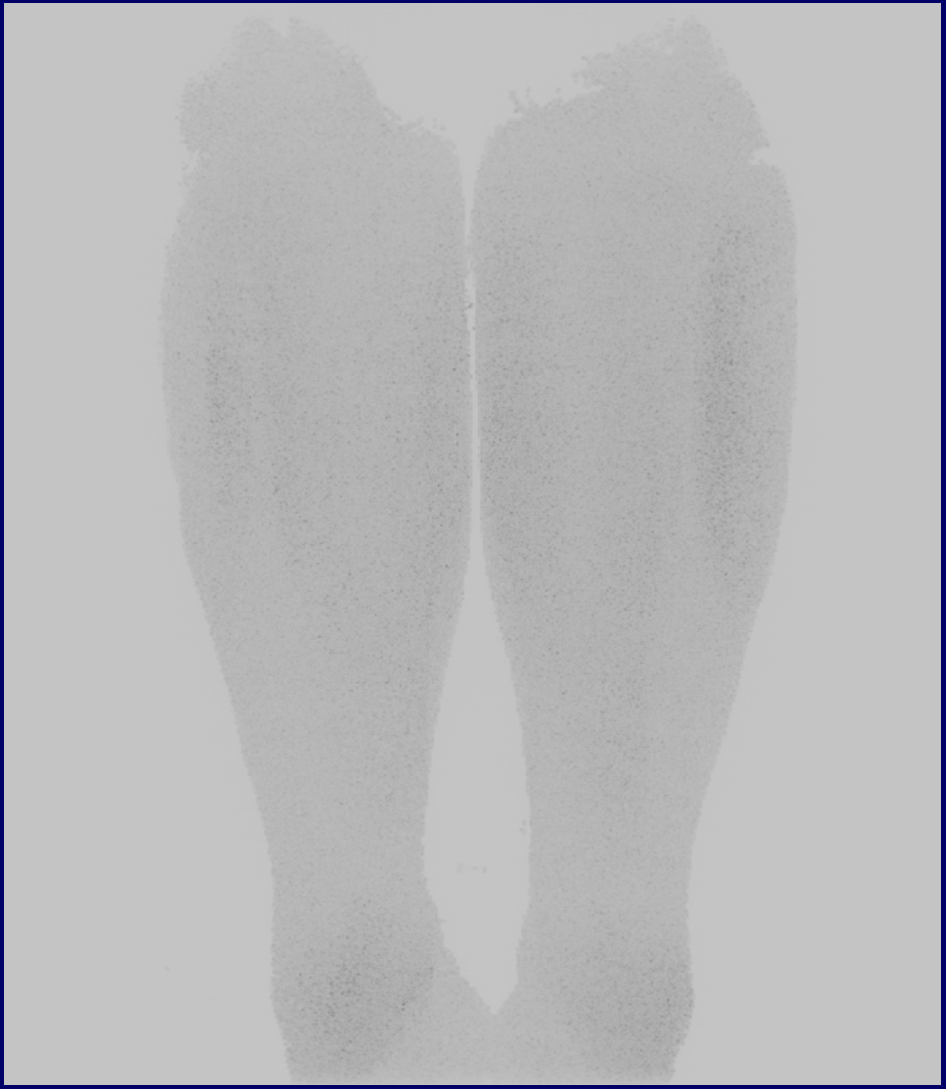
Video

Clinical Study of Calf Vessels

- Patient
  - 65 year old woman with a left femoral-popliteal artery bypass in 1998
  - Referred for assessment of critical ischemia and a non-healing ulcer
- Sampling Parameters – standard calf
  - 1 mm^3 spatial resolution
  - 4.9 sec frame time
  - 19.6 sec temporal footprint

In Vivo Results: 8-fold 2D SENSE, 8 Channel Array

CAPR (IUT = 4.9 sec, TF = 19.6 sec)



14.7 sec post injection

In Vivo Results: 8-fold 2D SENSE, 8 Channel Array

CAPR (IUT = 4.9 sec, TF = 19.6 sec)

19.6 sec post injection

In Vivo Results: 8-fold 2D SENSE, 8 Channel Array

CAPR (IUT = 4.9 sec, TF = 19.6 sec)

24.5 sec post injection

In Vivo Results: 8-fold 2D SENSE, 8 Channel Array

CAPR (IUT = 4.9 sec, TF = 19.6 sec)

29.4 sec post injection

In Vivo Results: 8-fold 2D SENSE, 8 Channel Array

CAPR (IUT = 4.9 sec, TF = 19.6 sec)

39.2 sec post injection

MAYO CLINIC

In Vivo Results: 8-fold 2D SENSE, 8 Channel Array

CAPR (IUT = 4.9 sec, TF = 19.6 sec)

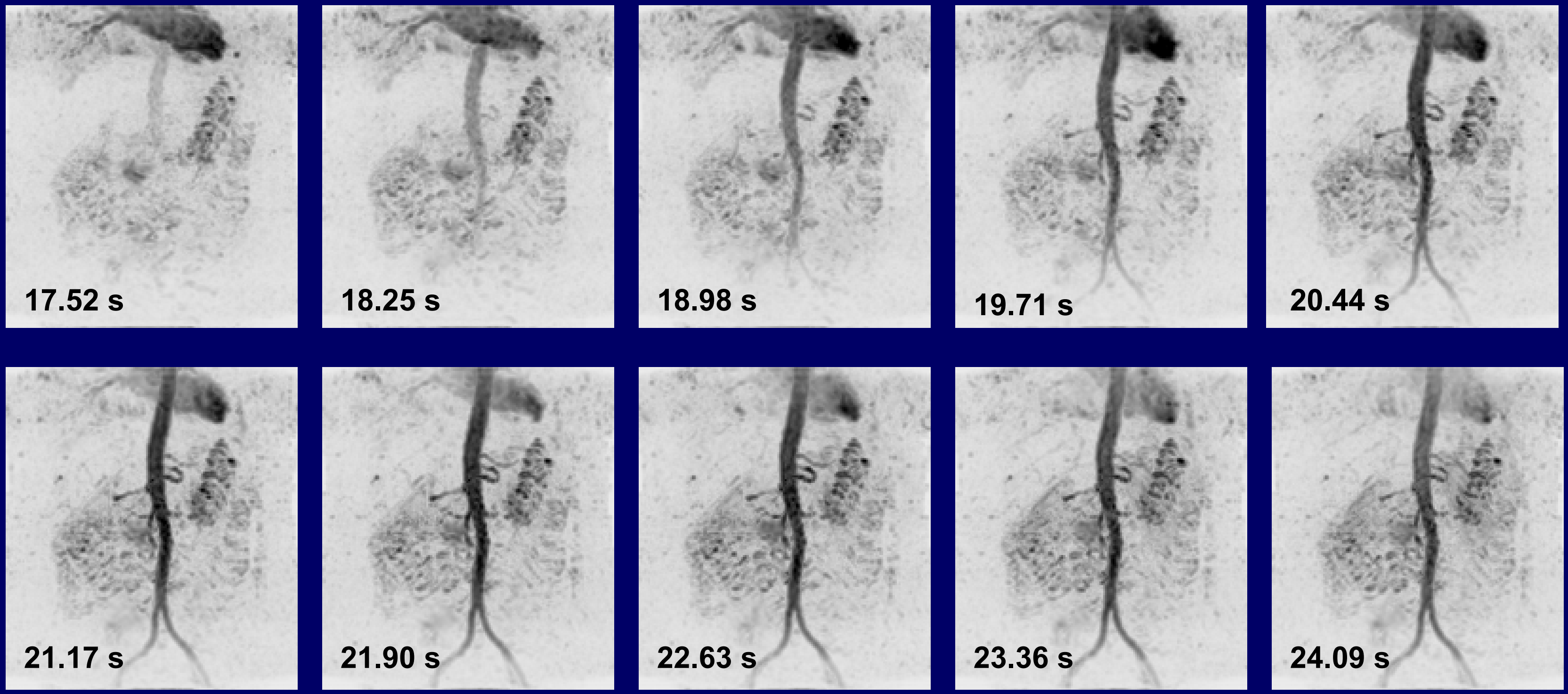
34.3 sec post injection

Movie

Results: Volunteer #10 Timing Bolus

MOVIE

Consecutive Coronal MIPs

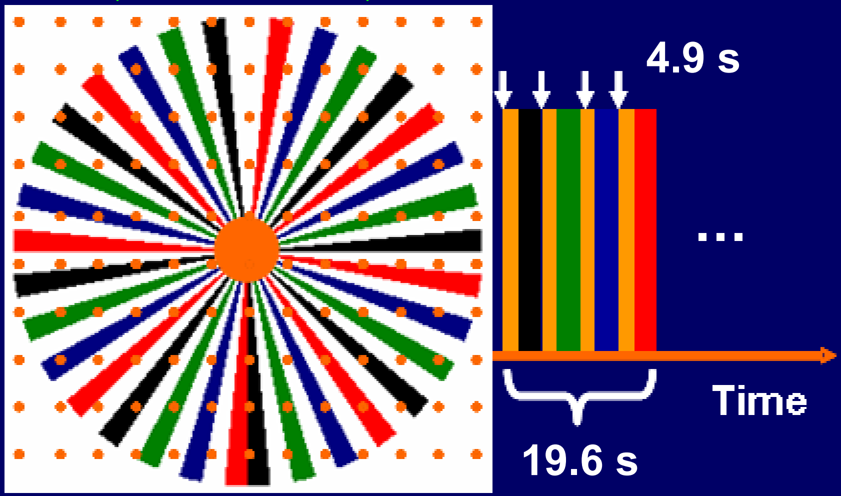


Sampling	SENSE Accel.	Matrix size	FOV (cm^3)	Spatial resolution (mm^3)	Frame time
CAPR: N3, center = 200	$R_Y = 4$, $R_Z = 2$	96 x 96 x 80	34 x 40.8 x 28.8	4.25 x 4.25 x 4.0	0.73 sec

Methodology: Cartesian Acquisition with Projection Reconstruction (Max CAPR)

N4, 320x132, 4x 2D SENSE

CAPR MRA of calves: four vane sets per 3D image



$R_{Corners} = 1$

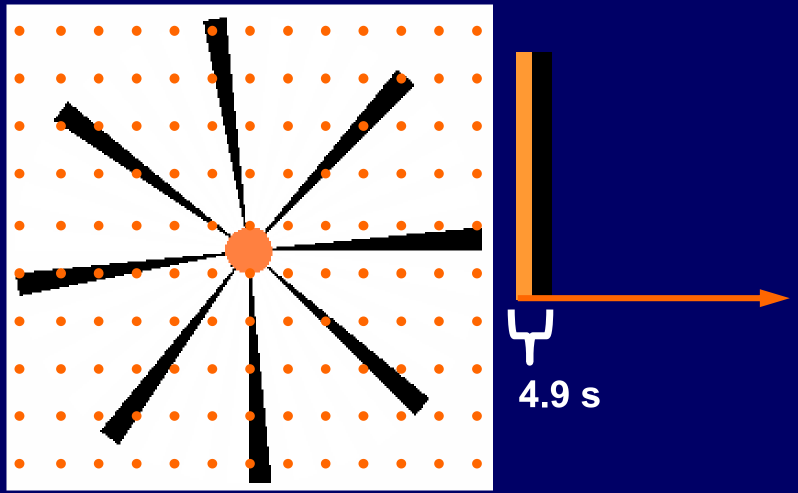
$R_{PF} = 1.8$

$R_{SENSE} = 8$

$R_{net} = 14.6$

N4, Max CAPR, 320x132, 8x 2D SENSE

MaxCAPR: use only one vane set per 3D image



$R_{Corners} = 1$

$R_{PF} = 1.8$

$R_{SENSE} = 8$

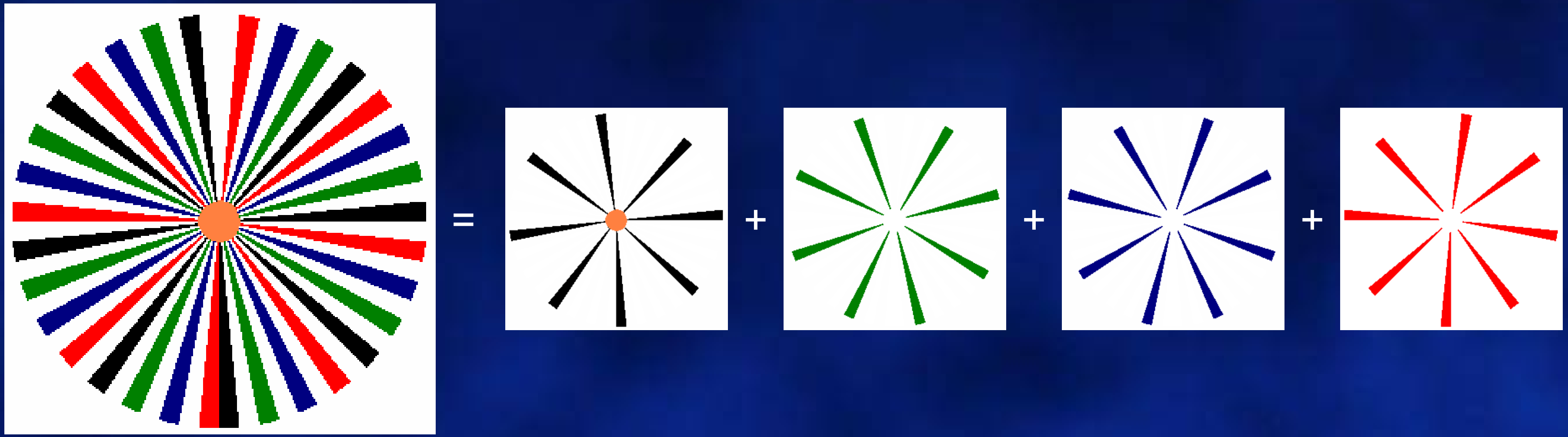
$R_{US} = 2.6$

$R_{net} = 37.4$

MAYO CLINIC

Methodology: Max CAPR Temporal Footprint

CAPR with View Sharing Reconstruction of Img 1



CAPR without View Sharing Reconstruction of Img 1

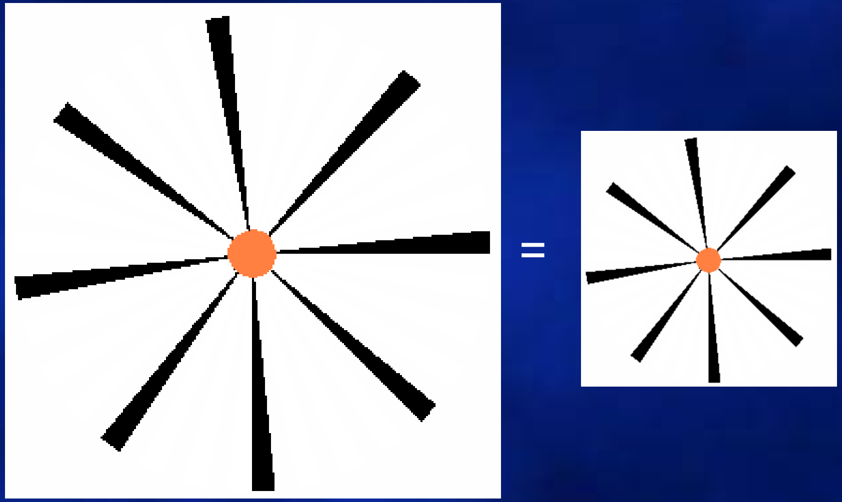
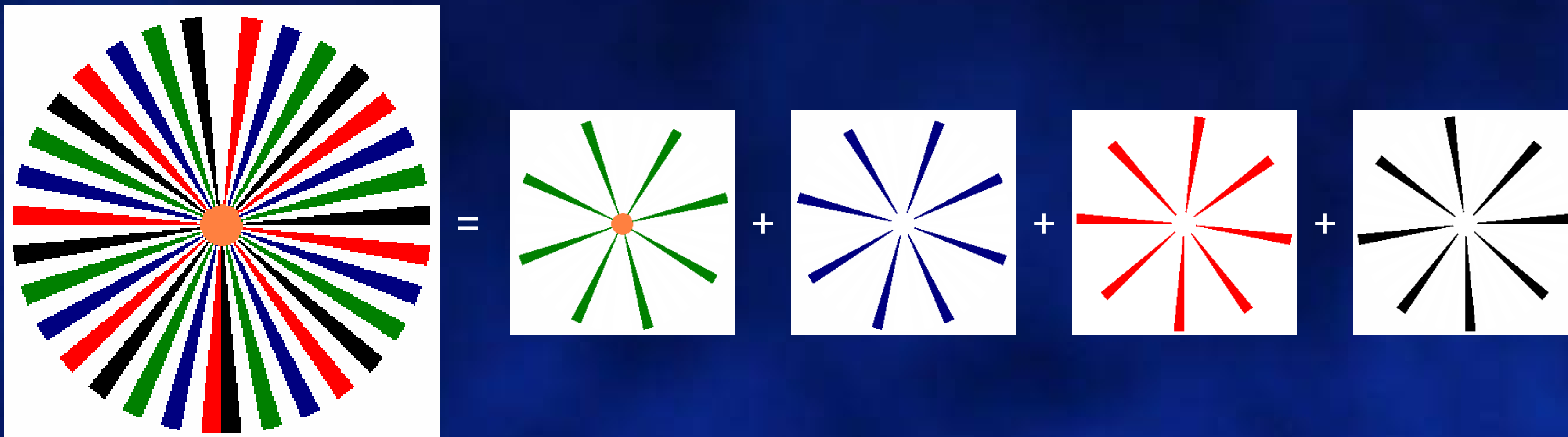


Image Update Time == Temporal Footprint

Methodology: Max CAPR Temporal Footprint

CAPR with View Sharing Reconstruction of Img 2



CAPR without View Sharing Reconstruction of Img 2

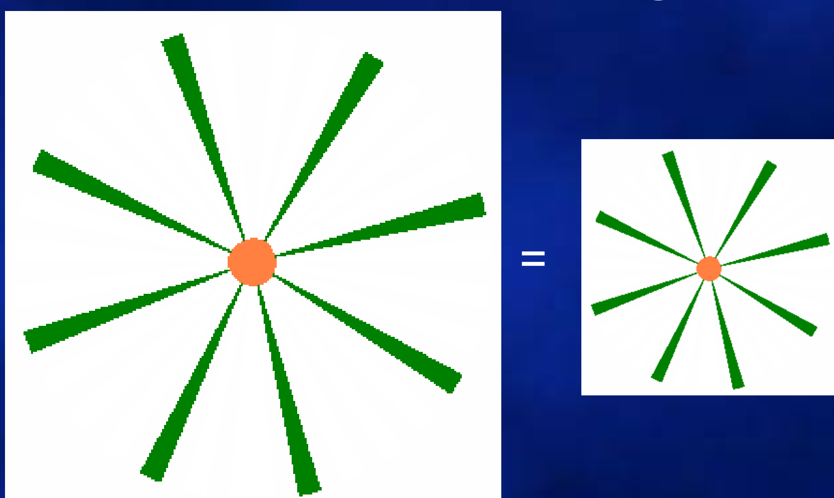
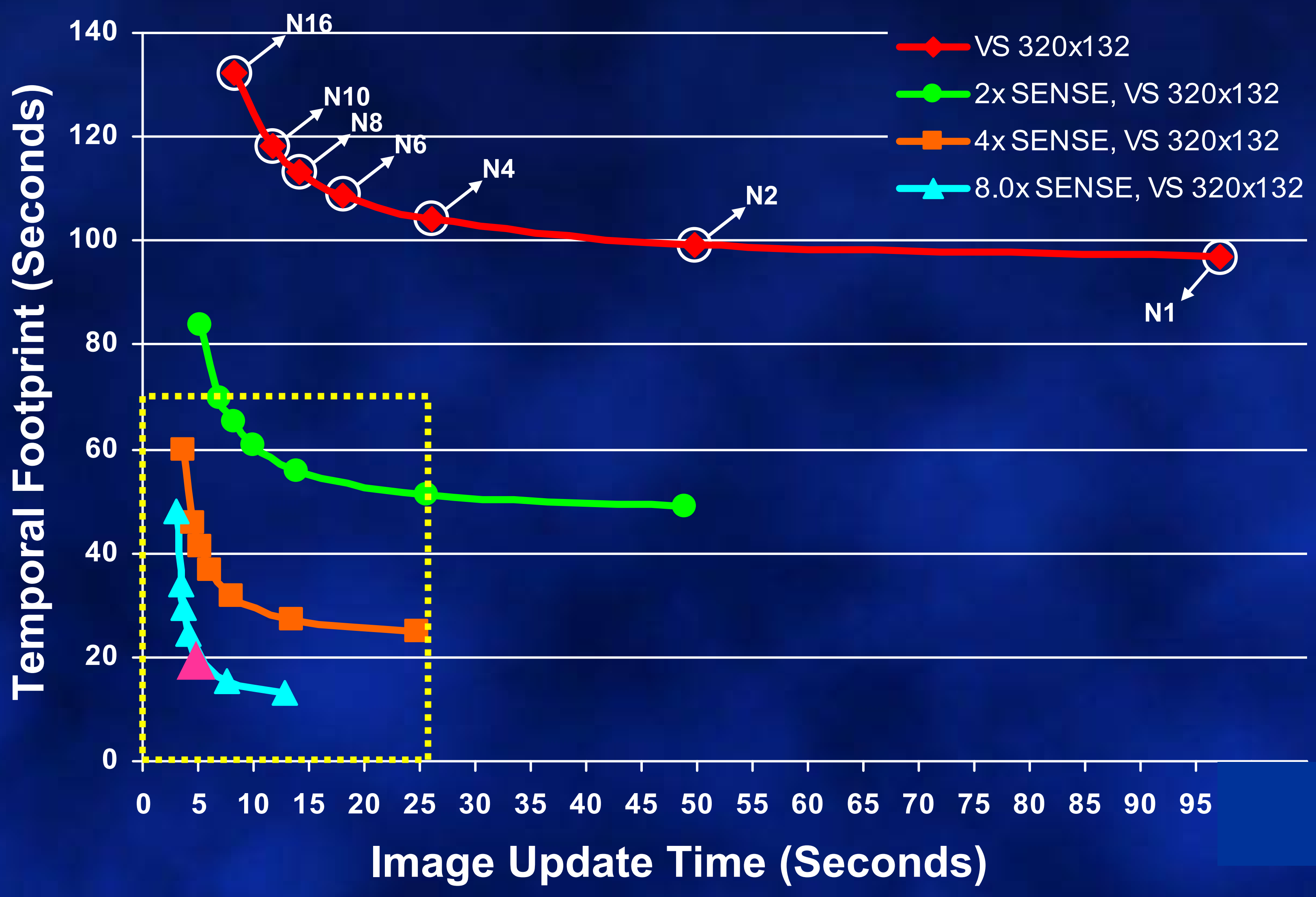
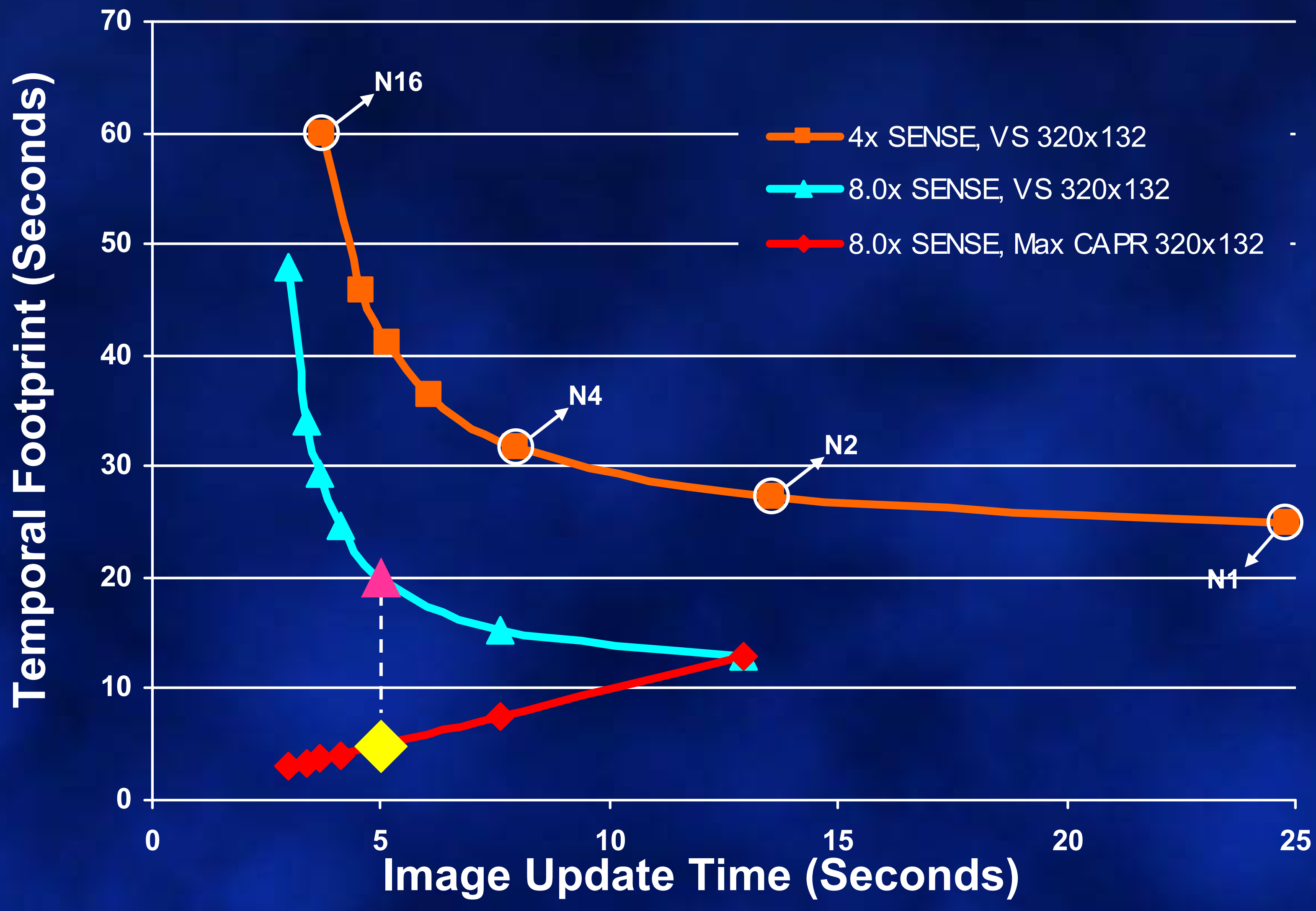


Image Update Time == Temporal Footprint

Technical Performance: CAPR Fixed Spatial Resolution



Technical Performance: CAPR Fixed Spatial Resolution



Clinical Result (3): 8-fold 2D SENSE, 8 Channel Array

Max CAPR (TF = 4.9 sec, R_{net} = 37.7)

39.2 sec post injection

Clinical Result (3): 8-fold 2D SENSE, 8 Channel Array

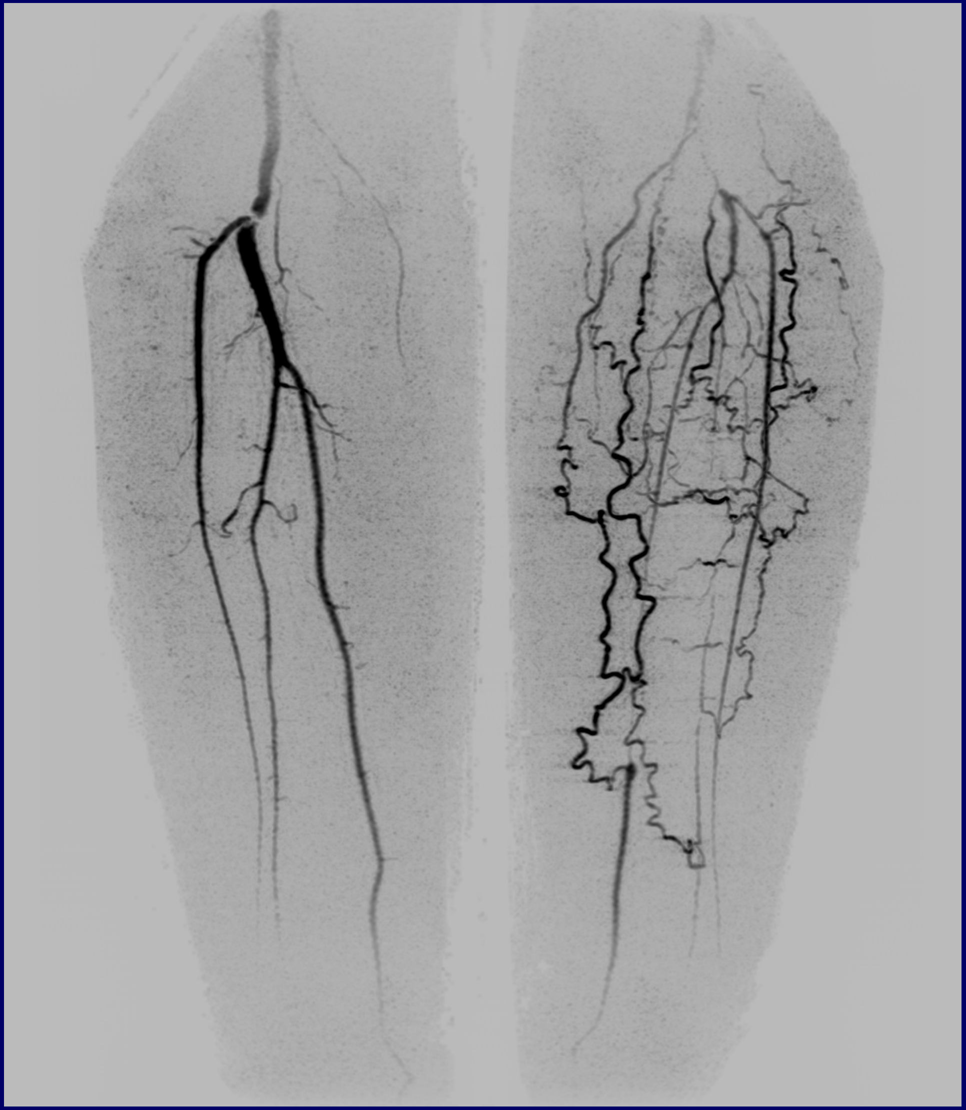
Max CAPR (TF = 4.9 sec, R_{net} = 37.7)

44.1 sec post injection

MAYO CLINIC

Clinical Result (3): 8-fold 2D SENSE, 8 Channel Array

Max CAPR (TF = 4.9 sec, R_{net} = 37.7)



49.0 sec post injection

Summary

1. MRI is imperfect in depicting a time-varying phenomenon because the MR data acquisition is non-infinitesimal.
2. View sharing provides an increased frame rate but also image-to-image correlation.
3. Acceleration with $R \geq 10$ has allowed a radical improvement in the spatiotemporal resolution of CE-MRA vs. a decade ago.

Summary

4. For accurate depiction of a time-varying phenomenon the MRI sequence should
   - have **consistent** frame-to-frame sampling
   - have **compact** sampling of central k-space
   - benefit from **acceleration** methods
5. Acceleration applied with centric encoding to CE-MRA has resistance to the standard SNR falloff of $1 / g \sqrt{R}$.
6. Accelerated CE-MRA using CAPR has been effectively applied to imaging of the vasculature of the body.

Acknowledgements

Staff Collaborators

Norbert G. Campeau, MD
Joel P. Felmlee, PhD
James F. Glockner, MD, PhD
John Huston III, MD
Phillip M. Young, MD

Lab Staff

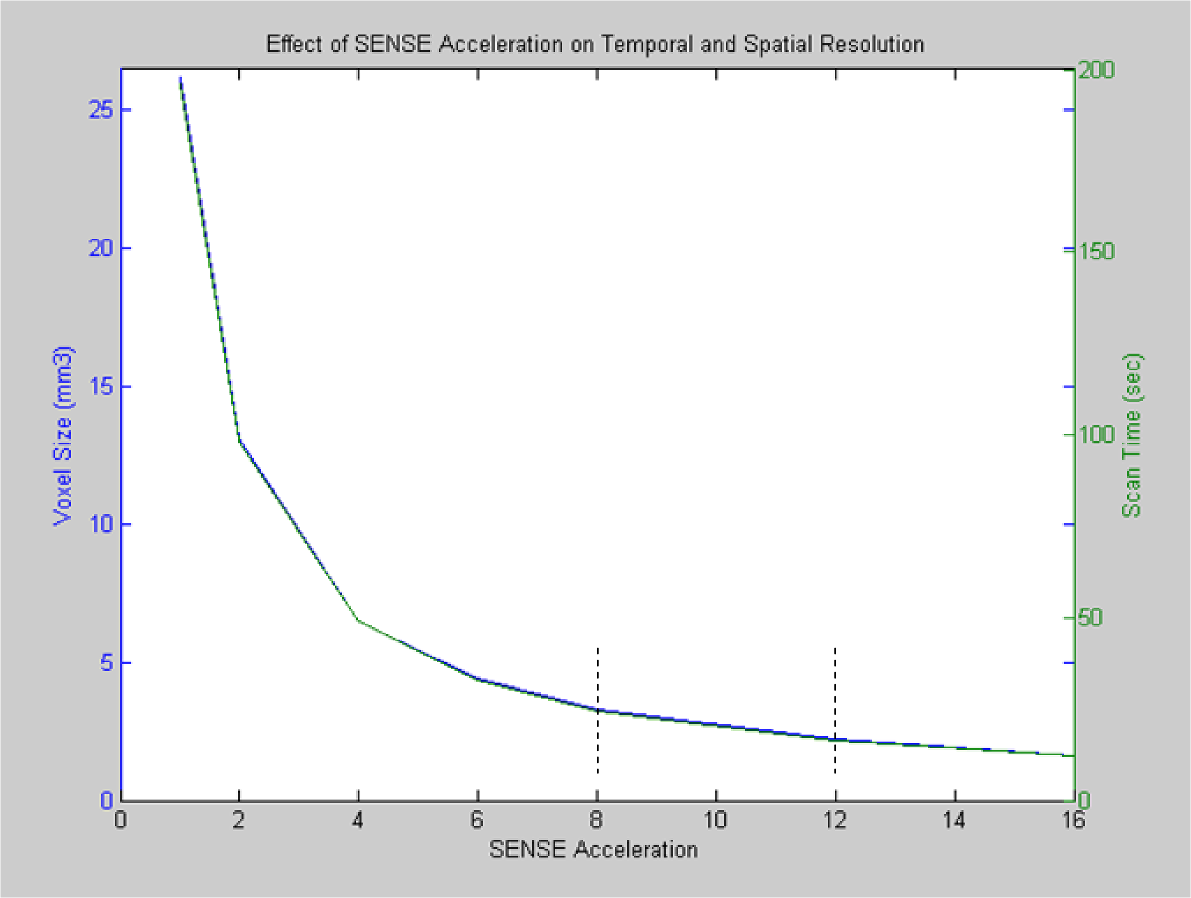
Eric A. Borisch
Roger C. Grimm
Mary C. Goltz
Thomas C. Hulshizer
Christine C. La Plante
Phillip J. Rossman

Past / Present Students

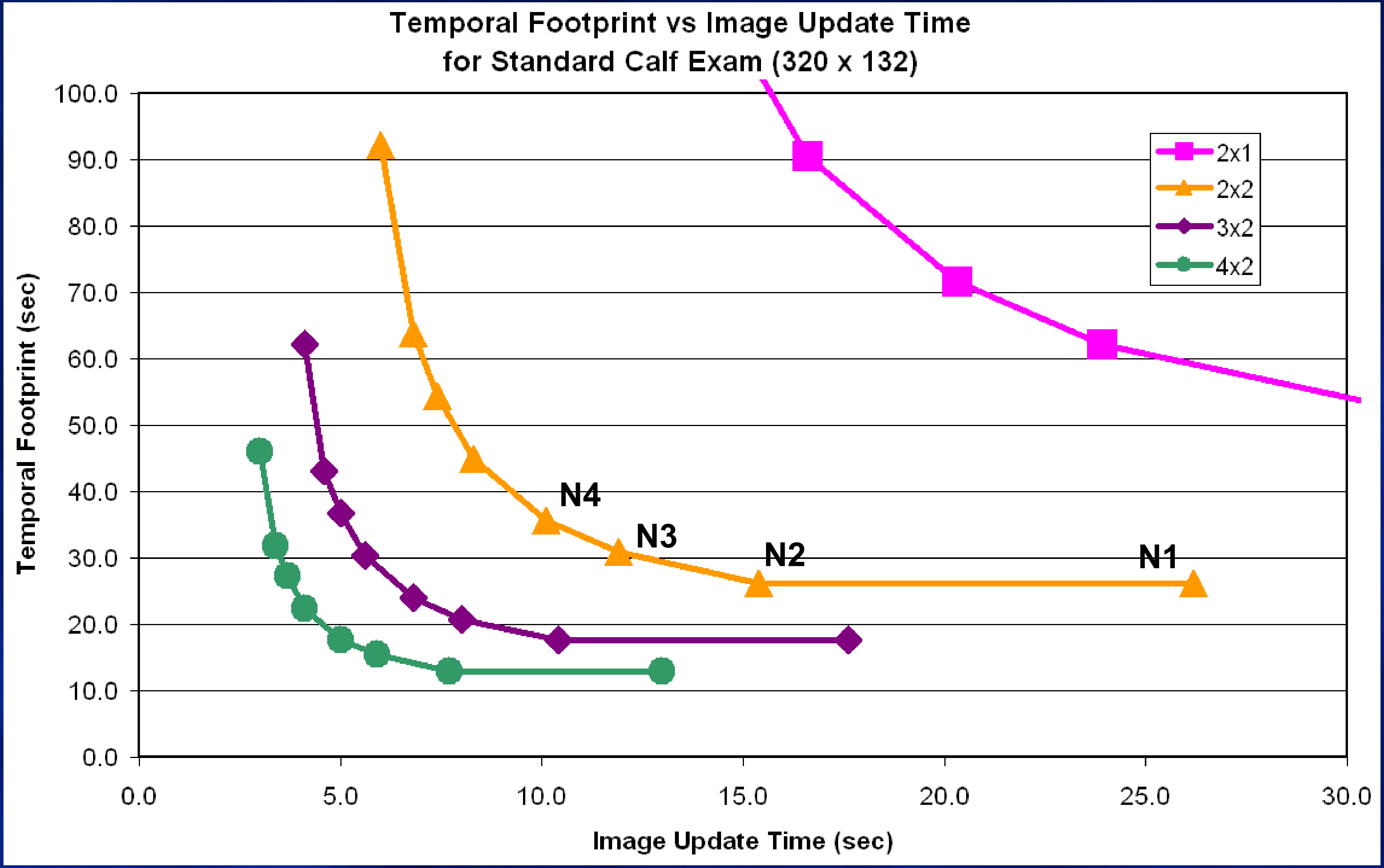
Reed F. Busse, PhD
Sean B. Fain, PhD
Clifton R. Haider, PhD
Harry Hu, PhD
Petrice M. Mostardi, PhD
Ek Tsoon Tan, PhD
Casey P. Johnson
Thomas W. Polley
Eric G. Stinson
Paul T. Weavers


Thanks to organizers of
BASP (1) for hosting a
wonderful meeting
Hiking near Bretaye
7 Sept 2011

Figure 2.12. Effects of SENSE acceleration on temporal and spatial resolution. The effects of SENSE are demonstrated for an example abdominal CE-MRA acquisition with FOV 35 x 35 x 28 cm^3, and Nx = 256 to fix the TR at 4.0 msec. The voxel size (left) is plotted versus SENSE acceleration for a scan with an acquisition time of 16.1 sec. The scan time (right) is plotted versus SENSE acceleration for a scan with a voxel size of 2.2 mm^3. The target parameters are a scan time of approximately 20 sec and spatial resolution of ≤ 1.2 mm isotropic. To achieve these temporal and spatial parameters over a large abdominal FOV, accelerations of 8-12x are required.



CAPR Temporal Resolution



SENSE
Effects on Time-Dependent Phenomena

- SENSE increases the rate of k-space coverage by a virtual reduced FOV
- SENSE provides reduced resolution loss from decaying magnetization

$$\text{PSF Width} \approx \sqrt{\frac{1}{\tau}\,\frac{TR}{R\,\Delta k_Y\,\Delta k_Z}} \approx \sqrt{\frac{FOV_Y\;FOV_Z\;TR}{R\,\tau}}$$

- SENSE also provides improved venous suppression (venous arrival occurs further out in k-space)