Cartesian Methods for Rapid Time-Resolved MR Angiography

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Advanced Angiographic Imaging Techniques
AAPM Meeting
Monday, July 30, 2012

Disclosure

- Multiple technologies presented have been licensed by the authors to MRI vendors:
  - General Electric Healthcare
  - Siemens
  - Philips
  - Hitachi
  - Toshiba

Focus

- This talk will focus on imaging the temporal passage of contrast-enhanced blood through the vascular system.
- "Time-resolved" MRA w/o contrast agents is also possible; e.g.
  - *tag spins – evolve – measure* for applications in stroke and perfusion

Objectives

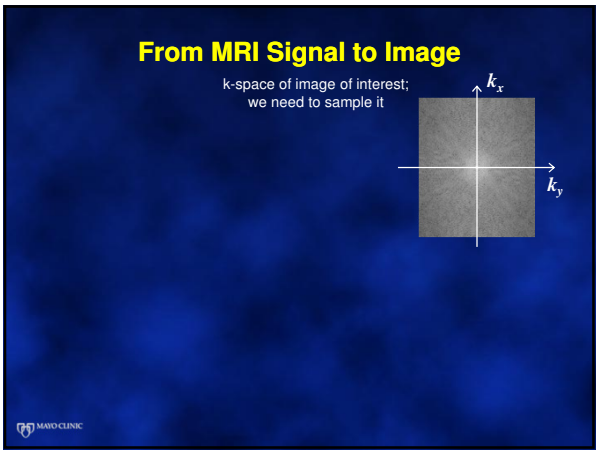
- Give a sense of the progressive improvement in CE-MRA over the last decade.
- Give an overview of contemporary applications of time-resolved CE-MRA

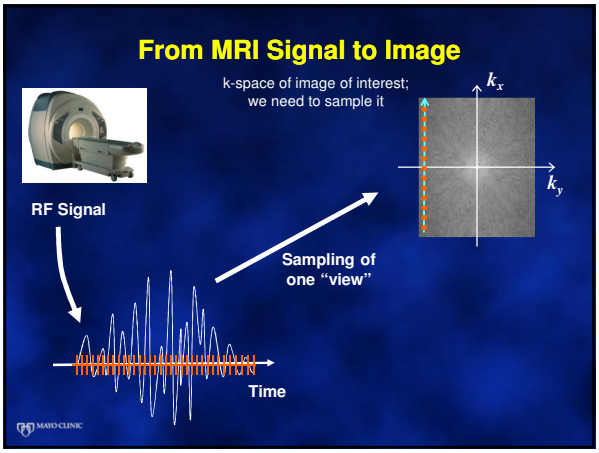
Outline

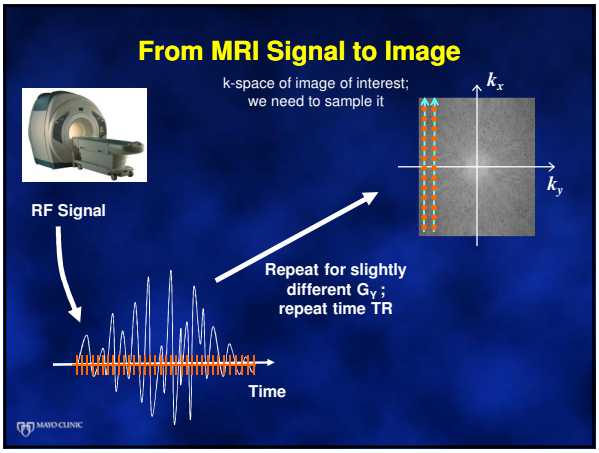
- Cartesian Sampling
- Temporal vs. Spatial Resolution
- View Sharing
- Parallel Acquisition
- Image Quality in Time-Resolved MRA
- Applications and Examples

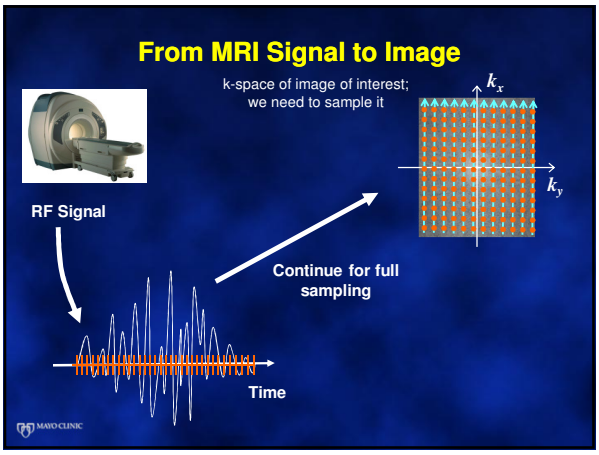
MR Sampling

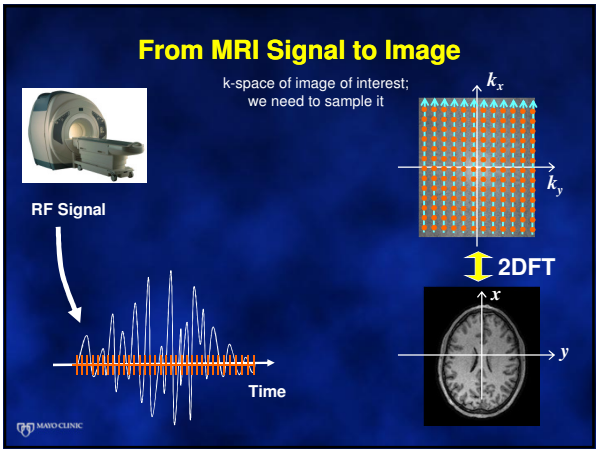
- MRI raw data sample the Fourier space or “k-space” of the final image.
- The x, y, z gradient waveforms control the k-space sampling trajectory
- The time sampling controls the spacing between k-space points

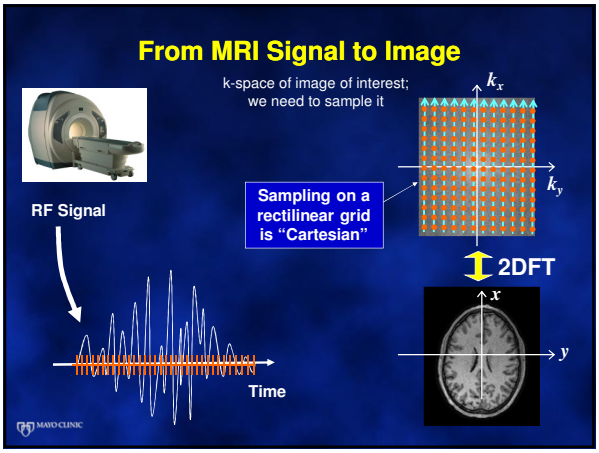

From MRI Signal to Image
k-space of image of interest;
we need to sample it
k_x
k_y
MAYO CLINIC

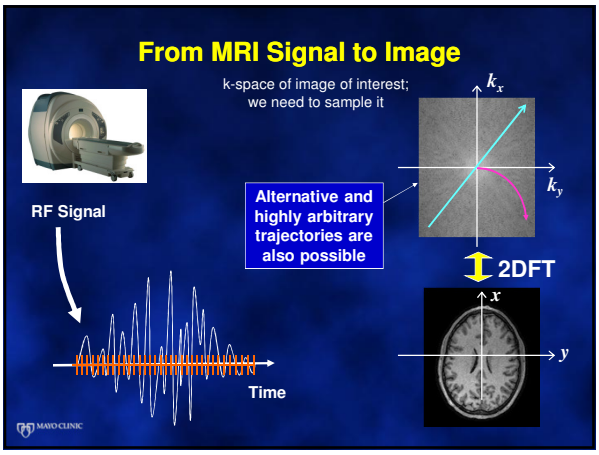

From MRI Signal to Image
k-space of image of interest;
we need to sample it
k_x
k_y
RF Signal
Sampling of
one "view"
Time
MAYO CLINIC

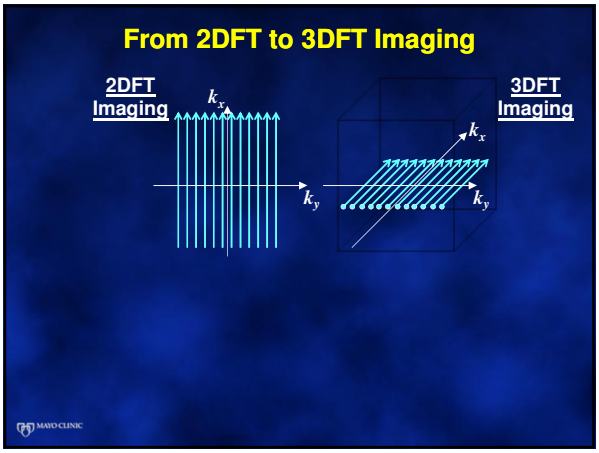

From MRI Signal to Image
k-space of image of interest;
we need to sample it
k_x
k_y
RF Signal
Repeat for slightly
different G_y ;
repeat time TR
Time
MAYO CLINIC

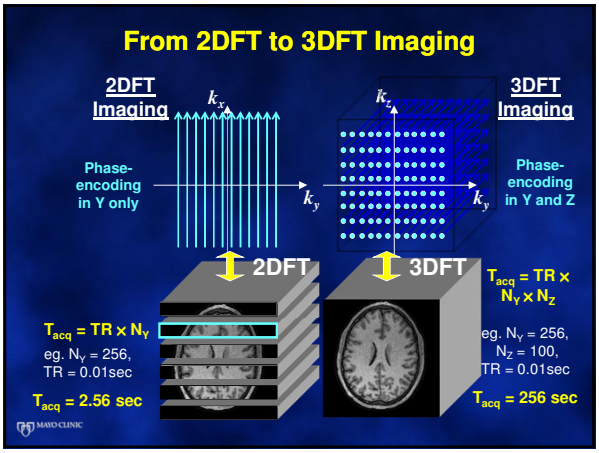

From MRI Signal to Image
k-space of image of interest;
we need to sample it
k_x
k_y
RF Signal
Continue for full
sampling
Time

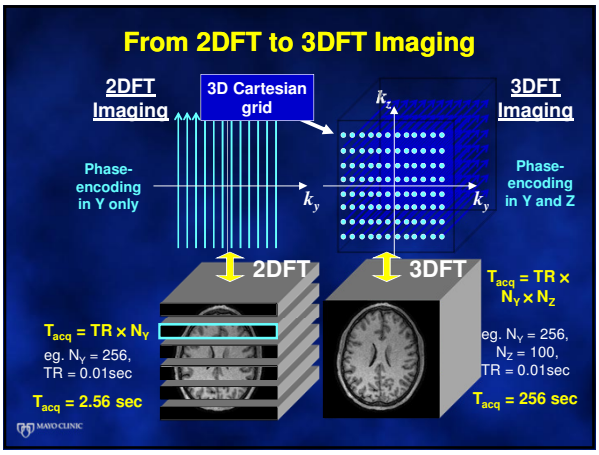

From MRI Signal to Image
k-space of image of interest;
we need to sample it
k_x
k_y
RF Signal
2DFT
x
y
Time


From MRI Signal to Image
k-space of image of interest;
we need to sample it
k_x
k_y
RF Signal
Sampling on a
rectilinear grid
is "Cartesian"
2DFT
x
y
Time


From MRI Signal to Image
k-space of image of interest; we need to sample it
k_x
k_y
Alternative and highly arbitrary trajectories are also possible
RF Signal
2DFT
x
y
Time
MAYO CLINIC


From 2DFT to 3DFT Imaging
2DFT Imaging
3DFT Imaging
k_x
k_y
k_x
k_y
MAYO CLINIC


From 2DFT to 3DFT Imaging
2DFT Imaging
3DFT Imaging
Phase-encoding in Y only
Phase-encoding in Y and Z
k_x
k_y
k_z
k_y
2DFT
3DFT
$T_{acq} = TR \times N_Y$
eg. $N_Y = 256$, TR = 0.01sec
$T_{acq} = 2.56$ sec
$T_{acq} = TR \times N_Y \times N_Z$
eg. $N_Y = 256$, $N_Z = 100$, TR = 0.01sec
$T_{acq} = 256$ sec
MAYO CLINIC



3DFT Pulse Sequence
Acquisition Times

	Y x Z: 64 x 16	96 x 32	128 x 48
TR: 10 msec	10 sec	30	61
7 msec	7	21	43
4 msec	4	12	25

3DFT Pulse Sequence
Acquisition Times

*	5 mm x 10 mm	3.8 mm x 5 mm	2.5 mm x 3 mm
	Y x Z: 64 x 16	96 x 32	128 x 48
TR: 10 msec	10 sec	30	61
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*approximate axial spatial resolution for CE-MRA of calves

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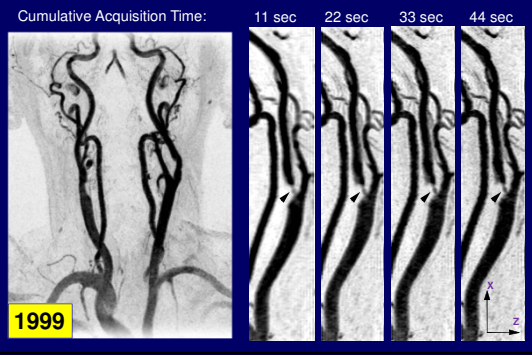
*approximate axial spatial resolution for CE-MRA of calves

Tradeoff: temporal vs. spatial resolution
Six 7 sec images with limited spatial resolution or one 43 sec image with good spatial resolution

Spatial Resolution in CE MRA
Importance of Acquisition Time – Clinical Example

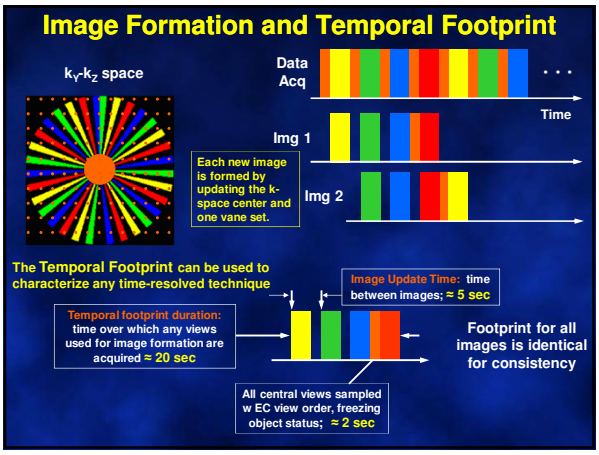


View Sharing

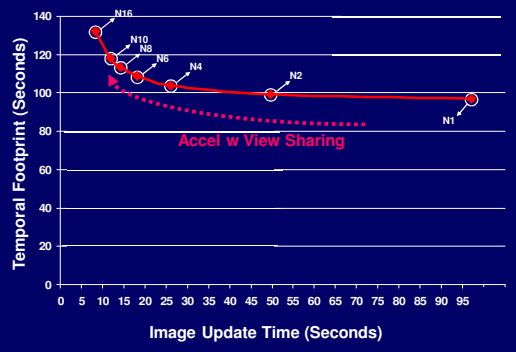
- Continuous cyclical sampling of k-space using some view ordering
- Reconstruct a full image after only partial replacement of the k-space data
- Image update rate is higher than intrinsic full sampling rate
- Potential to sample central k-space more frequently than periphery for improved time resolution
- Successive images in sequence are correlated.

Riederer, MRM, 1988

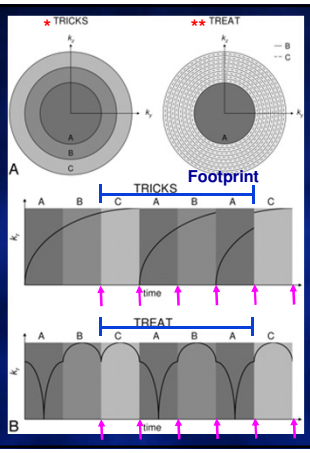
Image Formation and Temporal Footprint



Methodology: Time-Resolved 3D CE-MRA Fixed Spatial Resolution (1 mm³)



Other Examples of View Sharing and Footprint



*Korosec, MRM 1996
**Carroll, AJNR 2006

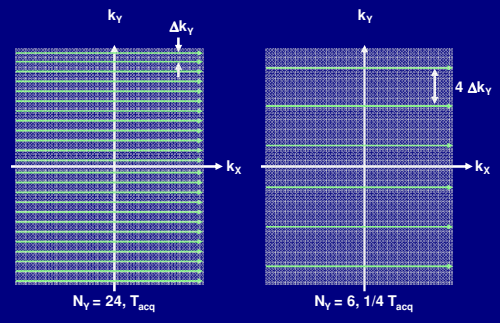
Parallel Acquisition

- Use redundant information from multiple coil elements to reduce scan time.
- Original images are artifactual superpositions of signals from multiple pixels across the imaging field of view.
- Need to mathematically account for the superposition . . . can do this algebraically.

Pruessmann, MRM, 1997

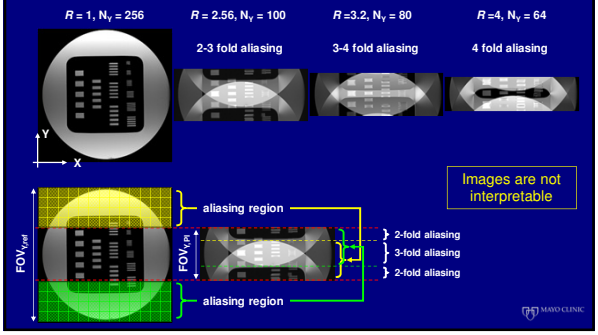
2DFT Acquisition

Suppose N_Y is reduced? Any consequence?

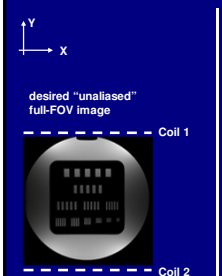


Consequences of FOV Reduction: Foldover or "Aliasing"

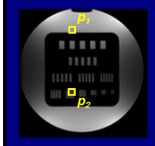
$\Delta k_r = 1/FOV_r$, if $\Delta k_r \uparrow$, $FOV_r \downarrow$



Parallel Acquisition: exploit two separate aliased images from different coils



Images from two coils are acquired at the same time, 2x reduced scan time vs. reference



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.

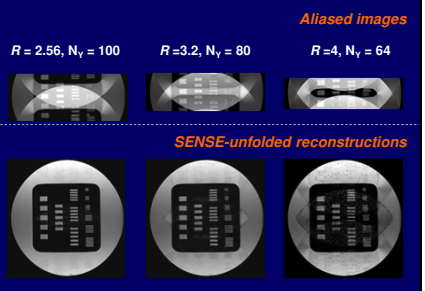
The signal for the second coil is identical except with different coil sensitivity.

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.

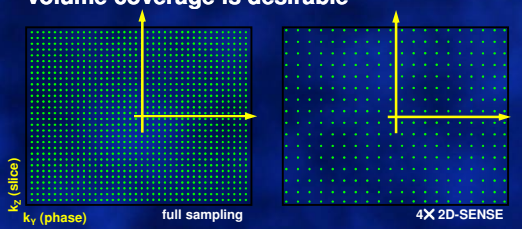
Parallel Acquisition
Effect of increasing acceleration R



As R increases, SNR can degrade and artifacts can appear

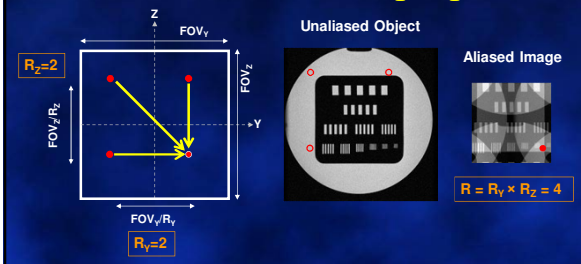
3DFT Acquisition
2D Parallel Imaging

- Perform parallel acquisition along two phase encode directions
- Assumes that 3D acquisition with large volume coverage is desirable



Weiger, MAGMA 2002

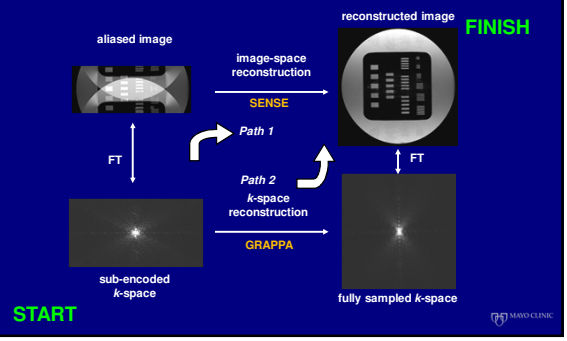
2D Parallel Imaging



- Aliasing occurs from two dimensions, and "un-wrapping" must account for this simultaneously in the reconstruction algorithm.
- For a given R, 2D acceleration is in general far more robust than 1D acceleration.

Parallel Imaging Reconstruction Approaches

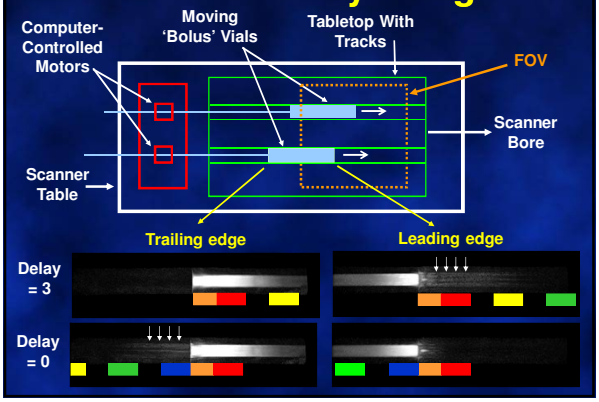
- All PI methods account for the inherent aliasing due to sub-encoding by using coil sensitivity information to "un-alias" or "un-wrap".



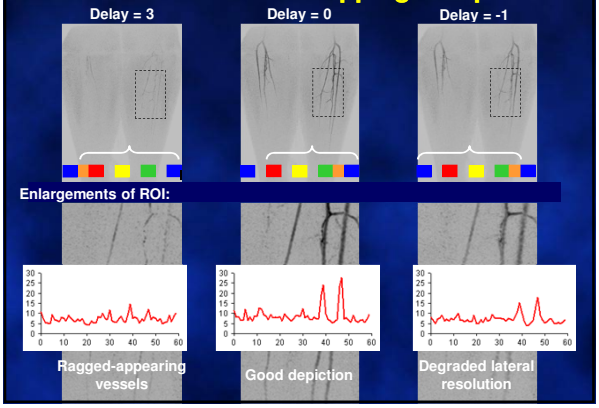
Fidelity of Image of Contrast Bolus

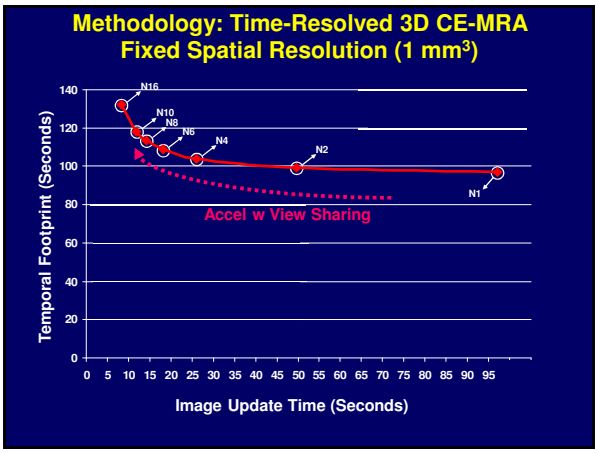
- All MR sequences have a finite (non-zero) acquisition time.
- Consequently, an image of the contrast bolus at some time deviates from reality.
- Ideally a time-resolved MRA sequence:
  - Accurately portrays bolus edge **position**
  - Provides **minimal blur** of the bolus edge
  - Accurately portrays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

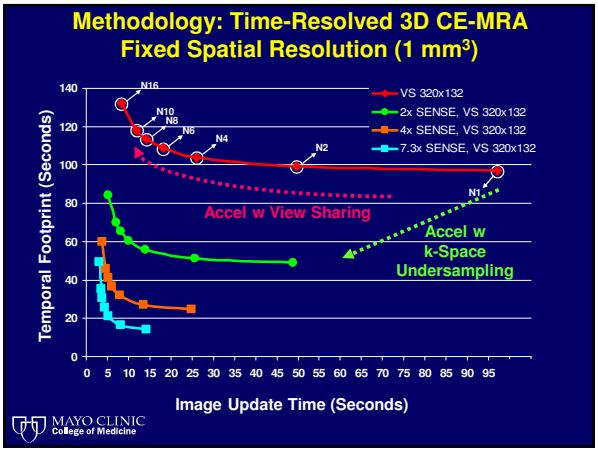
Phantom Study Design

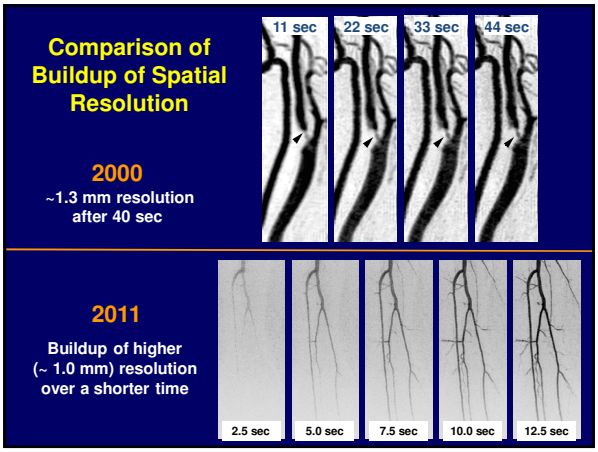


In Vivo Results: Overlapping Footprints




Methodology: Time-Resolved 3D CE-MRA
Fixed Spatial Resolution (1 mm³)
Temporal Footprint (Seconds)
Image Update Time (Seconds)
N16
N10
N8
N6
N4
N2
N1
Accel w View Sharing

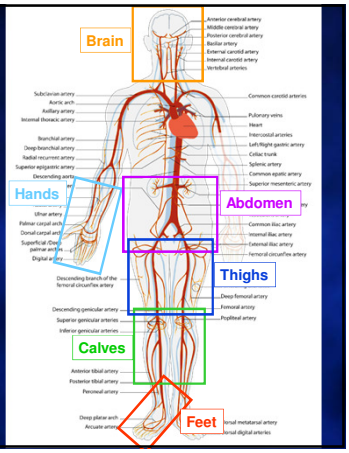

Methodology: Time-Resolved 3D CE-MRA
Fixed Spatial Resolution (1 mm³)
Temporal Footprint (Seconds)
Image Update Time (Seconds)
VS 320x132
2x SENSE, VS 320x132
4x SENSE, VS 320x132
7.3x SENSE, VS 320x132
Accel w View Sharing
Accel w k-Space Undersampling
MAYO CLINIC College of Medicine


Comparison of Buildup of Spatial Resolution
2000
~1.3 mm resolution after 40 sec
11 sec
22 sec
33 sec
44 sec
2011
Buildup of higher (~ 1.0 mm) resolution over a shorter time
2.5 sec
5.0 sec
7.5 sec
10.0 sec
12.5 sec

Applications to Cardiovascular System

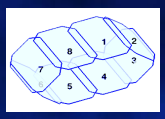
CE-MRA using accelerated, view-shared Cartesian techniques has been applied to multiple vascular regions

Critical to effective implementation are high-performance multi-element receiver coils



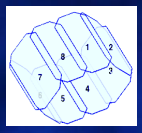
Comparison of Coils

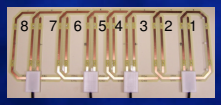
Original Eight-Element Array



All elements: 21.5 x 14.3 cm^2

Modified Eight-Element Array





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

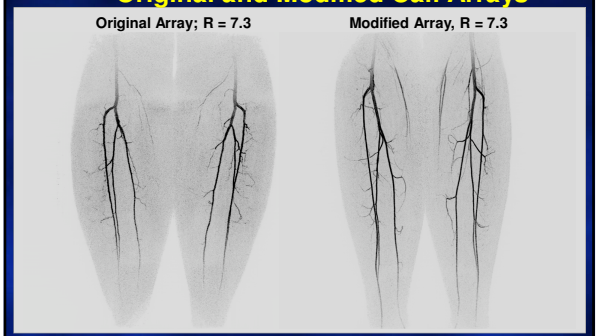
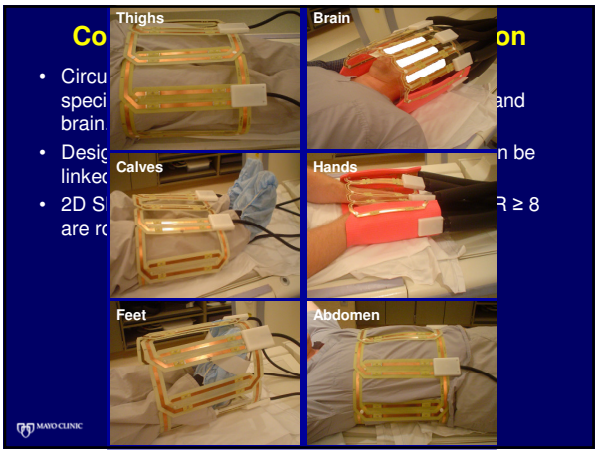
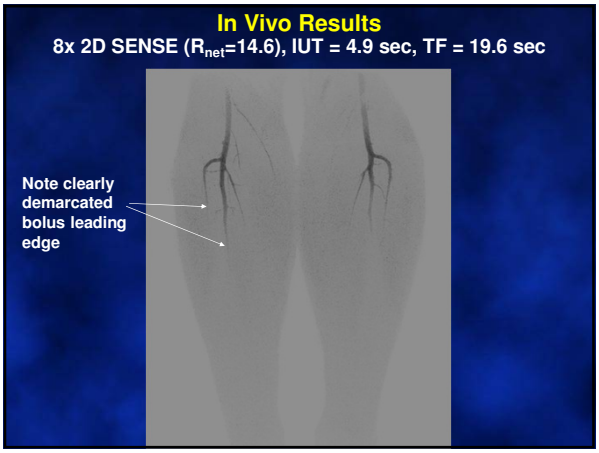
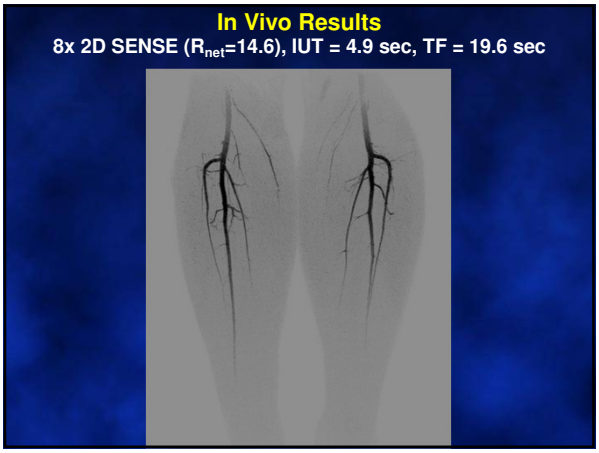


Image Update Time 5.3 sec
Temporal Footprint 21.2 sec


Co
on
• Circu
speci
brain
and
• Desig
linkec
n be
• 2D S
are rc
R ≥ 8
Thighs
Brain
Calves
Hands
Feet
Abdomen
MAYO CLINIC


In Vivo Results
8x 2D SENSE (R_{net}=14.6), IUT = 4.9 sec, TF = 19.6 sec
Note clearly demarcated bolus leading edge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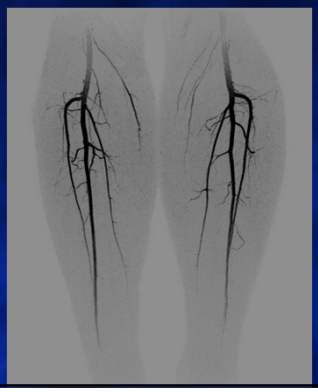
In Vivo Results

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



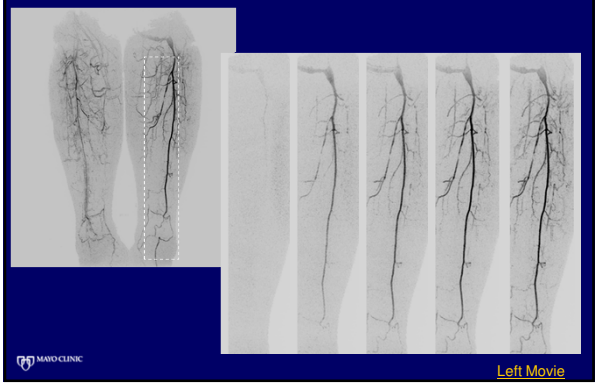
Clinical Study of Calf Vessels

- 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

MAYO CLINIC

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

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

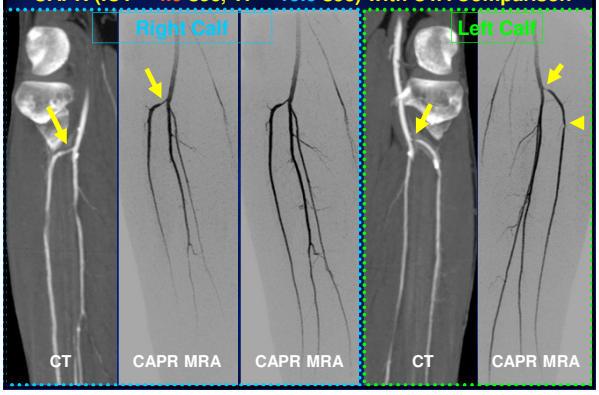


MAYO CLINIC

Left Movie

Patient Study (2): 8-fold 2D SENSE, 8 Channel Array

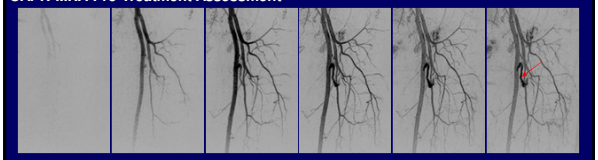
CAPR (IUT = 4.9 sec, TF = 19.6 sec) with CTA Comparison



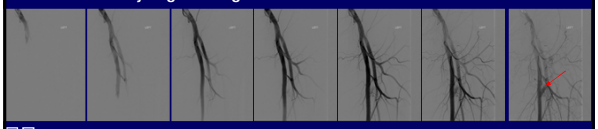
Results: Patient #11

Vascular Malformation of Thigh
Comparison with Treatment Angiography

CAPR MRA Pre-Treatment Assessment



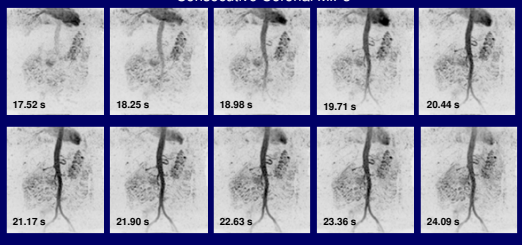
Conventional X-ray Angio During Treatment



MAYO CLINIC

Results: Volunteer #10 Timing Bolus

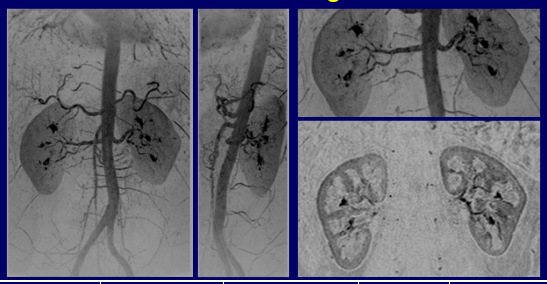
Consecutive Coronal MIPs



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

Specific Aim #3: Abdominal CE-MRA

5.4. Results: Volunteer #10 High Resolution MRA

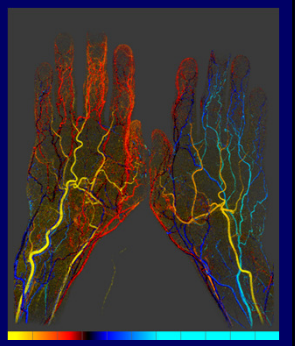


FOV (cm^3)	Matrix	Spatial resolution (mm^3)	Temporal resolution	Acceleration
34.0 x 40.8 x 28.8	256 x 288 x 180	1.33 x 1.41 x 1.6	17.4 sec	$R_Y = 4$, $R_Z = 2$

Patient Study of the Hands

- **Time-of-Arrival Map**
  - **Produced from CAPR images from preceding slide**
  - **Scale at bottom matches color to arrival time; each hash mark is one frame time (4.5 sec); start of color scale is 24 sec post-injection**
  - **Note obvious TOA differences between L and R hands.**

Time-of-Arrival Mapping



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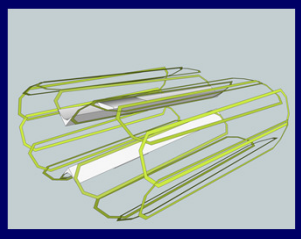
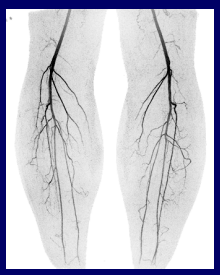
Ongoing Coil Development



Fixed-width 40cm long; N_C = 16 element array; angled medial anterior and posterior elements



12x 2D SENSE; 1.8x PF; RNET=21.6; FOV: 42cm x 33.6cm x 13.2cm; 3.5sec updates, $1mm^3$ voxels

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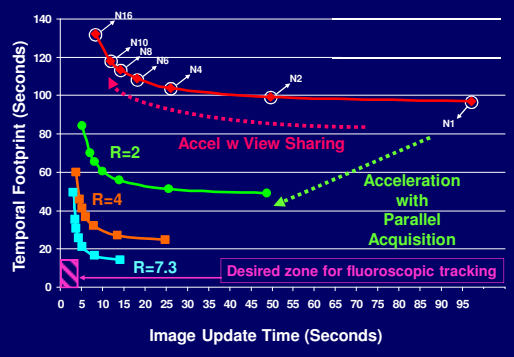
Peripheral (Long FOV) CE-MRA

- Fundamental challenge:
  - Stay at an axial level long enough to acquire enough data for high spatial resolution
  - Keep station dwell time short enough to keep pace with advancing contrast bolus
- All methods are subject to this tradeoff
- Approaches
  - Reduce spatial resolution at proximal stations
  - Continuous table motion to eliminate dead time
  - Hybrid dual injection methods
  - Parallel acquisition

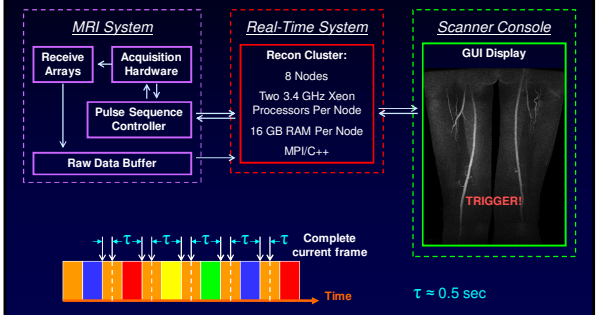
Fluoroscopic Tracking

- **Method for multi-station peripheral CE-MRA**
- **Image proximal stations in real time**
  - **High spatial resolution for diagnosis (1.0 – 1.5 mm iso)**
  - **High temporal resolution to observe bolus arrival and traversal across FOV (2.5 sec frame time)**
- **Allow longer frame time at distal-most station for higher quality**

Methodology: Time-Resolved 3D CE-MRA Fixed Spatial Resolution (1 mm³)



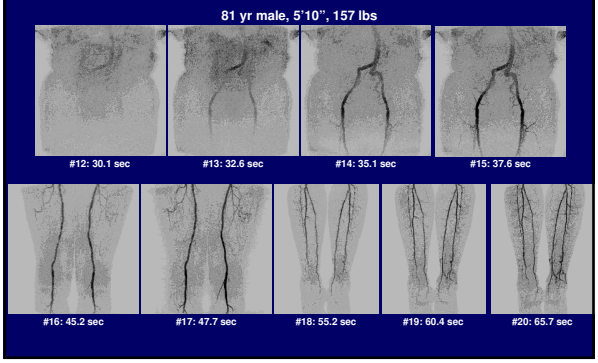
Fluoroscopic Tracking

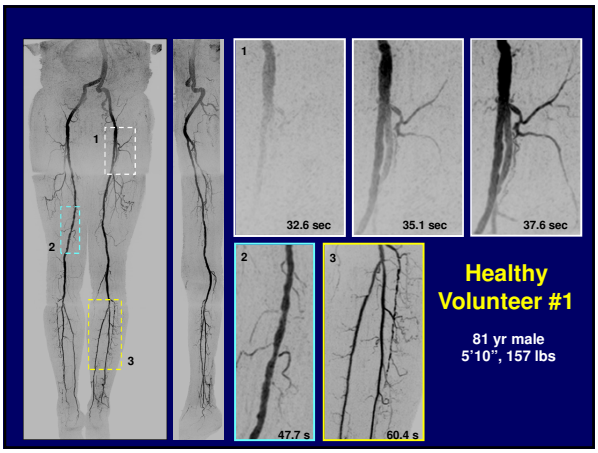


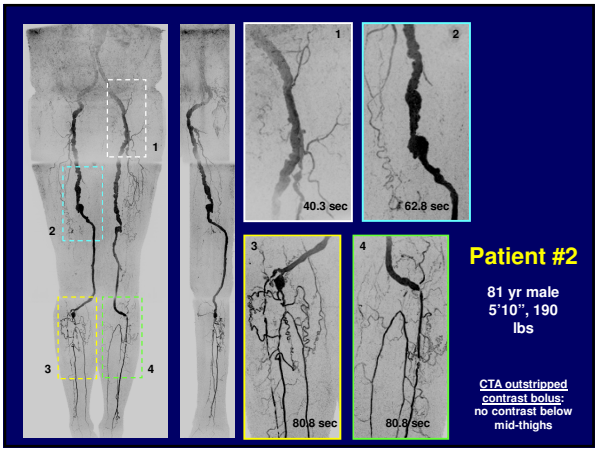
System Components

- High spatiotemporal resolution is allowed with 2D acceleration (R≥8)
- Technical enabler: multi-element coils with circumferential placement

Healthy Volunteer #1







Summary

1. Contrast-enhanced MRA has markedly improved in the last decade.
2. View sharing and parallel acquisition are routinely used in contemporary time-resolved CE-MRA.
3. Parallel acquisition readily allows a 10× reduction in the amount of data necessary to form a single image.

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

   Cartesian sampling readily allows these.
5. **Synergistic combination of the techniques presented with compressive sensing and related methods may provide further advances.**

Acknowledgments

Staff Collaborators
Norbert G. Campeau, MD
Joel P. Felmlee, PhD
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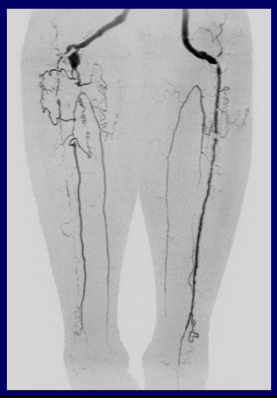
Ek Tsoon Tan, PhD
Casey P. Johnson, PhD
Thomas W. Polley
Eric G. Stinson
Paul T. Weavers

Acknowledgments

- NIH C06 RR018898
- NIH R01 HL070620
- NIH R01 EB000212
- General Electric Healthcare

Patient #2



Fluoroscopic Tracking: What Is It?

- Method for multi-station CE-MRA
- Image proximal stations in real time
  - High spatial resolution for diagnosis
  - High temporal resolution to observe bolus arrival and traversal across FOV
  - Short dwell time to keep pace with advancing contrast bolus
  - Short reconstruction time to allow real-time triggering of table advance to next station
- Allow longer frame time at distal-most station for higher quality

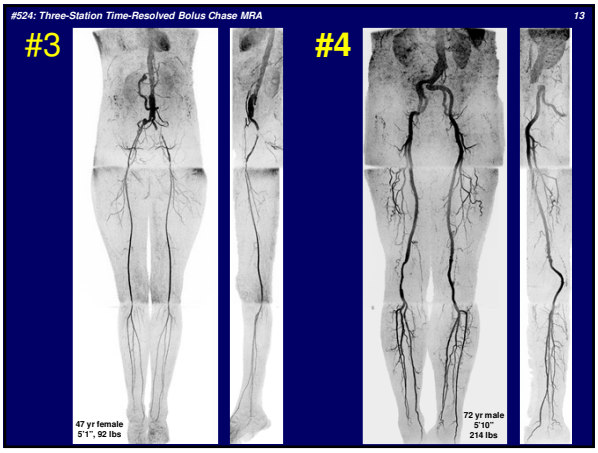
Fluoroscopic Tracking: Potential Advantages

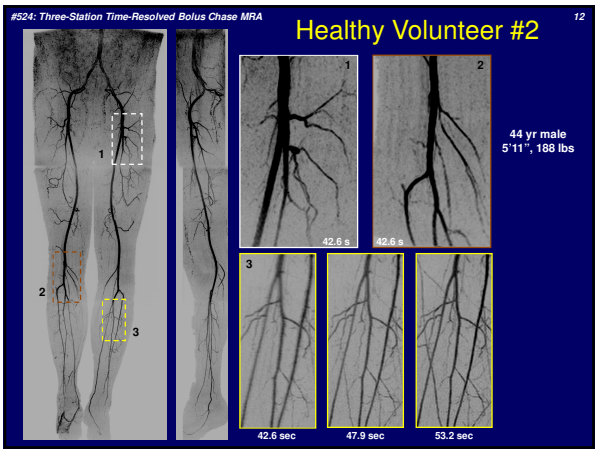
- High spatiotemporal resolution over an extended FOV
- Single injection of contrast material
- Accurate, reliable, and patient-specific timing of table motion to advancing contrast bolus
- Routine avoidance of venous contamination
- Relatively simple and short exam protocol

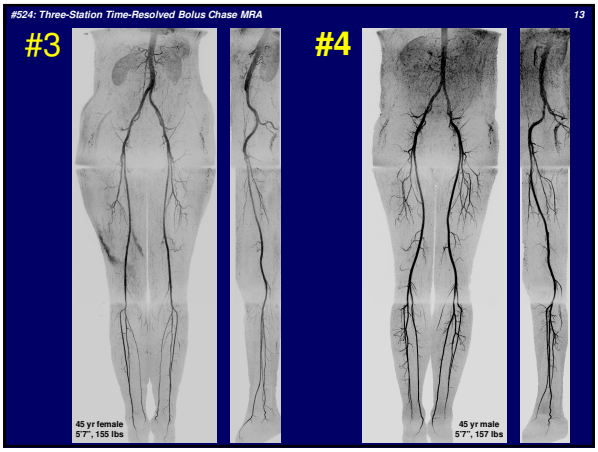
Courtesy Casey Johnson

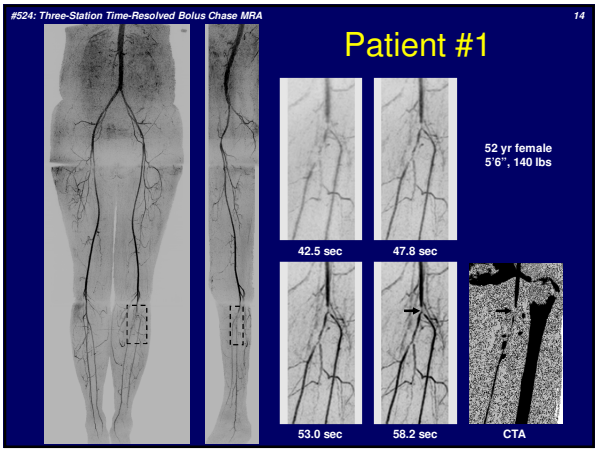
Fluoroscopic Tracking: Technical Challenges

- Method for multi-station CE-MRA
- Image proximal stations in real time
  - High spatial resolution for diagnosis
    sub-1.0 to 1.5 mm isotropic resolution
  - High temporal resolution to observe bolus arrival and traversal across FOV
    frame time ≤ 2.5 sec
  - Short dwell time to keep pace with advancing contrast bolus
    temporal footprint ≤ 15 sec
  - Short reconstruction time to allow real-time triggering of table advance to next station
    recon time << 2.5 sec frame time
- Allow longer frame time at distal-most station for higher quality




#524: Three-Station Time-Resolved Bolus Chase MRA
12
Healthy Volunteer #2
1
2
3
42.6 s
42.6 s
44 yr male
5'11", 188 lbs
42.6 sec
47.9 sec
53.2 sec


#524: Three-Station Time-Resolved Bolus Chase MRA
13
#3
#4
45 yr female
5'7", 155 lbs
45 yr male
5'7", 157 lbs


#524: Three-Station Time-Resolved Bolus Chase MRA
14
Patient #1
52 yr female
5'6", 140 lbs
42.5 sec
47.8 sec
53.0 sec
58.2 sec
CTA

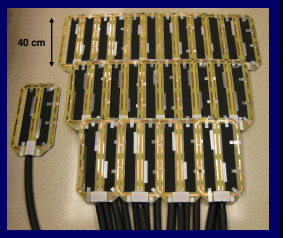
Imaging Parameters

Typical values from literature	Abdomen-Pelvis		Thighs		Calves-Feet
FOV (cm: S/I × L/R × A/P)	42 × 42 × 14.4		42 × 42 × 13.2		42 × 33.6 × 13.2
Sampling Matrix (S/I × L/R × A/P)	280 × 280 × 96		280 × 280 × 88		420 × 336 × 132
Resolution (mm: S/I × L/R × A/P)	1.5 × 1.5 × 1.5	1.6-1.9 mm isotropic	1.5 × 1.5 × 1.5		1.0 × 1.0 × 1.0
Flip Angle (°)	30		30		30
Bandwidth (kHz)	±62.5		±62.5		±62.5
TR / TE (ms)	4.7 / 2.0		4.7 / 2.0		6.0 / 2.7
Receiver Coils	12-14		10		8
View Sharing Sequence	N3 CAPR		N3 CAPR		N4 CAPR
2D SENSE Acceleration (L/R × A/P)	R=8 (4×2)	R=3.5	R=8 (4×2)	R=4	R=8 (4×2)
2D Partial Fourier Acceleration	1.9		1.9		1.8
Frame Time (sec)	2.5	8-20 sec	2.5	20-60 sec	5.2
Temporal Footprint (sec)	6.9		6.6		18.6

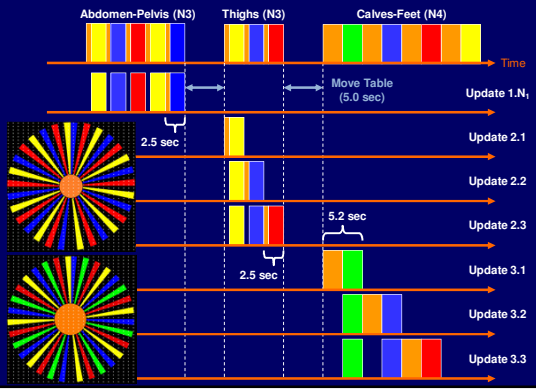
To date: 8 healthy volunteers; 7 patients with CTA comparisons

System Components

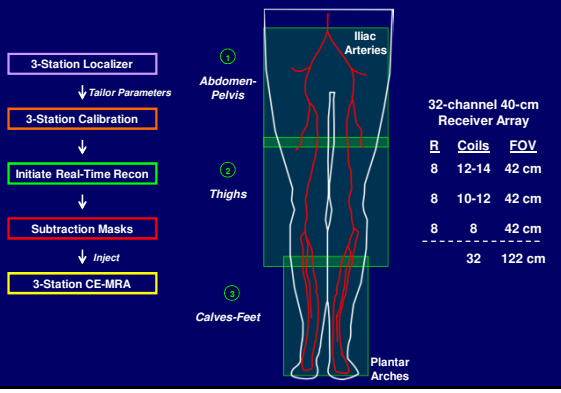
- 32-channel modular receiver coil array
  - Actively switched for each station
  - 8x 2D SENSE at each station
  - 122 cm longitudinal coverage
- Real-time reconstruction using custom hardware and software
  - ~110ms recon time
- 3T GE MR750 (v22)
  - Flexible station-specific imaging parameters



Sequence Temporal Playout



Three-Station Protocol

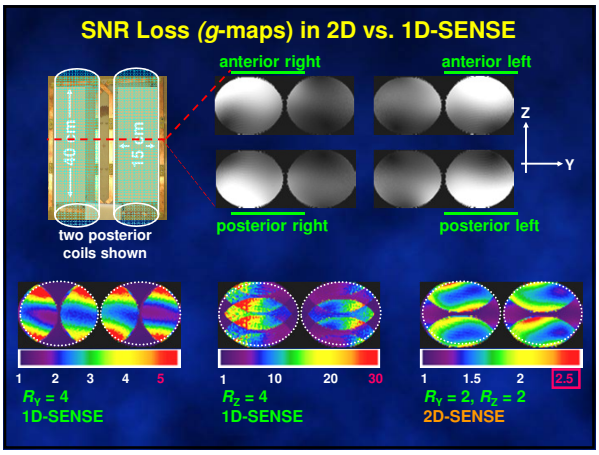


Parallel Acquisition

- The above example described parallel acquisition along one phase encode direction with an acceleration of R = 2.
- This allows 2x reduction of T_{ACQ}.
- In MRI in general accelerations of R = 2 – 3 are possible.
- This is balanced by loss of SNR

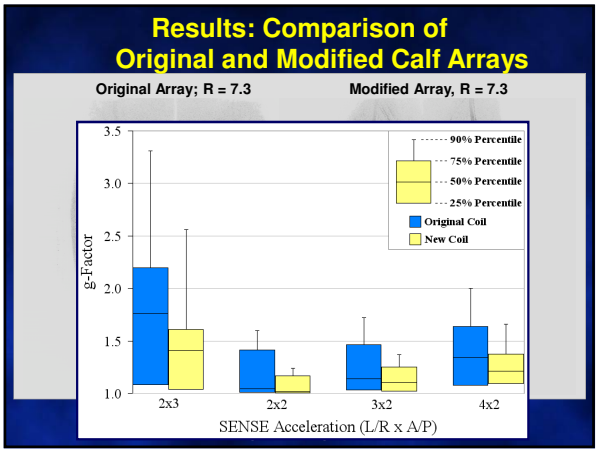
Parallel Imaging:
Potential for High Acceleration Factors

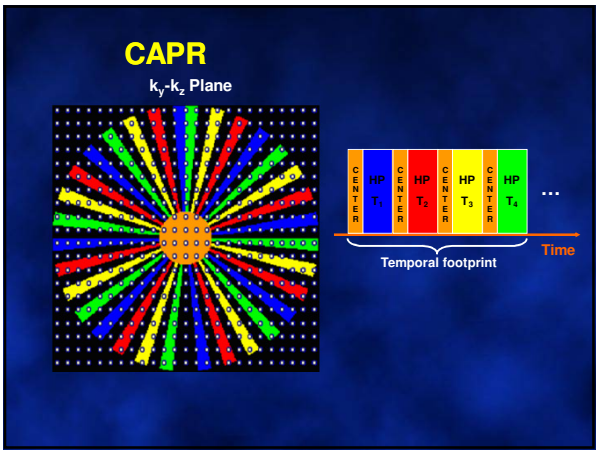
- **R = acceleration factor, factor by which data for the underlying image is reduced.**
- **For R > 3 along a single direction, SENSE inversion becomes poorly conditioned; "g-factor" grows**
- **Although possible, are larger R values practical?**

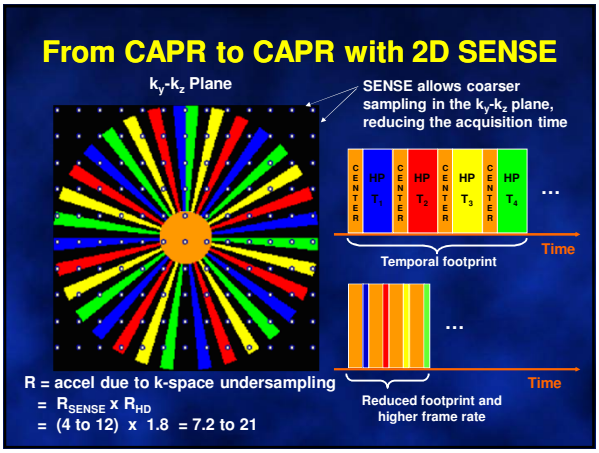


Parallel Acquisition

- $T_{ACQ} = N_Y \cdot TR$ single slice
  $T_{ACQ} = N_Y \cdot N_Z \cdot TR$ 3D volume
- Is there some way to reduce scan time?
- 1990s: extensive development of receiver coils. Perhaps this be further used?







Background

- Mid-1990s: development of basic contrast-enhanced MR angiography (CE-MRA)
- Late-1990s: technical optimization for generation of high quality, single phase images
- Fundamental tradeoff:
  temporal vs. spatial resolution
- 2000-2010: developments in acceleration (10x) have radically changed this tradeoff.
- Time-resolved CE-MRA is possible today with superior spatial resolution to single phase CE-MRA a decade ago.