C-arm cone-beam CT imaging in future ischemic acute stroke treatment: One-stop-shop imaging

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Acknowledgement

Interventional Stroke Imaging Research Team at UW-Madison:

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Members (Basic Science):

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Members (Clinical):

Pengfei Yang, David Niemann, Azam Ahmed, Howard Rowley, and Pat Turski

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International consortium on interventional stroke imaging:

Clinical team led by Drs. Doerfler and Struffert at the University of Erlangen-Nuremberg

Clinical team led by Dr. Guo in Taiwan

Outline

- Clinical motivation of one-stop-shop imaging
- Technical challenges
- Enabling technology for one-stop-shop imaging: SMART-RECON and SMART IV 3D-DSA
- One-stop-shop imaging using SMART-RECON: non-contrast CBCT images, time-resolved CBCT angiography, and CBCT perfusion maps
- Summary and discussion

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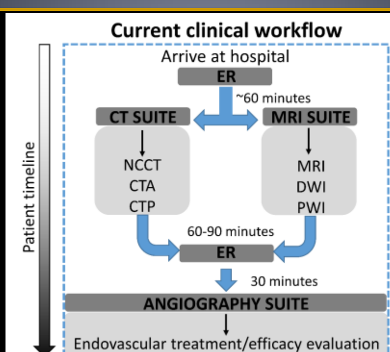
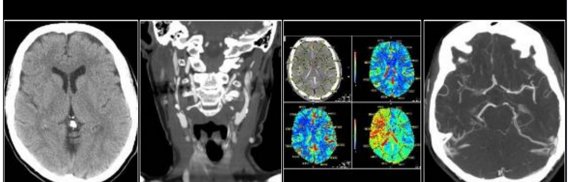
Current stroke imaging workflow



Stroke imaging components



Non-Contrast CT	CTA Head/Neck	CT Perfusion	CT Head with Contrast
Excludes hemorrhage	Carotid and vertebral	Blood flow to brain tissue	Vessels in the brain

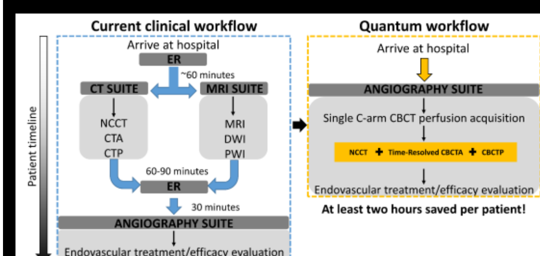
Courtesy of Dr. Howard Rowley

Time is brain!

In a typical acute ischemic stroke,
in every minute, the brains loses: 2 million neurons
14 billion synapses
7.5 miles of myelinated nerve fibers

JL Saver, Time is Brain---Quantified, Stroke, Vol. 37: 263-266 (2006)

One-stop-shop stroke imaging workflow



Needed imaging information in One-Stop-Shop clinical flow

- Non-contrast whole brain DynaCT images to exclude hemorrhage
- Time-resolved angiography to perform collateral analysis
- Whole brain cone-beam CT Perfusion to detect penumbra and infarction core

Plus:

- Reduced motion artifacts
- Reduced radiation dose
- Reduced contrast dose
- ……

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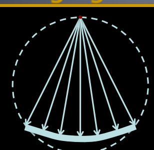
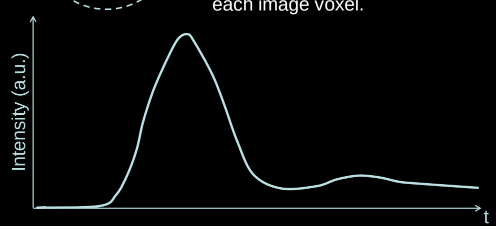
Temporal resolution requirement in CTP imaging: better than 2s per frame



- Why MDCT in perfusion imaging?

  Superior temporal resolution (better than 0.5 seconds!)
- Perfusion calculation is based on the contrast enhancement curve of each image voxel.



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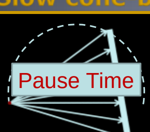
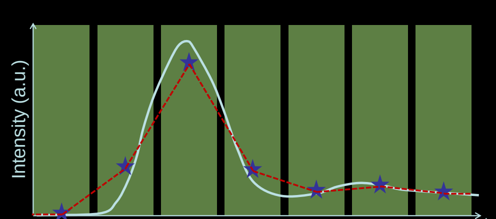
Workhorse in Angiography Suite: Slow cone-beam CT acquisitions



- Low temporal resolution (5.87 seconds)-temporal average deviates from the true uptake values
- Low temporal sampling density (7 or 10 data points) – a smooth curve cannot be recovered from so few sampling points



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Comparison of key technical parameters

	Diagnostic MDCT	C-arm (Siemens Biplane)
Data acquisition	Continuous rotation	Back-and-forth multiple sweeps
Temporal resolution	0.5 s	4.3 s
Sampling interval	0.5 s	5.87 s

Summary: A factor of 3-4 times improvement in temporal resolution is needed to enable C-arm cone-beam CT perfusion imaging!

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Odds are against us…

Slow C-arm Gantry

High Temporal resolution and high sampling density needed for perfusion imaging

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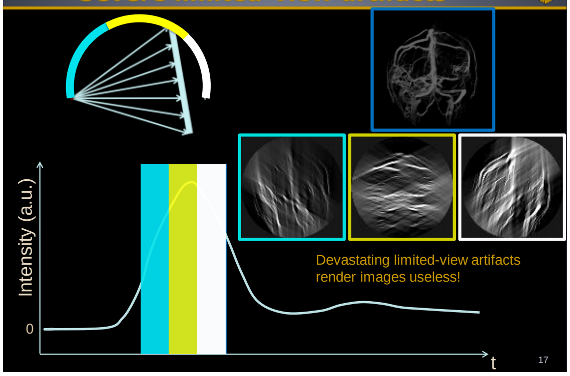
Software consideration

Why can't we reconstruct images using data acquired within a temporal window shorter than 2 seconds to improve temporal resolution and increase temporal sampling density?

Hardware considerations

- Safety concerns limit the fastest C-arm gantry to about 3 seconds for a short-scan acquisition;
- Slow detector readout speed limits the number of projections acquired in fast acquisitions (more severe view aliasing artifacts);
- The negative impacts of the gantry pause (~1.5 seconds) increases for fast acquisitions (inaccuracy in perfusion measurements);
- Mechanical vibrations are more severe in fast acquisitions (severe artifacts);
- Limited availability of fast acquisition devices in clinical practice.

Narrower temporal window: Severe limited-view artifacts



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C-arm cone-beam CT perfusion: a revolution is needed in reconstruction

- At least a short-scan angular span is required to reconstruct C-arm cone-beam CT images without limited-view artifacts with the current Filtered Backprojection (FBP) method;
- This alone limits the temporal resolution in current C-arm bi-plane systems to about 6 seconds
- The need for a factor of 3-4 temporal resolution improvement in C-arm CT perfusion imaging requires a breakthrough in image reconstruction to enable limited-view artifact free cone-beam CT reconstructions from data acquired in an angular span of only 50-60 degrees!

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Synchronized Multi-Artifacts Reduction in Tomographic RECONstruction (SMART-RECON)

Medical Physics Letter

Synchronized multiartifact reduction with tomographic reconstruction: A statistical model based iterative image reconstruction method to eliminate limited-view artifacts and to mitigate the temporal-average artifacts in time-resolved CT

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Guang-Hong Chen and Yinsheng Li, Synchronized Multi-Artifact Reduction with Tomographyic RECONstruction (SMART-RECON), Med. Phys., Vol. 42 (8):(2015).

Synchronized Multi-Artifacts Reduction in Tomographic RECONstruction (SMART-RECON)

Main Result: SMART-RECON enables the reconstruction of the entire dynamic image object from an angular span of 50~60 degrees with no limited-view artifacts!

This feature allows us to improve the temporal resolution by a factor of 3-4 for any current C-arm imaging platform and enable highly accurate perfusion measurements and time-resolved angiography.

Guang-Hong Chen and Yinsheng Li, Synchronized Multi-Artifact Reduction with Tomographyic RECONstruction (SMART-RECON), Med. Phys., Vol. 42 (8):(2015).

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Mathematics of SMART-RECON

$$\vec{X} = \arg\min_{X} \left[\frac{1}{2}(\vec{\mathcal{Y}} - \mathcal{A}\vec{X})^{tr} D(\vec{\mathcal{Y}} - \mathcal{A}\vec{X}) + \lambda \|X_A\|_*\right].$$

$$\vec{X} = vec(X).$$

$$X_A = (\vec{X}^P|X) =: \begin{pmatrix} X_1^P & X_1^1 & X_1^2 & \cdots & X_1^T \\ X_2^P & X_2^1 & X_2^2 & \cdots & X_2^T \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ X_M^P & X_M^1 & X_M^2 & \cdots & X_M^T \end{pmatrix},$$

X_p is the prior image reconstructed from all of the acquired data.

D is a diagonal matrix to incorporate photon statistics

Guang-Hong Chen and Yinsheng Li, Synchronized Multi-Artifact Reduction with Tomographyic RECONstruction (SMART-RECON), Med. Phys., Vol. 42 (8):(2015).

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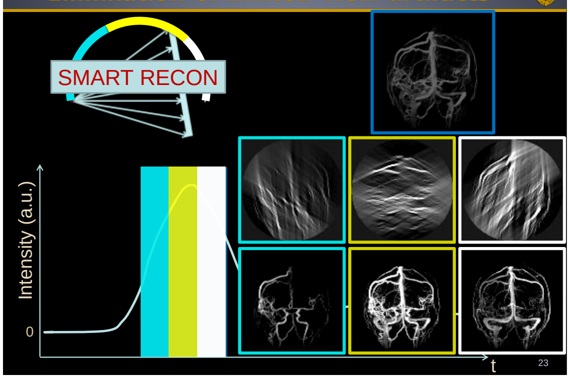
SMART-RECON: Elimination of limited-view artifacts



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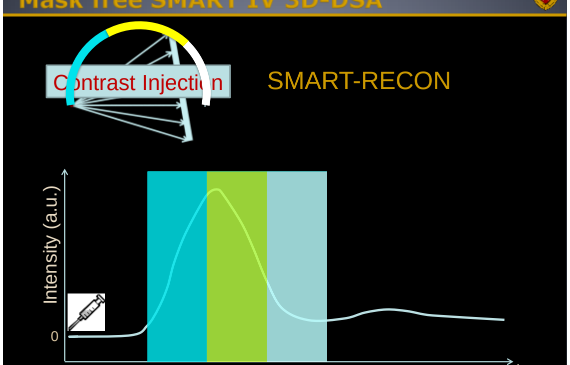
What about temporal fidelity? Mask free SMART IV 3D-DSA



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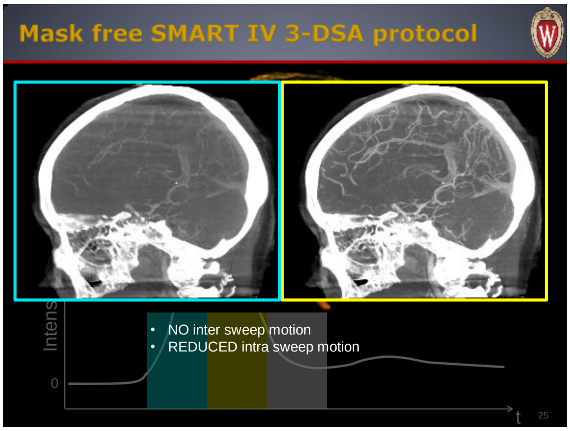
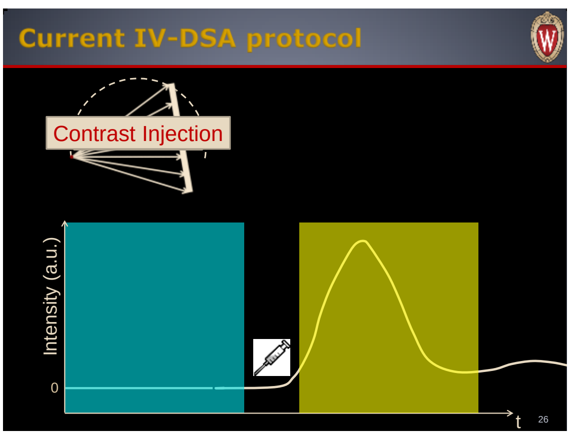

Mask free SMART IV 3-DSA protocol
NO inter sweep motion
REDUCED intra sweep motion
0
t
25


Current IV-DSA protocol
Contrast Injection
Intensity (a.u.)
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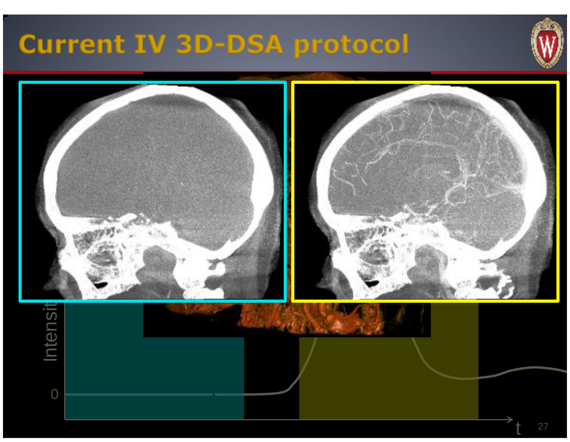
Current IV 3D-DSA protocol
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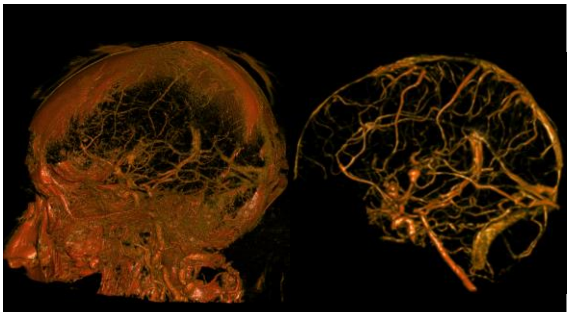

- Inter sweep motion
- Intra sweep motion

- NO inter sweep motion
- REDUCED intra sweep motion

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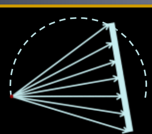
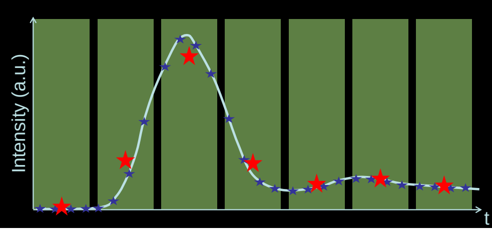
SMART-RECON in CBCT perfusion



- 5.87 s temporal resolution reduced to 1.5 s temporal resolution (5.9/4=1.5)
- Increased sampling density (7x4=28, or 10x4=40)



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One-stop-shop imaging

Quantum workflow

Arrive at hospital

↓

ANGIOGRAPHY SUITE

↓

Single C-arm CBCT perfusion acquisition

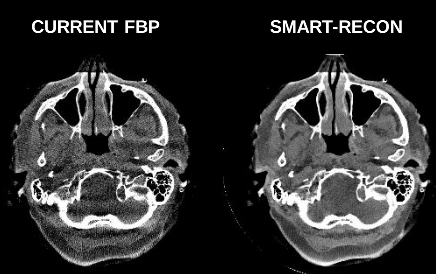
↓

NCCT + Time-Resolved CBCTA + CBCTP

↓

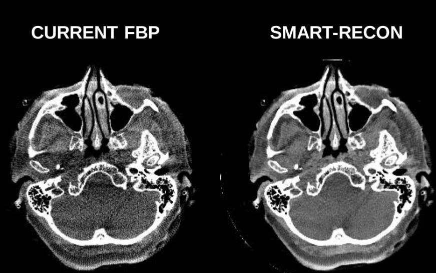
Endovascular treatment/efficacy evaluation

One-Stop-Shop non-contrast CBCT images from SMART-RECON



Reduced noise and artifacts

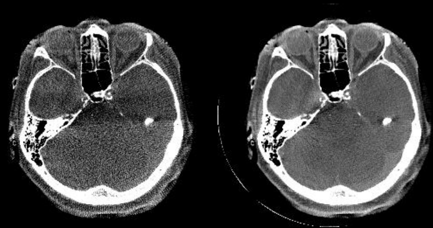
One-Stop-Shop non-contrast CBCT images from SMART-RECON



Reduced noise and artifacts

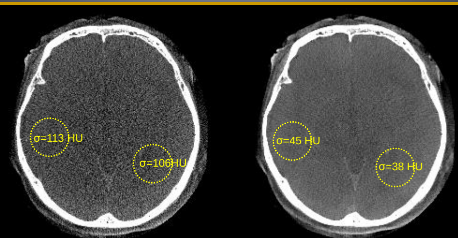
One-Stop-Shop non-contrast CBCT images from SMART-RECON

CURRENT FBP　　　SMART-RECON



Reduced noise and artifacts

One-Stop-Shop non-contrast CBCT images from SMART-RECON



Summary:

1. CNR improved by factor of 2.5~3.0
2. Reduced beam-hardening, noise streaks, and motion artifacts

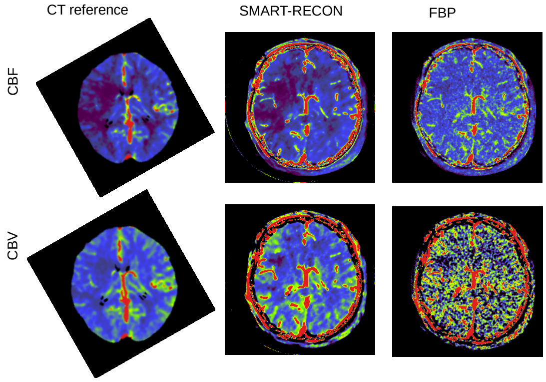
Key elements in future hemorrhage detection using C-arm CBCT.

One-Stop-Shop Time-Resolved CBCT Angiography from SMART-RECON

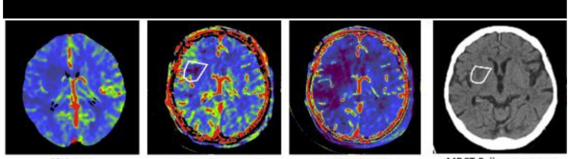
PRE-TREATMENT　　　POST-TREATMENT

How about C-arm cone beam CT perfusion imaging?

Slice # = 132, 5 mm slice thickness. Comparison with CT reference



Follow-up study to confirm lesion



CBV map: CT Reference

CBV map, C-Arm CT: SMART-RECON

CBF map, C-Arm CT: SMART-RECON

MDCT Follow-up exam

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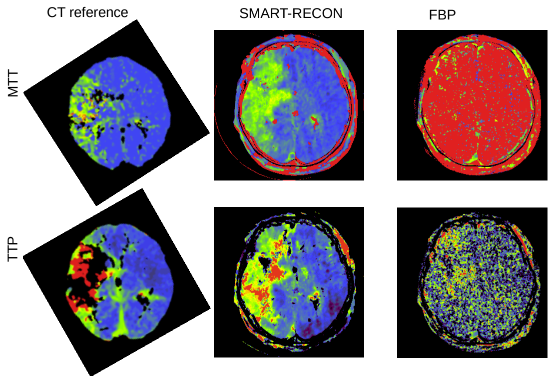
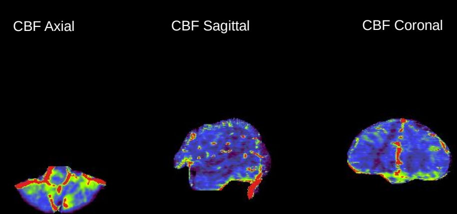
Slide # = 132, 5 mm slice thickness. Comparison with CT reference



Whole brain volume coverage



Maps 5.0 mm slice thickness. Pre-treatment. C-arm cone beam CT perfusion w/ SMART-RECON

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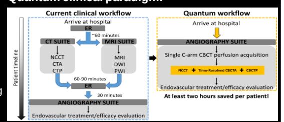
Time is brain; time is life!

Clinical need:
- In each hour between onset and treatment a patient loses:
  - 120 Million neurons,
  - 840 Billion Synapses
  - 450 Miles of myelinated nerve fibers
- A quantum paradigm shift in clinical workflow is needed to save two hours from stroke onset to start time in endovascular therapy
- The major limiting factor is the need to use multiple imaging modalities in different locations to determine how to best treat each patient

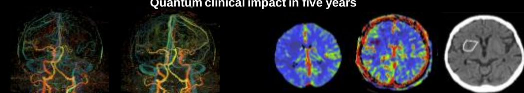
Technical need:
- For stroke imaging we require sub-2 second temporal resolution, however current C-arm systems can only achieve 6 second temporal resolution
- Therefore, quantum image reconstruction technology is needed to achieve a quantum transition in temporal resolution and enable time-resolved cone-beam CT angiography and whole brain perfusion to enable new clinical workflow.

Quantum clinical paradigm:



Quantum Reconstruction Technology:
- SMART-RECON enables a quantum transition by enabling a factor of 3-4 times improvement in temporal resolution, achieving the needed sub-2 second temporal resolution
- This quantum innovation provides true one-stop-shop imaging for stroke patients.

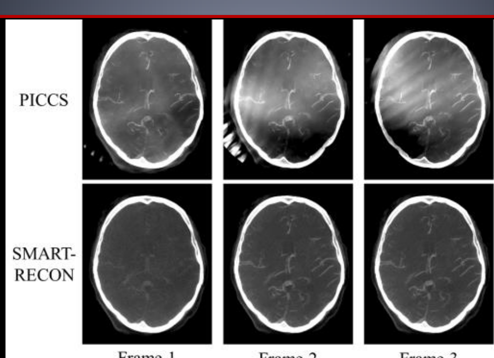
Quantum clinical impact in five years



Pre-Endovascular Therapy | Post Therapy | Reference CBV | SMART-RECON CBV | Follow-up MDCT

Thank You

PICCS vs SMART-RECON



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Reconstruction time

A PC equipped with two GPUs (GTX Titan Z and GTX 980).

Image matrix of 256x256x256

Data set: 348x616x480 projections

W/O optimization in implementation, total reconstruction time of 7.5 minutes for the results presented in this presentation.

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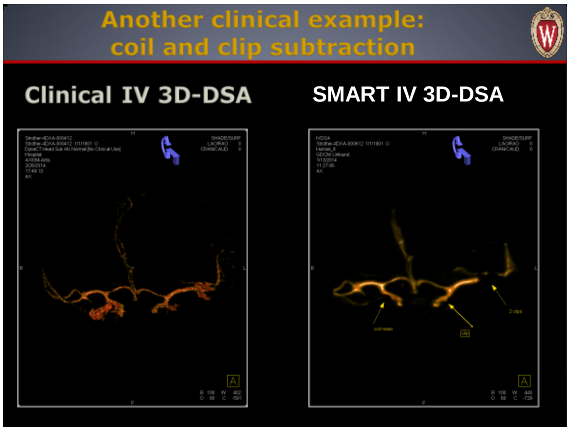
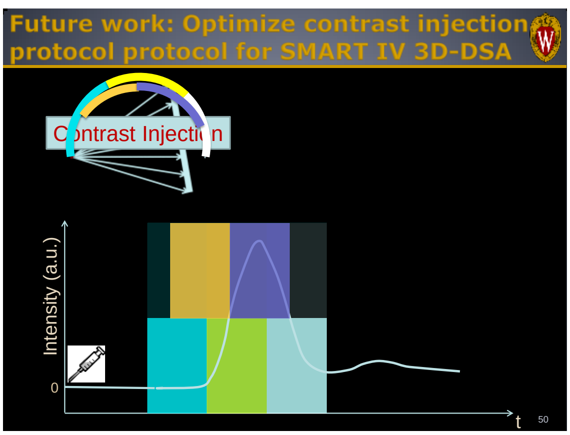
Summary and discussion

- SMART-RECON enables one-stop-shop stroke imaging with the current C-arm CBCT systems without significant hardware modifications, generating:
  - non-contrast CBCT images
  - time-resolved CBCT angiography
  - and CBCT perfusion maps
- SMART-RECON enables improved image quality with a reduction of:
  - motion artifacts,
  - image noise,
  - And of other artifacts.

Summary and discussion

- SMART-RECON enables one-stop-shop stroke imaging to generate non-contrast DynaCT, time-resolved CBCT angiography, and CBCT perfusion maps with the current Siemens bi-plane systems without significant hardware modifications
- SMART-RECON enables improved image quality with reduced motion artifacts, reduced noise, and a reduction of other artifacts
- SMART-RECON enables one-stop-shop imaging with reduced radiation dose and contrast dose for repeated acquisitions if needed


Another clinical example:
coil and clip subtraction
Clinical IV 3D-DSA
SMART IV 3D-DSA


Future work: Optimize contrast injection protocol protocol for SMART IV 3D-DSA
Contrast Injection
Intensity (a.u.)
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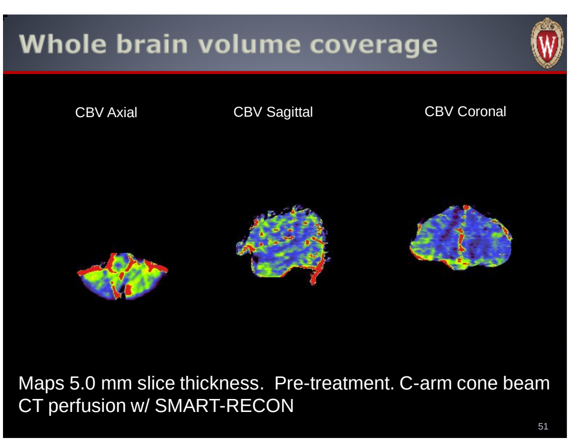
50


Whole brain volume coverage
CBV Axial
CBV Sagittal
CBV Coronal
Maps 5.0 mm slice thickness. Pre-treatment. C-arm cone beam CT perfusion w/ SMART-RECON
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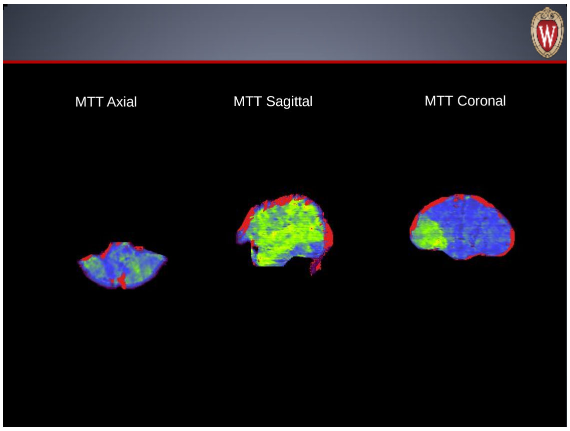
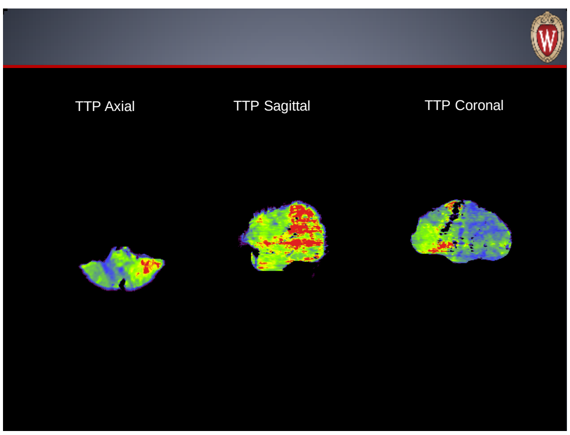
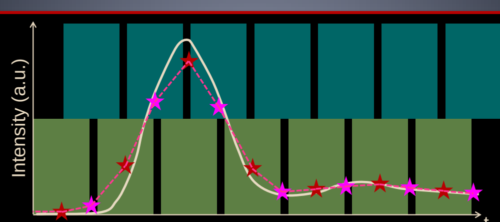




Interleaved injection



- Improves temporal sampling density, but not to improve the accuracy of intensity value at a given temporal point
- Assumes repeatable perfusion curves
- Requires double injections and double scans

Ganguly, et.al., Proc. SPIE 7625, 2010; Ganguly, et.al., AJNR 32(8), 2011; Fieselmann, et.al., IEEE TMI 31(4), 2012

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Two major challenges in C-arm CBCT perfusion

- Low temporal sampling density:
  - To recover a curve, we need adequate sampling points.
- Low temporal resolution:
  - If there is rapid change of contrast in the sampling window, the reconstructed intensity may be inaccurate.

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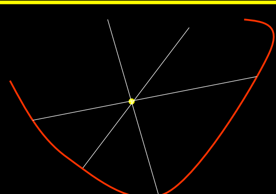
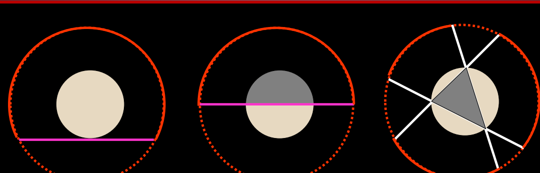
Tuy data sufficiency condition

For any image point inside a region of interest (ROI), any straight line passing through the image point should intersect the source trajectory at least once!



K. Tuy, "An inversion formula for cone-beam reconstruction," SIAM Journal on Applied Mathematics, Vo. 43:546-552 (1983).

Short-scan, super-short scan, and local ROI imaging



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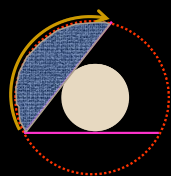
Super-short may not be super useful?



Yes, the super short-scan reconstruction method does allow us to reconstruct the crescent area. Unfortunately, that area is completely outside the field of view and thus useless in practice!

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Dynamic image reconstruction

- Wider data acquisition temporal window, stronger is the temporal-average artifacts:

  distortion artifacts
  streaking artifacts
  shading artifacts
  lower signal values for contrast enhanced area

- Narrower temporal window for data acquisition is desired!

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Dynamic Image Reconstruction

- Narrower data acquisition temporal window, easier to violate the Tuy data sufficiency condition and thus limited-view artifacts:

  Shading artifacts
  Distortion artifacts

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The most wanted in practice

In dynamic CT image reconstruction, it is highly desirable to look for an image reconstruction algorithm that enables us to reconstruct the entire image object with data acquired in a temporal window corresponding to an angular span of 120 degrees or even less.

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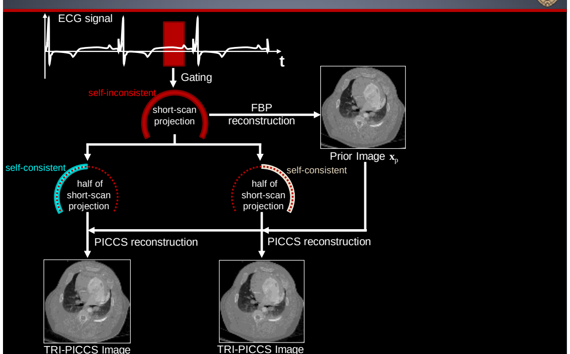
State-of-the-art: TRI-PICCS



Chen et. al., *Med. Phys.* (35), 2008; Chen et. al., *Med. Phys.* (36), 2009; Tang et. al., *Med. Phys.* (37), 2010

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Go below 120 degrees??

- Synchronized Multi-Artifacts Reduction with Tomographic Reconstruction (SMART-RECON)
- Enable to reconstruct the entire dynamic image object from 50-60 degree angular spans without limited-view artifacts!

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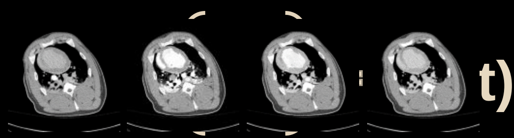
From vector to spatial-temporal matrix

- Static statistical image reconstruction: Each static image can be described by a vector.
- SMART-RECON: Variable is a spatial-temporal matrix.



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Math Formulation of SMART-RECON

$$X^* = \underset{X}{\arg\min}\{F(X) + \lambda\Psi(X)\},$$

$$F(X) = \frac{1}{2}\|\vec{y} - \mathcal{A}\vec{X}\|_D^2 = \frac{1}{2}(\vec{y} - \mathcal{A}\vec{X})^T D(\vec{y} - \mathcal{A}\vec{X}).$$

$$\vec{X} = vec(X).$$

$$\vec{\mathcal{Y}} = \mathcal{A}\vec{X}.$$

$$\Psi(X) = |X_A|_* = |U\Sigma V^{tr}|_* = \sum_i \sigma_i,$$

$$X_A = (\vec{X}_p|X)$$

X_p is the prior image reconstructed from all of the acquired data.

D is a diagonal matrix to incorporate photon statistics

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One-Stop-Shop Stroke Imaging

- Time is brain!
- Quantum paradigm shift in clinical workflow to save two hours from stroke onset to start time in endovascular therapy;
- Quantum image reconstruction technology for a quantum transition in temporal resolution to enable time-resolved cone-beam CT angiography and whole brain perfusion to enable new clinical workflow;
- Quantum clinical impact in five years.

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