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

Guang-Hong Chen, PhD

**Acknowledgement**

Interventional Stroke Imaging Research Team at UW-Madison:
PIs: Guang-Hong Chen, Charlie Strother, and Beverly Aagaard-Kienitz
Members (Basic Science):
Yinsheng Li, Kai Niu, Yijing Wu, John Garrett, Ke Li
Members (Clinical):
Pengfei Yang, David Niemann, Azam Ahmed, Howard Rowley, and Pat Turski
Siemens Support: Sebastian Schafer, Kevin Royalty, Klaus Klingenbeck
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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

[Images and diagrams related to CT imaging and stroke workflow]
Time is brain!

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


One-stop-shop stroke imaging workflow

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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Clinical motivations

Technical challenges

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One-stop-shop imaging using SMART-RECON: non-contrast CBCT images, time-resolved CBCT angiography, and CBCT perfusion maps

Summary and discussion

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.

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
### Comparison of key technical parameters

<table>
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<th>Diagnostic MDCT</th>
<th>C-arm (Siemens Biplane)</th>
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<tr>
<td>Data acquisition</td>
<td>Continuous rotation</td>
<td>Back-and-forth multiple sweeps</td>
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<td>Temporal resolution</td>
<td>0.5 s</td>
<td>4.3 s</td>
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<tr>
<td>Sampling interval</td>
<td>0.5 s</td>
<td>5.87 s</td>
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Summary: A factor of 3-4 times improvement in temporal resolution is needed to enable C-arm cone-beam CT perfusion imaging!

### Odds are against us...

Slow C-arm Gantry  
High Temporal resolution and high sampling density needed for perfusion imaging

### 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

- Devastating limited-view artifacts render images useless!

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-Artifact 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

Guang-Hong Chen
Department of Medical Physics, University of Wisconsin-Madison, Madison, Wisconsin 53792 and Department of Radiology, University of Wisconsin-Madison, Madison, Wisconsin 53792

Yinsheng Li
Department of Medical Physics, University of Wisconsin-Madison, Madison, Wisconsin 53792

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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.

Mathematics of SMART-RECON

\[ \hat{X} = \arg \min_{\hat{X}} \left[ \frac{1}{2} (\hat{Y} - \mathcal{A}X)^T \mathbf{D} (\hat{Y} - \mathcal{A}X) + \lambda \| \mathbf{X} \| \right] \]

\[ \mathbf{X} = \text{vec}(\mathbf{X}) \]

\[ \mathbf{X}_0 = \begin{pmatrix} x_1^0 & x_1^1 & x_1^2 & \ldots & x_1^F \\ x_2^0 & x_2^1 & x_2^2 & \ldots & x_2^F \\ \vdots & \vdots & \vdots & \ldots & \vdots \\ x_M^0 & x_M^1 & x_M^2 & \ldots & x_M^F \end{pmatrix} \]

\( \mathbf{X}_0 \) is the prior image reconstructed from all of the acquired data.

\( \mathbf{D} \) is a diagonal matrix to incorporate photon statistics.


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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

Current IV-DSA protocol

Contrast Injection

Current IV 3D-DSA protocol
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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)
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

CURRENT FBP

SMART-RECON

Reduced noise and artifacts

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

CURRENT FBP

SMART-RECON

Reduced noise and artifacts
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.

σ = 38 HU
σ = 106 HU
σ = 45 HU
σ = 113 HU
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
Slice #: 132, 5 mm slice thickness. Comparison with CT reference

MTT

TTP

Comparison with CT reference

MTT SMART-RECON FBP

TTP SMART-RECON FBP

Whole brain volume coverage

CBF Axial CBF Sagittal CBF Coronal

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

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Summary and discussion
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 2 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:
- SMART-RECON enables this 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 impact in five years

Thank You

PICCS vs SMART-RECON

PICCS

SMART-RECON

Frame 1  Frame 2  Frame 3
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.

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 for SMART IV 3D-DSA

Whole brain volume coverage

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

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.

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!


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

- Short scan mode
- Super-short scan mode: less than 180 degrees plus fan angle
- Disjoint segments: Local ROI imaging
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!

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!

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
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.

**State-of-the-art: TRI-PICCS**

- 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**!
Static statistical image reconstruction: Each static image can be described by a vector.

SMART-RECON: Variable is a spatial-temporal matrix.

\[ X^* = \arg\min_X (F(X) + \lambda \Psi(X)) \]
\[ F(X) = \frac{1}{2} \| \tilde{y} - A\tilde{X} \|_D^2 = \frac{1}{2} (\tilde{y} - A\tilde{X})^T D (\tilde{y} - A\tilde{X}) \]

\[ \tilde{X} = \text{vec}(X) \]
\[ \tilde{y} = A\tilde{X} \]

\[ \Psi(X) = |X_d| = |U \sum V^T| = \sum \sigma_i \]

\[ X_d = (\tilde{y}_d|X) \]

\( X_d \) is the prior image reconstructed from all of the acquired data.

\( D \) is a diagonal matrix to incorporate photon statistics.

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.