Digital Tomosynthesis for Target Localization

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AAPM 2009

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Acknowledgements

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- Researchers from other institutions who kindly shared their slides

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Objectives

- To understand the technical challenges and clinical potential of using DTS for target localization in radiation therapy
- To understand the latest developments in DTS reconstruction and registration methods
- To understand the clinical feasibility and efficacy of kV DTS compared to kV CBCT
- To learn about the latest developments in MV DTS and brachytherapy DTS applications

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Outline

- DTS Imaging Fundamentals
- On-board kV DTS for Image Guided Radiation Therapy
- MV DTS
- Unique registration challenges
- Clinical localization studies (H&N, prostate, liver, breast)
- DTS for managing respiratory motion

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Outline

- Rapid Arc verification using DTS
- DTS-guided adaptive radiation therapy (ART)
- Applications in brachytherapy
- Alternative scan geometries
- Creating truly 3D volumetric DTS images using prior patient-specific 3D images

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DTS Imaging Fundamentals

Radiograph DTS CBCT

- Limited rotation (e.g. 40°)
- Moderate depth resolution
- Good soft-tissue contrast
- Low dose (10% CBCT?)
- Fast (<10 sec) = breath-hold!

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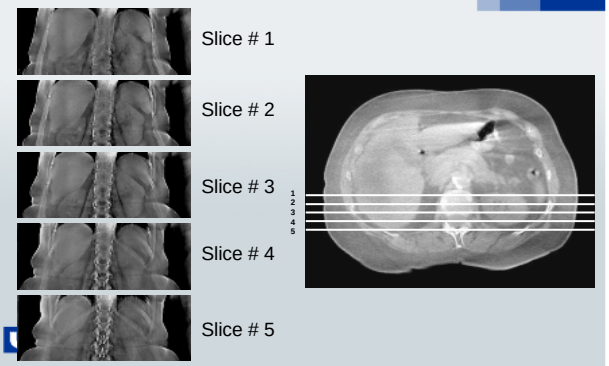
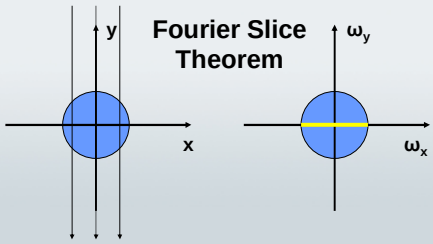
DTS Imaging Fundamentals



DTS Image Characteristics



X-ray projection → FT → Slice of object's Fourier spectra

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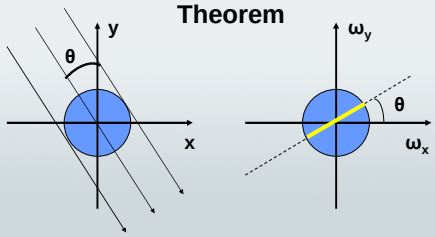
Fourier Slice Theorem



X-ray projection → FT → Slice of object's Fourier spectra

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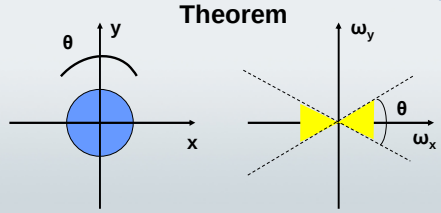
Fourier Slice Theorem



Series of x-ray projections → Sampled region of Fourier domain

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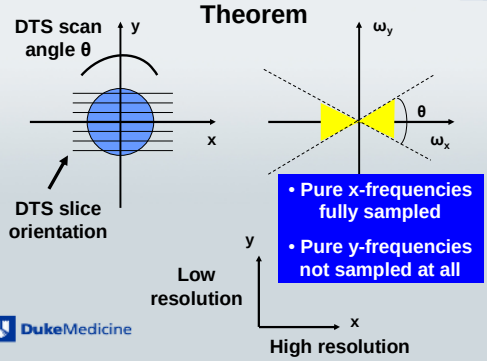
Fourier Slice Theorem



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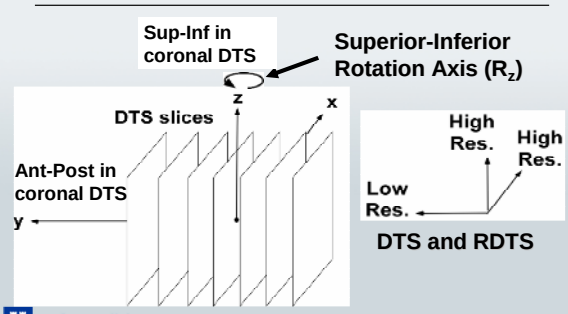
DJG1

On-board DTS Resolution Characteristics



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Slide 12

DJG1 Classic tradeoff! Decreased resolution in the plane-to-plane dimension means less dose is required to achieve equivalent image noise. This is one of the major advantages of DTS!
Devon Godfrey, 7/16/2009

DTS Image Characteristics

One benefit of reduced plane-to-plane resolution:

– less stochastic noise

→ DTS requires less dose than CBCT!

Typical DTS / CBCT exposure ratio = ~1/5th (sagittal DTS) to ~1/10th (coronal DTS)

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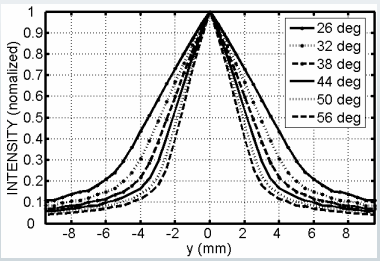
Isocentric DTS slice profile vs. scan angle



Isocentric DTS point-spread function in the plane-to-plane dimension

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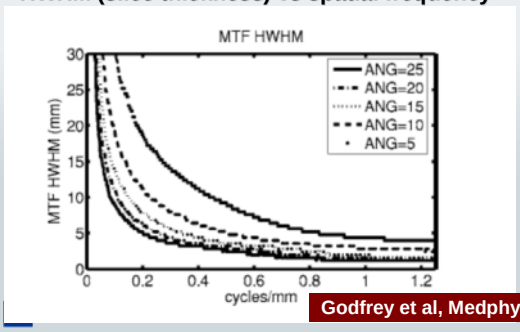
Blessing et al AAPM 2006

MITS (linear tomosynthesis geometry)

HWHM (slice thickness) vs spatial frequency



Godfrey et al, Medphys 2006

DTS Reconstruction Techniques

- Filtered backprojection (e.g., Feldkamp)
- Iterative or direct frequency domain deblurring (e.g., MITS, or iterative restoration)
- Algebraic reconstruction (e.g., ART, SART)
- Statistical techniques (e.g., MLEM, TV-EM, etc.)
- Techniques using patient-specific prior 3D image data

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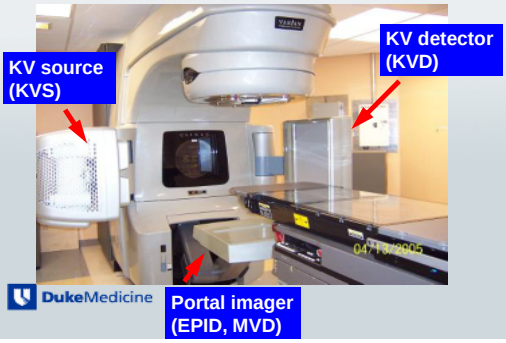
For more info, see Dobbins and Godfrey, "Digital x-ray tomosynthesis: current state of the art and clinical potential", PMB (2003)

IGRT with Onboard Imaging



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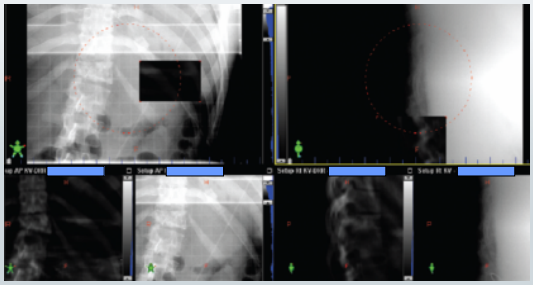
Challenges for Onboard 2D Images



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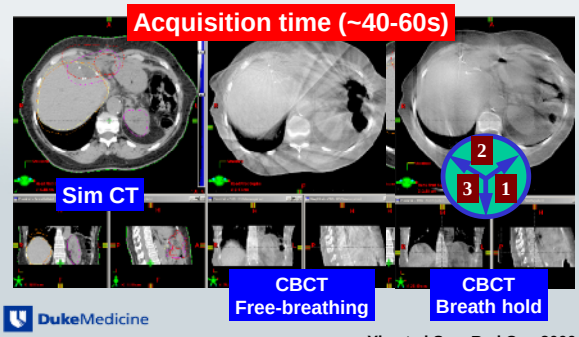
Challenges for Onboard CBCT



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Yin et al Sem Rad Onc 2006

Challenges for Onboard CBCT

Imaging dose

Modality	Dose/Exposure
Orthogonal set of MV digital images (Kutcher et al. 1994)	5–8 cGy
Orthogonal set of KV images	<0.1 cGy
CBCT Body scan (Fritsch et al. 1995; Yoshizumi et al. 2006)	3–4 cGy
CBCT Head scan (Yoshizumi et al. 2006)	8 cGy
MVCT of Tomotherapy (Sheng et al. 2005)	1 cGy
CT simulation scan (Judy et al. 1977)	3–4 rads

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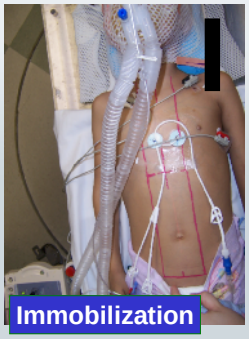
Challenges for Onboard CBCT

Mechanical constraints

Breast setup



Immobilization

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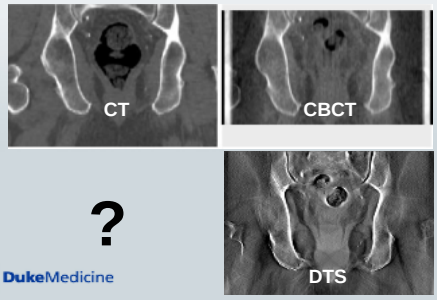
On-board Digital Tomosynthesis (DTS) for 3-D IGRT



360°

?

44°

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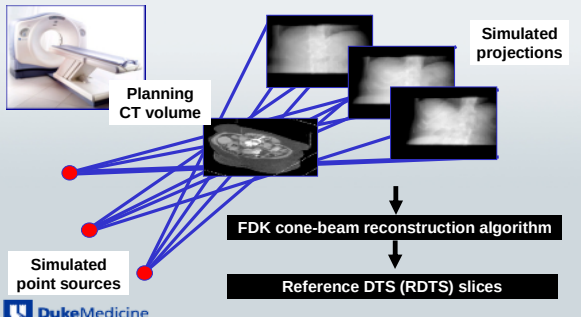
Reference DTS (RDTS) Images



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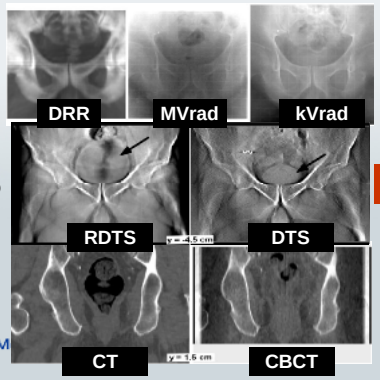
Godfrey et al IJROBP 2006

Prostate

0°

44°

360°



Godfrey et al IJROBP 2006

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MV DTS Imaging w/ EPID…

- E.g., Descovich et al (UCSF)
  - Modified imaging beam line: (4.2 MV, low Z target, no flattening filter, 0.3 cGy/MU)
  - Low dose MV DTS:
    - Examples: Lung (2 cGy), H&N (0.6 cGy), Prostate (0.7 cGy)

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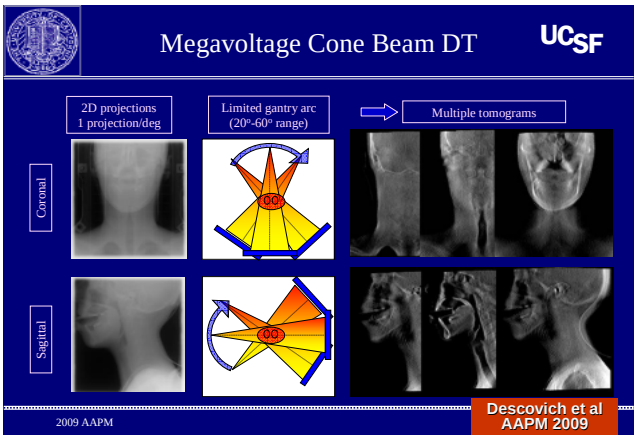

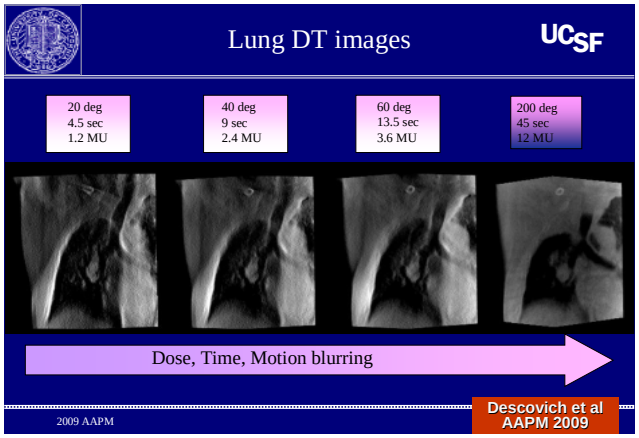

DTS Registration Characteristics

- Can we register on-board DTS volumes directly to the planning CT data, or do we need to compute reference DTS volumes?
- How sensitive is DTS to slight translations and rotations?

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Evaluation of DTS reference volumes using 3D mutual information

- 3D Volume of interest (VOI) in a chest phantom (4 cm S-I, 10 cm R-L, 8cm A-P)

Sample coronal slice from VOI

- Computed 3D MI shared by CT-DTS and RDTS-DTS pairs for all six rigid-body translations and rotations

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Godfrey et al
Med Phys July 2007

- Simulated translations of reference CT spanning +/- 5mm & +/- 5º in each direction
- Measured 3D MI (DTS-CT & DTS-RDTS)
  - Does peak MI occur when the on-board DTS data is correctly registered?
  - How quickly does MI fall off away from the correct registration pose (how sensitive is the data to misregistration)?

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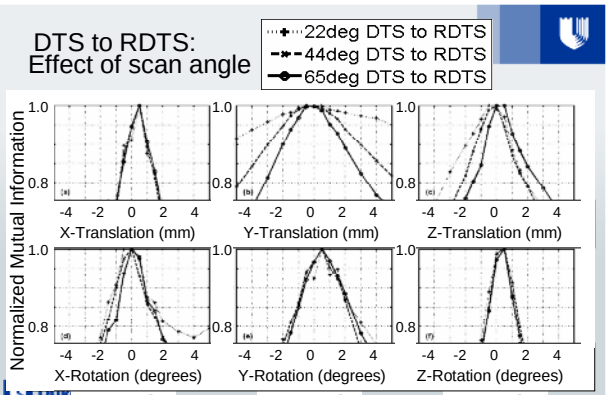
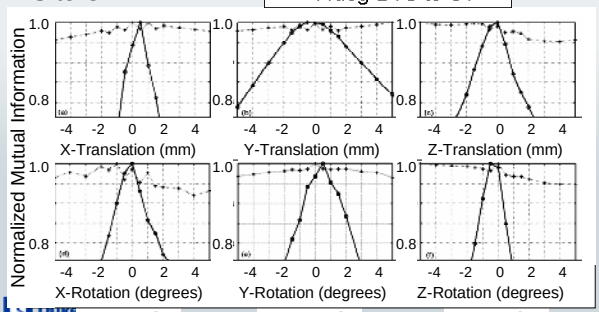
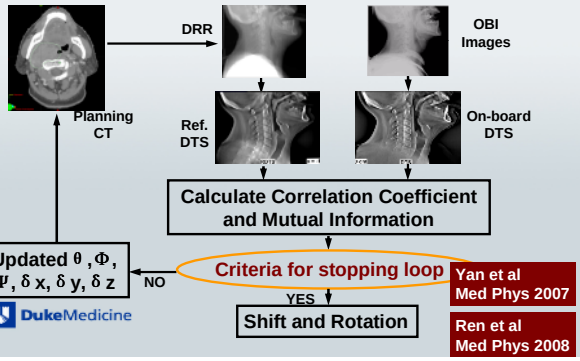
DTS to RDTS: Effect of scan angle



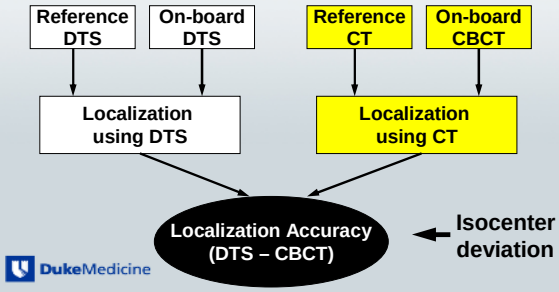
DTS to RDTS vs. DTS to CT:



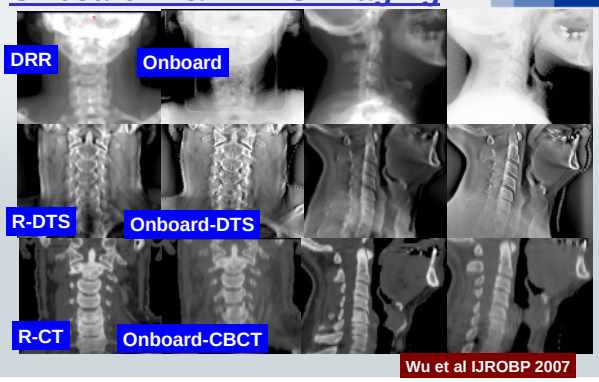
Autoregistration Scheme Using DTS



Clinical Feasibility Studies



Onboard H & N DTS Imaging



Wu et al IJROBP 2007

H&N DTS Bony Localization

Pearson Correlation 3DCBCT-2DRad = 0.80

	2D Radiograph	3D CBCT
20° DTS Coronal	0.81	0.94
40° DTS Coronal	0.81	0.95
20° DTS Sagittal	0.79	0.94
40° DTS Sagittal	0.80	0.95

Wu et al IJROBP 2007

H&N DTS Localization Accuracy (bony)

	20º DTS Sagittal	40º DTS Sagittal	20º DTS Coronal	40º DTS Coronal
Vertical	0.08 (0.07)	0.07 (0.07)	0.07 (0.07)	0.07 (0.07)
Longitudinal	0.07 (0.07)	0.06 (0.06)	0.09 (0.07)	0.08 (0.07)
Lateral	0.09 (0.08)	0.07 (0.06)	0.08 (0.07)	0.08 (0.06)
3D Vector	0.16 (0.09)	0.14 (0.08)	0.16 (0.08)	0.15 (0.08)

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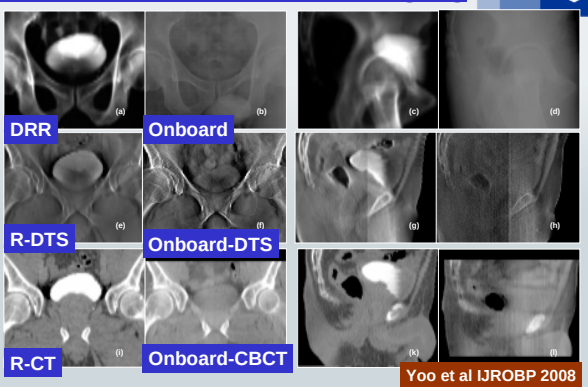
SD in parentheses. All values are in cm.

Onboard Prostate DTS Imaging



Yoo et al IJROBP 2008

Localization Accuracy - Prostate

Based on soft tissue

Mean difference between two methods		
(cm)	CBCT:Cor-DTS	CBCT:Sag-DTS
Lat	0.08 ± 0.07	0.15 ± 0.14
Lng	0.06 ± 0.06	0.09 ± 0.09
Ver	0.11 ± 0.12	0.17 ± 0.17
3D Vector	0.18 ± 0.11	0.29 ± 0.17

Yoo et al IJROBP 2008

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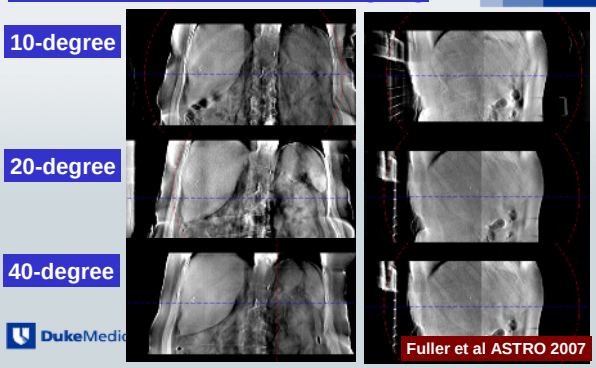
Onboard Liver DTS Imaging



Fuller et al ASTRO 2007

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Onboard Liver DTS Imaging

	40º DTS Sagittal	40º DTS Coronal
Vertical	0.16 (0.35)	0.09 (0.31)
Longitudinal	0.04 (0.33)	0.03 (0.28)
Lateral	0.03 (0.31)	0.03 (0.21)

SD in parentheses. All values are in cm.

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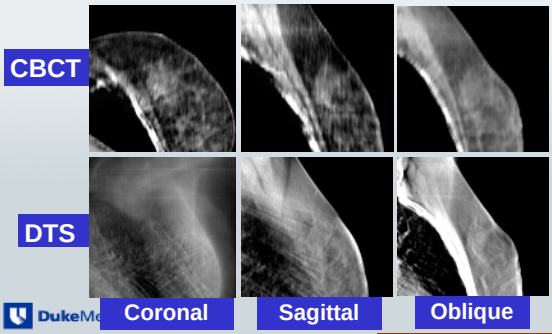
Wu et al ASTRO 2007, submitted to IJROBP 2009

Onboard Breast DTS Imaging



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Zhang et al IJROBP 2009

Onboard Breast DTS Imaging

Average Positioning Difference between DTS and CBCT (unit: cm)

	With Surgical Clips			Without Clips
	Coronal DTS-CBCT	Sagittal DTS-CBCT	Oblique DTS-CBCT	Oblique DTS-CBCT
Lateral	0.07	0.15	0.17	0.24
Longitudinal	0.12	0.12	0.10	0.21
Vertical	0.12	0.06	0.08	0.18
3D Vector	0.19	0.22	0.24	0.32

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Zhang et al IJROBP 2009

Managing Respiratory Motion using DTS

- **Breath-hold verification prior to breath-hold treatment (reduced ITV)**
- **4D verification prior to gated treatment**

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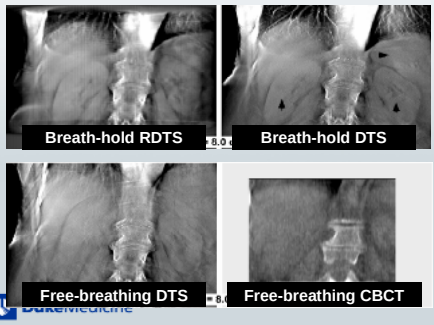
Breath-hold vs. Free-breathing



Godfrey et al IJROBP May 2006

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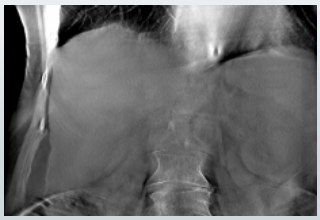

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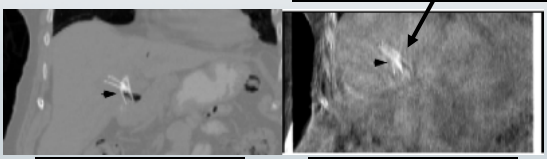
Unacceptable for breath-hold Tx setup

Target surrogate shifted 2cm superior!



Breath-hold Planning CT

Free-breathing CBCT

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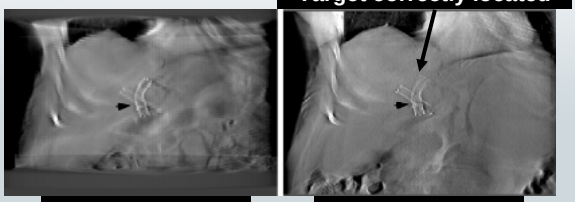
Effective alternative for breath-hold Tx setup

Target correctly located



Breath-hold Reference DTS

Breath-hold On-board DTS

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Liver Subject #2

Large low-contrast liver malignancy

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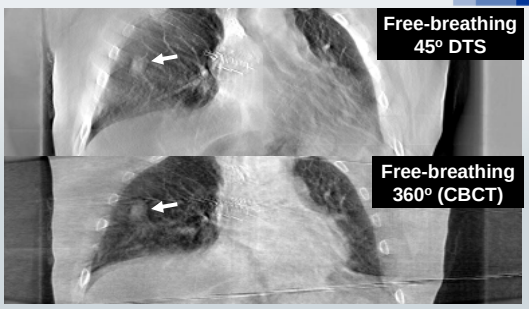
Lung Subject #1



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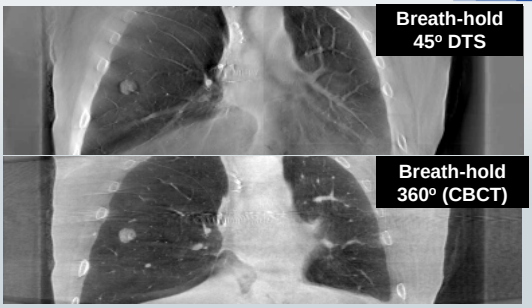
Lung Subject #1



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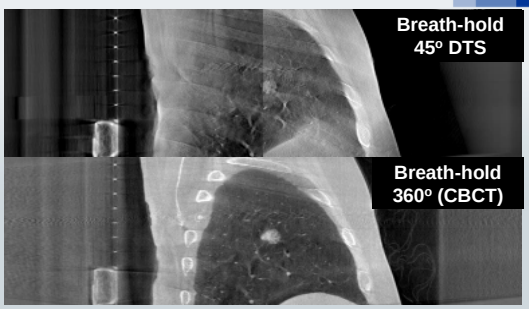
Lung Subject #1



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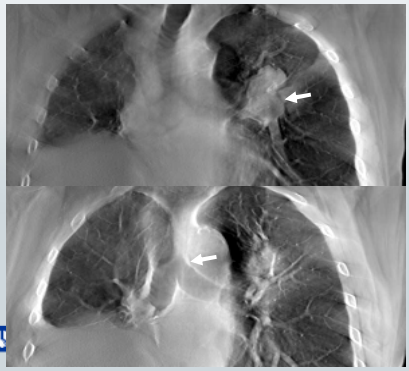
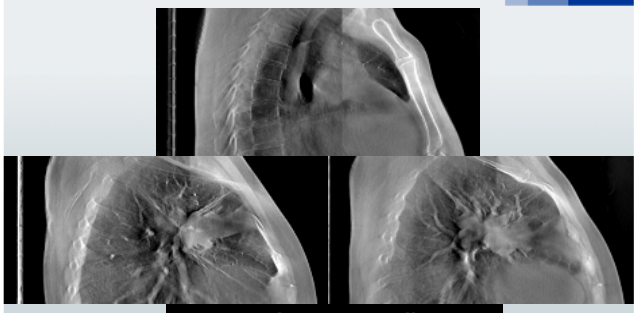
Lung Subject #2 (Breath-hold)



Sample 45º DTS Slices

Lung Subject #2 (Breath-hold)



Sample 45º DTS slices

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4D DTS

- Disadvantages of 4D CBCT
  - Scan Time
    - Lu et al. (2007) 7 min
  - Imaging Dose
    - Lu et al. (2007) 4.4 – 7.1 cGy
  - Streaking Artifacts
    - Sonke et al. (2005) 50 – 80 Projections per Phase

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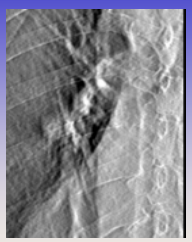
Maurer et al
Med Phys July 2008

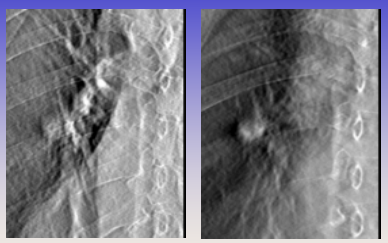
Results: Patient Study



Radiographic

Maurer et al
AAPM 2009. Scan data from Tinsu Pan (MD Anderson)

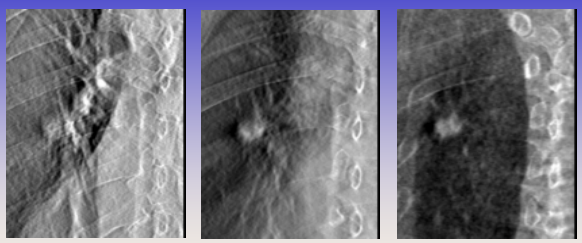
Results: Patient Study



Radiographic 30° 4D DTS

Maurer et al
AAPM 2009. Scan data from Tinsu Pan (MD Anderson)

Results: Patient Study



Radiographic 30° 4D DTS 200° CBCT

GRS = 0.75°/s FR = 7 fps

Maurer et al
AAPM 2009. Scan data from Tinsu Pan (MD Anderson)

Summary

- Acquisition Time
  - 0.65 to 1.52 minutes per 40°
- 4D DTS Dose Relative to 3D CBCT!
  - 0.17 to 0.51 per 40°
- 4D DTS Allows On-Board Motion Analysis
  - Lower Dose than even 3D CBCT
  - Scan time similar to 3D CBCT

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DTS for Rapid Arc Verification

- Collect DTS scans during rapid arc treatment?
- Use to monitor intrafraction motion

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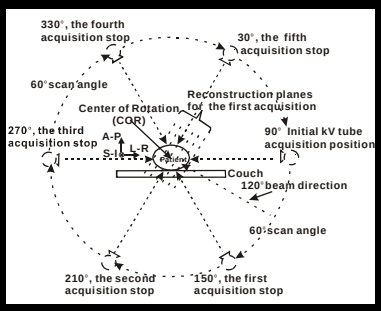
RUSH UNIVERSITY MEDICAL CENTER

A feasibility study for real-time tomosynthesis-guided Rapid Arc therapy

Jun Zhou, Julius Turian, and James Chu — Radiation Oncology, Rush University, Chicago, IL
Pengpeng (Perry) Zhang — Medical Physics, Memorial Sloan-Kettering Cancer Center, New York, NY



Zhou et al AAPM 2009

DTS-guided online adaptive radiation therapy (ART)

- E.g., Mestrovic et al (PMB 2009):
  - → kV DTS imaging while gantry is rotated to the next treatment angle, w/ simultaneous reconstruction
  - → Auto-segmentation of anatomy
  - → Adaptation of direct aperture optimization (DAO) plan. Adaptation of segment performed during delivery of previous segment.
    - ➢Total time added to treatment: 70 sec

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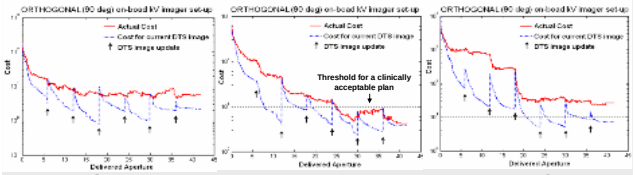
Part III: Imaging + Adaptation + Delivery

- **Results:**

Mestrovic et al PMB 2009



SMALL DEFORMATION | MEDIUM DEFORMATION | LARGE DEFORMATION

Brachytherapy DTS Applications

- Source/seed localization for real-time dose calculation
  - ➢T. Persons, "Three-dimensional tomosynthesis image restoration for brachytherapy source localization," Med Phys (2001).
  - ➢I. Tutal et al, "Tomosynthesis-based localization of radioactive seeds in prostate brachytherapy," Med Phys (2003).
- Real-time volumetric imaging during brachytherapy procedure (in-suite DTS)
  - ➢ Wake Forest University group (Baydush, McKee, et al)

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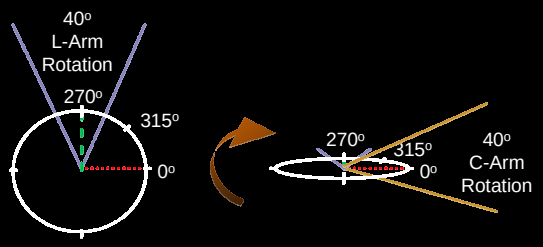
Dual-Arm Isocentric Motion

Wake Forest University Baptist MEDICAL CENTER

WAKE FOREST UNIVERSITY SCHOOL of MEDICINE

Gersh, McKee, King and Baydush
AAPM 2009



L-Arm Rotation
C-Arm Rotation

Wake Forest University Baptist MEDICAL CENTER

WAKE FOREST UNIVERSITY SCHOOL of MEDICINE

Gersh, McKee, King and Baydush
AAPM 2009

Alternative Scan Geometries

- Improved sampling of frequency space = reduced DTS blur…
  - E.g., Early 2000s in radiology:
    - Simple: Linear tomosynthesis
    - More Complex: Circular tomosynthesis
      - → Possible problem: Shape of blurring function can mimic patient anatomy

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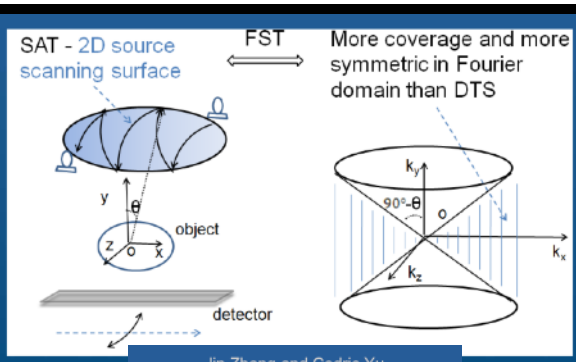
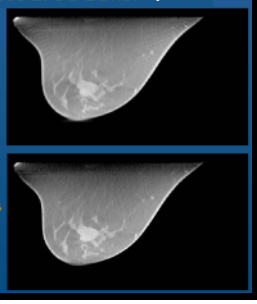


Jin Zhang and Cedric Yu
University of Maryland School of Medicine, Radiation Oncology

Simulation –breast

- Sagittal view of a numerical breast phantom, CT of a breast cancer patient.
- Obtained from dedicated breast CBCT imager developed at UC Davis. (John Boone)

- DTS vs. SAT
- DTS (upper). Total 120 projections in a scan range of 120 degrees.
- SAT (lower). Cylindrical scanning surface is composed of five 120 degree arcs in zigzag pattern. Total projections around 120.



Zhang, Yu (UMD)

Alternative Scan Geometries

Cine DTS with a multi-source array of carbon nanotube cathodes…

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XinRay systems

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

SIEMENS

Stationary Tomosynthesis Array for Radiotherapy (STAR)

A carbon nanotube-based multielement source for intrafractional image-guidance

Jonathan Maltz[†], Frank Sprenger[‡], Jens Fuerst[*], Ajay Paidi [†], Sha Chang[Δ] and Ali Bani-Hashemi[†]

[†] Siemens Medical Solutions USA, Inc. Oncology Care Systems Group, Concord CA.
[‡] XinRay Systems LLC, Research Triangle Park, NC.
[*] Siemens AG Healthcare, Components and Vacuum Technology, Erlangen, Germany.
[Δ] University of North Carolina, Chapel Hill

ISBI Boston, July 1, 2009

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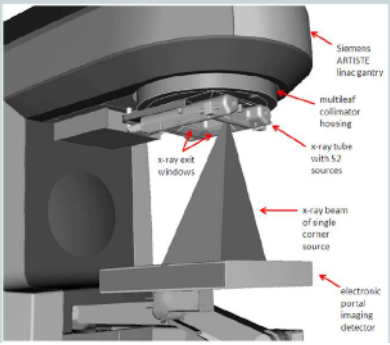
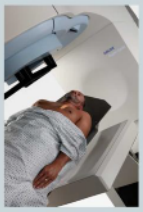
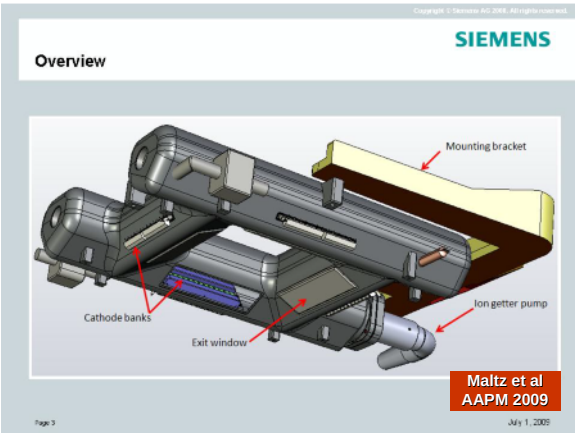
Overview

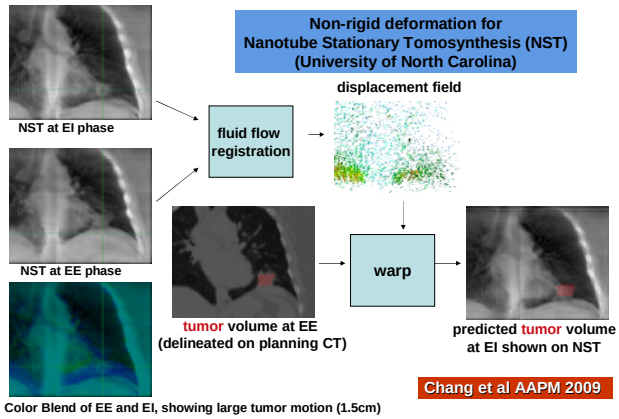




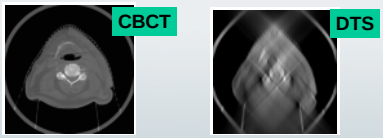
Maltz et al AAPM 2009

July 1, 2009





Truly volumetric DTS imaging?



How can you identify volume in DTS?

-- Poor axial view in traditional DTS

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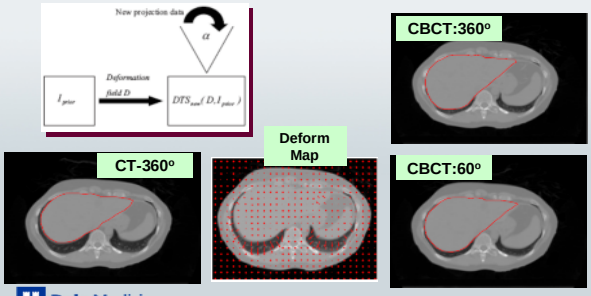
DTS from prior 3D image data



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Ren et al
Med Phys June 2008

DTS using deformation field map from prior 3D image data

Based on two constraints, the DTS reconstruction problem is converted into the following constrained optimization problem:

$$\min_{D}(E(D)),\ s.t.\ P\ DTS_{new}(D, I_{prior}) = Y$$

The above constrained problem can be further converted into the following unconstrained optimization problem:

$$min\left(\mu * E(D) + \left\|P\ DTS_{new} - Y\right\|_2^2\right)$$

where μ is the relative weight of the bending energy.

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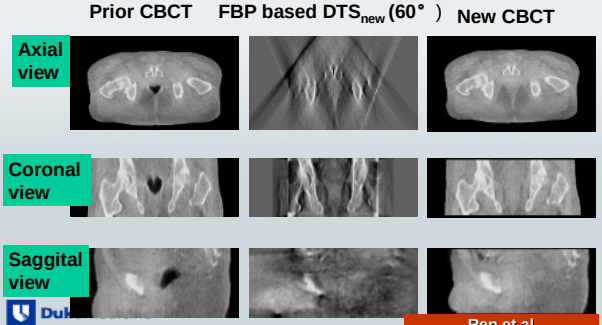
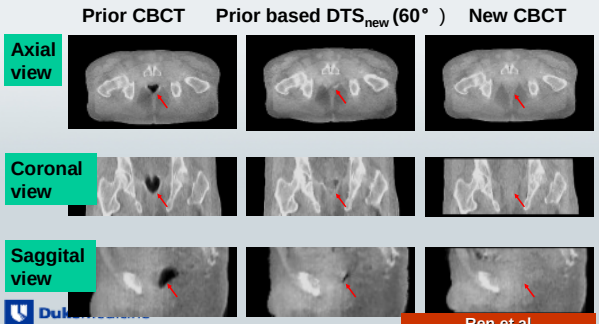
Ren et al
Med Phys June 2008

Prostate Patient Data



Ren et al
Med Phys June 2008

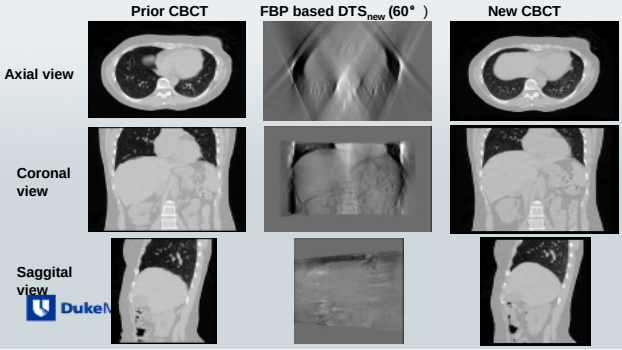
Prostate Patient Data



Ren et al
Med Phys June 2008

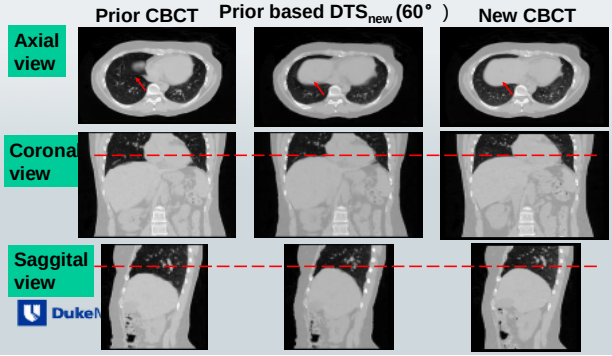
Liver Patient Data

Ren et al
Med Phys June 2008

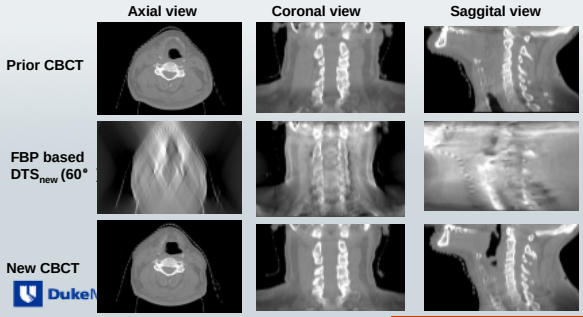


Liver Patient Data

Ren et al
Med Phys June 2008

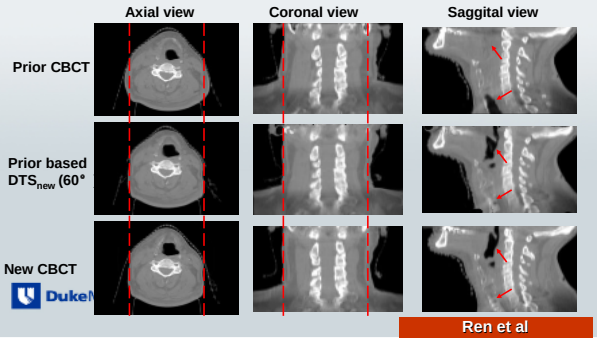


Head-and-neck Patient Data



Ren et al

Head-and-neck Patient Data



Ren et al

Summary

- Digital tomosynthesis is a promising technology for onboard target localization as well as brachytherapy applications
- It offers substantial advantages for motion management (4-D and breathhold imaging)
- 3D volumetric DTS is feasible
- Further investigation on clinical efficacy is warranted

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Thank you for your attention

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