Next Generation Radiotherapy Treatment Planning Based on GPU and Cloud Computing

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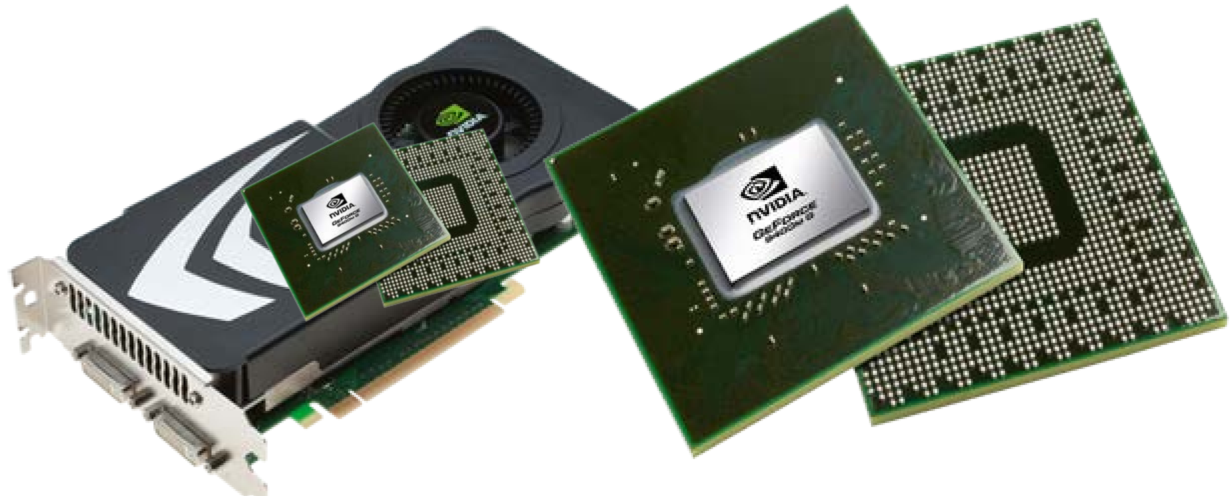
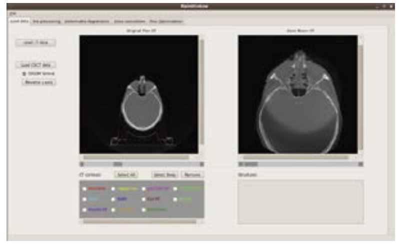
Vice Chair, Department of Radiation Oncology

UT Southwestern Medical Center

UT SOUTHWESTERN

GPU → Graphics Processing Unit





$1.5M UC Lab Fees Research Grant (1/09 – 12/11)

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Phys. Med. Biol. 54 (2009) 6287–6297 doi:10.1088/0031-

GPU-based ultra-fast dose calculation using a size pencil beam model

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Phys. Med. Biol. 5 /1/012

Impleme ion deformal on a

GPU-based ultra-fast dose calculation using a finite size pencil beam model

Xuejun Gu[1], Dongju Choi[2], Chunhua Men[1], Hubert Pan[1], Amitava Majumdar[2] and Steve B Jiang[1]

Received 10 August 2009, in final form 15 September 2009
Published 1 October 2009
Online at stacks.iop.org/PMB/54/6287

GPU-based ultrafast IMRT plan optimization

Chunhua Men[1], Xuejun Gu[1], Dongju Choi[2], Amitava Majumdar[2], Ziyi Zheng[3], Klaus Mueller[3] and Steve B Jiang[1]

Received 10 August 2009, in final form 21 September 2009
Published 14 October 2009
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han Yang[3], Dongju Choi[4], Edward Castillo[5], Amitava Majumdar[4],
e B Jiang

IOP PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY

1-9155/56/11/01

GPU-based ultra-fast direct aperture optimization for online adaptive radiation therapy

Chunhua Men, Xun Jia and Steve B Jiang

Received 28 March 2010, in final form 17 June 2010
Published 20 July 2010
Online at stacks.iop.org/PMB/55/4309

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Implementation and evaluation of various demons deformable image registration algorithms on a GPU

Xuejun Gu[1], Hubert Pan[1], Yun Liang[1], Richard Castillo[2], Deshan Yang[3], Dongju Choi[4], Edward Castillo[5], Amitava Majumdar[4], Thomas Guerrero[5] and Steve B Jiang[1]

Received 3 September 2009, in final form 28 October 2009
Published 11 December 2009
Online at stacks.iop.org/PMB/55/207

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Development of a GPU-based Monte Carlo dose calculation code for coupled electron–photon transport

Xun Jia[1], Xuejun Gu[1], Josep Sempau[2], Dongju Choi[3], Amitava Majumdar[3] and Steve B Jiang[1]

Received 28 October 2009, in final form 22 March 2010
Published 12 May 2010
Online at stacks.iop.org/PMB/55/3077

University

GPU-based fast gamma index calculation

Xuejun Gu, Xun Jia and Steve B Jiang

Received 24 November 2010, in final form 18 January 2011
Published 11 February 2011
Online at stacks.iop.org/PMB/56/1431

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Medical Physics Letter

Ultrafast treatment plan optimization for volumetric modulated arc therapy (VMAT)

Chunhua Men
Center for Advanced Radiotherapy Technologies and Department of Radiation Oncology, University of California San Diego, La Jolla, California 92037-0843

H. Edwin Romeijn
Department of Industrial and Operations Engineering, University of Michigan, Ann Arbor, Michigan 48109-2117

Xun Jia and Steve B. Jiang[a]
Center for Advanced Radiotherapy Technologies and Department of Radiation Oncology, University of California San Diego, La Jolla, California 92037-0843

(Received 26 May 2010; revised 26 July 2010; accepted for publication 30 August 2010; published 14 October 2010)

A GPU-based finite-size pencil beam algorithm with 3D-density correction for radiotherapy dose calculation

Xuejun Gu[1], Uwe Jelen[2], Jinsheng Li[3], Xun Jia[1] and Steve B Jiang[1]

Received 3 March 2011, in final form 31 March 2011
Published 10 May 2011
Online at stacks.iop.org/PMB/56/3337

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4th Short Course on

GPU Programming for Medical Physics and Medical Imaging Research

Sponsor: Center for Advanced Radiotherapy Technologies (CART), University of California San Diego (UCSD), La Jolla, CA 92093

Date: October 19 and 20, 2012

Place: San Diego Supercomputer Center (SDSC), University of California San Diego

Course Director:
Steve Jiang, Ph.D., Professor, CART, UCSD

Course Co-directors:
Xun Jia, Ph.D., Assistant Professor, CART, UCSD
Amitava Majumdar, Ph.D., Associate Professor, SDSC and CART, UCSD

Physics in Medicine and Biology
l. 54 (2009) 6565–6573 doi:10.1088/0031-9155/54/21/008

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Physics in Medicine and Biology
iol. 56 (2011) 1431–1441 doi:10.1088/0031-9155/56/5/014

GPU-based ultra-fast direct aperture optimization for online adaptive radiation therapy

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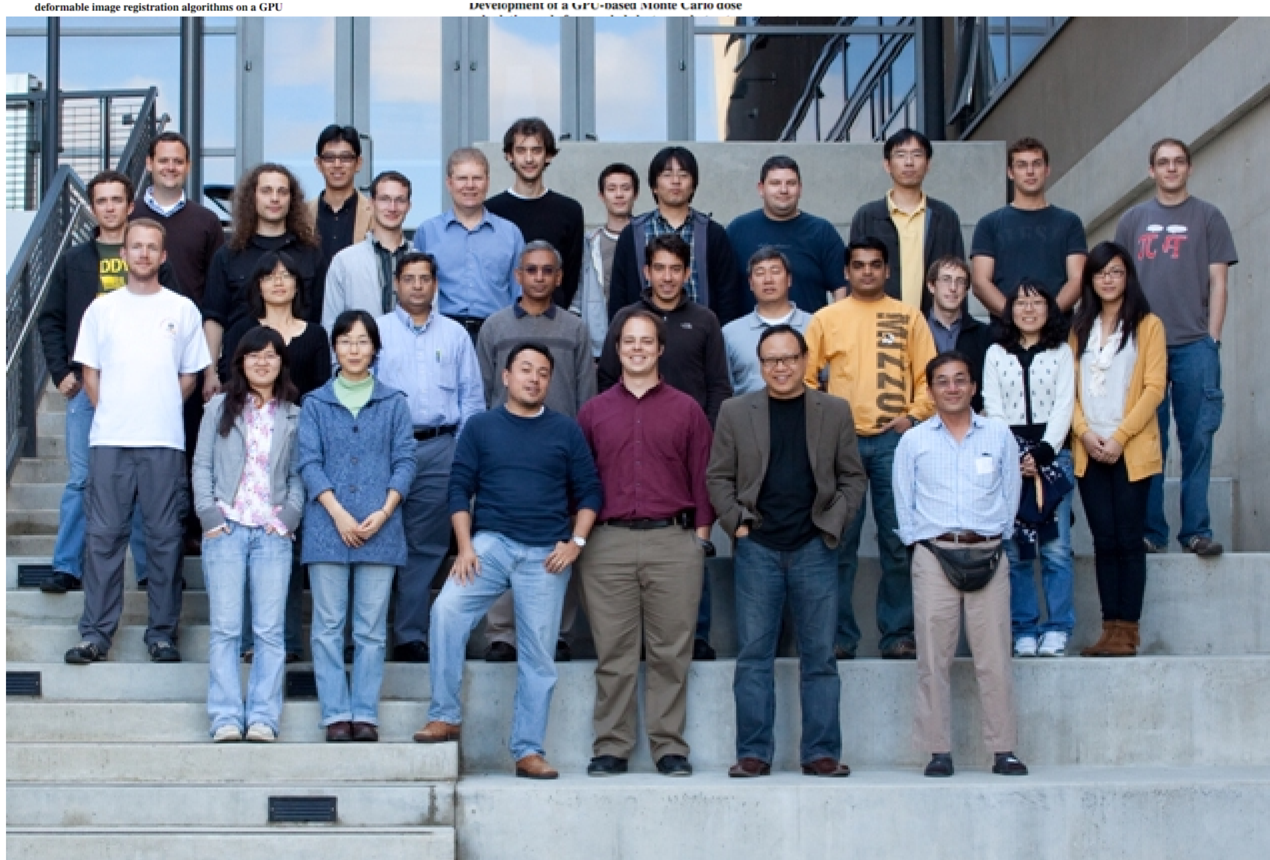
deformable image registration algorithms on a GPU

Development of a GPU-based Monte Carlo dose



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Video Game Graphics Cards Slash Radiation Doses for Cancer Treatment

By TechNewsDaily Staff
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News

Gaming GPUs Improve Image-Guided Rad

By **Mike Sharkey** | Jul 19, 2010

UCSD team used Nvidia graphics card to efficiently create t

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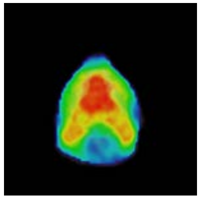
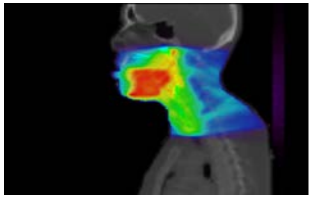
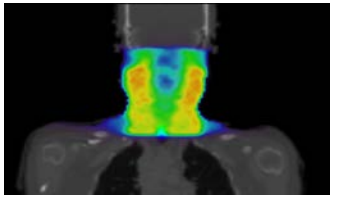
NBC Evening News

Dose Engine #1: GPU-based FSPB model

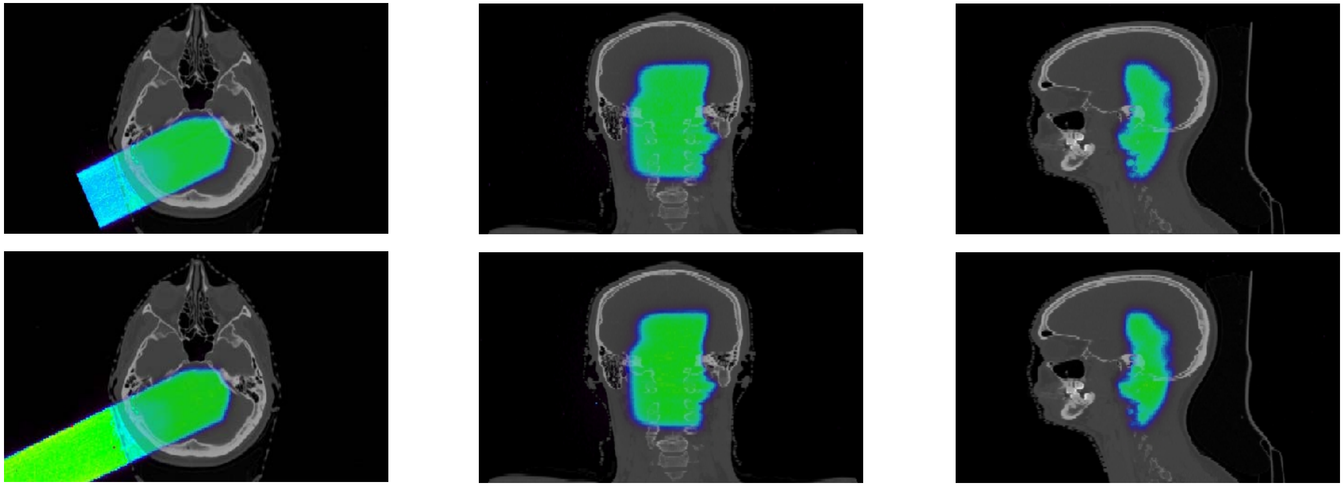
- **Version 1**
  - Gu et al *Phys Med Biol.* 54(20):6287-6297, 2009
  - **Conventional FSPB model**
- **Version 2**
  - Gu et al *Phys Med Biol.* 56(11): 3337-3350, 2011
  - **With 3D density correction**
  - **Accuracy greatly improved**
  - **Still extremely efficient: <1 s for IMRT, ~15 s for VMAT**

Dose Engine #2: GPU version of DPM MC code

- **Version 1**
  - Jia et al *Phys Med Biol.* 55(11): 3077–3086, 2010
  - **A straightforward implementation**
  - **Only 5-6x speed up**
- **Version 2**
  - Jia et al *Phys Med Biol.* 56(22):7017-7031, 2011
  - **More GPU friendly**
  - **~ 60x speed up**
  - **~ 40 s for IMRT and VMAT**
- **Version 3**
  - Townson et al *Phys Med Biol.* 58(12):4341-4356, 2013
  - **Phase space files and commissioning procedure**

Dose Engine #3: gPMC – GPU-based Proton MC



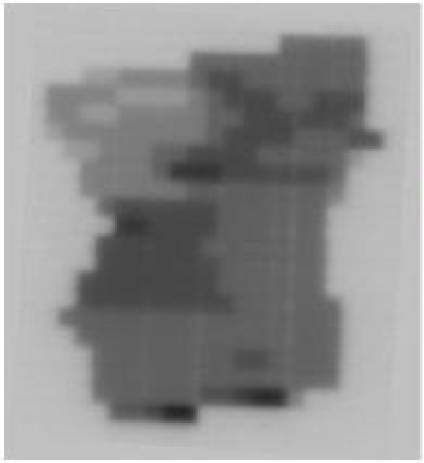
TOPAS

gPMC

Phantom	Energy (MeV)	3%/3mm Gamma passing rate (%)	Time (sec)	CPU time (hr)
Water	100	100	6.7	10.8
Water	200	100	22.1	39.5
Bone	100	100	6.1	20.8
Bone	200	99.9	19.6	70.0
Plastic	100	100	6.3	10.2
Plastic	200	99.9	20.8	78.7
Inhomogeneous	100	100	8.6	15.9

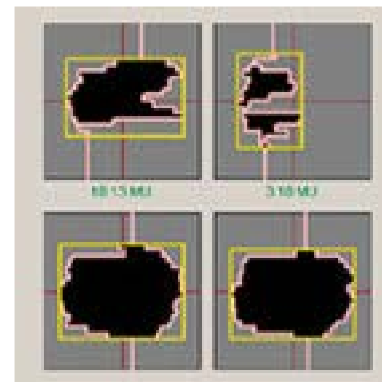
Jia, Schuemann, Paganetti, Jiang, *Phys Med Biol*, 57(23):7783-7797, 2012

Three GPU-based Optimization Models



Men et al *Phys Med Biol.* 54(21):6565-6573, 2009

< 1 second



Men et al *Phys Med Biol.* 55(15):4309-4319, 2010

~ 2 seconds

Men et al *Med Phys* 37(11): 5787-5791, 2010

Peng et al *Phys Med Biol.* 57(14):4569-88, 2012

~ 20-60 seconds

Deformable Image Registration (DIR) for ART

- **Demons on GPU**
  - Gu et al *Phys Med Biol* 55(1): 207-219, 2010
- **Contour-guided DIR**
  - Gu et al *Phys Med Biol* 58(6):1889-1901, 2013
- **CT/CBCT DIR with intensity correction**
  - Zhen et al *Phys Med Biol* 57: 6807-6826, 2012
- **CT/CBCT DIR with truncation**
  - Zhen et al *Phys Med Biol 58:7979-7993, 2013*

1. Implement Demons DIR on GPU

Gu, Pan, Liang, Castillo, Yang, Choi, Castillo, Majumdar, Guerrero, and Jiang
Phys Med Biol 55(1): 207-219, 2010

GPU-based Demons DIR

- **Iterative method**

$$\mathbf{u}^{k+1} = \left(\mathbf{u}^{k} + \frac{\left(I(\mathbf{x}+\mathbf{u}^{k}) - J(\mathbf{x}) \right) \nabla J(\mathbf{x})}{\left| \nabla J(\mathbf{x}) \right|^{2} + \left(I(\mathbf{x}+\mathbf{u}^{k}) - J(\mathbf{x}) \right)^{2}} \right) \circ G(\sigma)$$

- **Key assumptions:**
  - Intensity constancy: a point in the Moving image $I(\mathbf{x})$
    looks the same in the Target image $J(\mathbf{x})$
  - Small motion

- **Six variants:**

1. Passive force; 2. Evolved Passive force; 3. Active force;

4. Double force; 5. Normalized double force; 6. Inverse consistency;

GPU-based Demons DIR

- **Images size ~256*256*100**
- **~100x speedup compared to an Intel Xeon 2.27 GHz CPU**

Computational time (unit: sec)

Method	Case 1	Case 2	Case 3	Case 4	Case 5	Average
1	6.80	7.18	7.39	6.49	7.24	7.02
2	6.82	7.20	7.42	6.56	7.08	7.02
3	8.29	9.24	8.79	7.75	8.44	8.50
4	7.71	8.65	8.02	8.30	8.44	8.22
5	8.36	8.69	8.97	7.77	8.70	8.50
6	11.07	11.47	11.54	10.46	10.98	11.10

2. Contour-guided Demons DIR

- ❑ **After DIR contour propagation, manual inspection and revision (if needed)**
- ❑ **DVF updating for accurate dose accumulation**

Gu, Dong, Wang, Yordy, Mell, Jia and Jiang *Phys Med Biol.* 58(6):1889-1901, 2013.

Contour-Guided Deformable Registration

Energy function:

$$E(d\mathbf{r}) = \frac{1}{2}\left\| I_0(\mathbf{r} + d\mathbf{r}) - T_0(\mathbf{r}) \right\|_2^2 + \sum_i \frac{\lambda_i}{2} \left\| I_{s_i}(\mathbf{r} + d\mathbf{r}) - T_{s_i}(\mathbf{r}) \right\|_2^2$$

$$d\mathbf{r} = \arg\min E(d\mathbf{r})$$

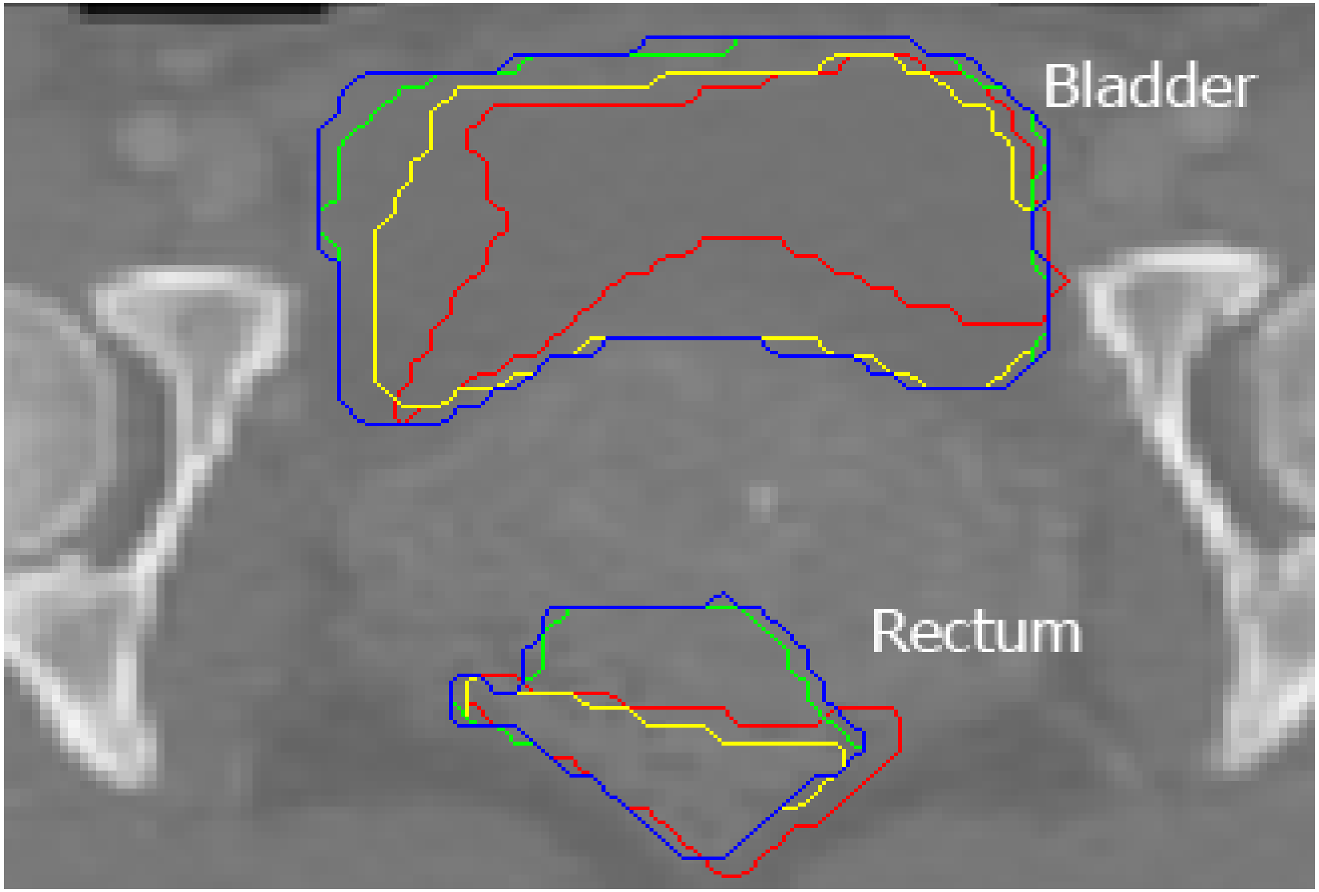
Key assumption:

$$d\mathbf{r} = v\mathbf{n}, \text{with } \mathbf{n} = \frac{\nabla I_0(\mathbf{r}) + \sum_i \lambda_i \nabla I_{s_i}(\mathbf{r})}{\left| \nabla I_0(\mathbf{r}) + \sum_i \lambda_i \nabla I_{s_i}(\mathbf{r}) \right|}$$

Solution:

$$v = \frac{(\nabla I_0(\mathbf{r}) \cdot \mathbf{n})(T_0(\mathbf{r}) - I_0(\mathbf{r})) + \sum_i \lambda_i (\nabla I_{s_i}(\mathbf{r}) \cdot \mathbf{n})(T_{s_i}(\mathbf{r}) - I_{s_i}(\mathbf{r}))}{(\nabla I_0(\mathbf{r}) \cdot \mathbf{n})^2 + \sum_i \lambda_i (\nabla I_{s_i}(\mathbf{r}) \cdot \mathbf{n})^2 + (T_0(\mathbf{r}) - I_0(\mathbf{r}))^2}$$

Contour-Guided Deformable Registration



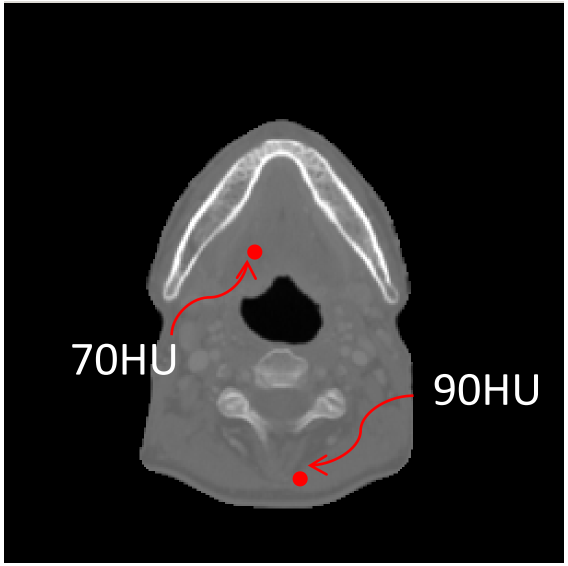
Red lines: manual contours on pCT and mapped on tCT through rigid registration
Blue lines: manual contours on tCT
Yellow line: deformed contours through demons registration
Green line: deformed contours through CG-DIR registration

3. CT/CBCT DIR with Intensity Correction

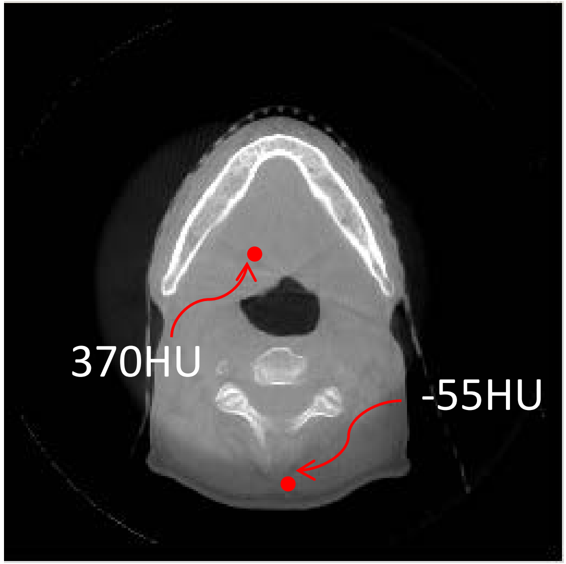
Zhen, Gu, Yan, Zhou, Jia, and Jiang *Phys Med Biol 57: 6807-6826, 2012*

Intensity Inconsistency between CT and CBCT

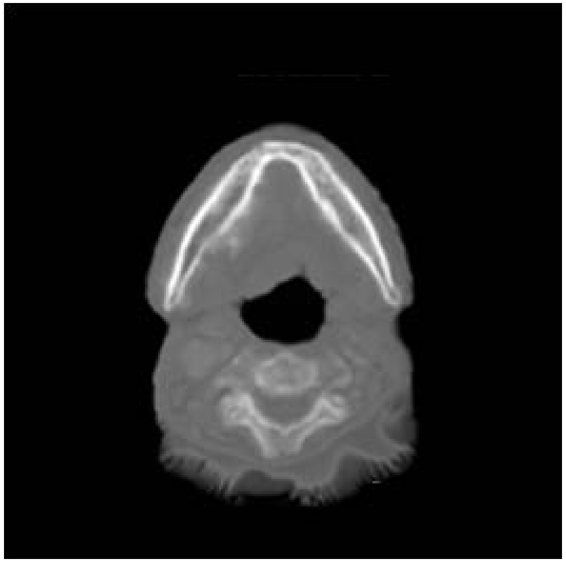
- ❑ Scatter artifacts in CBCT
- ❑ Bowtie filter artifact
- ❑ Different scan geometry
- ❑ Different level of noise, beam hardening, etc

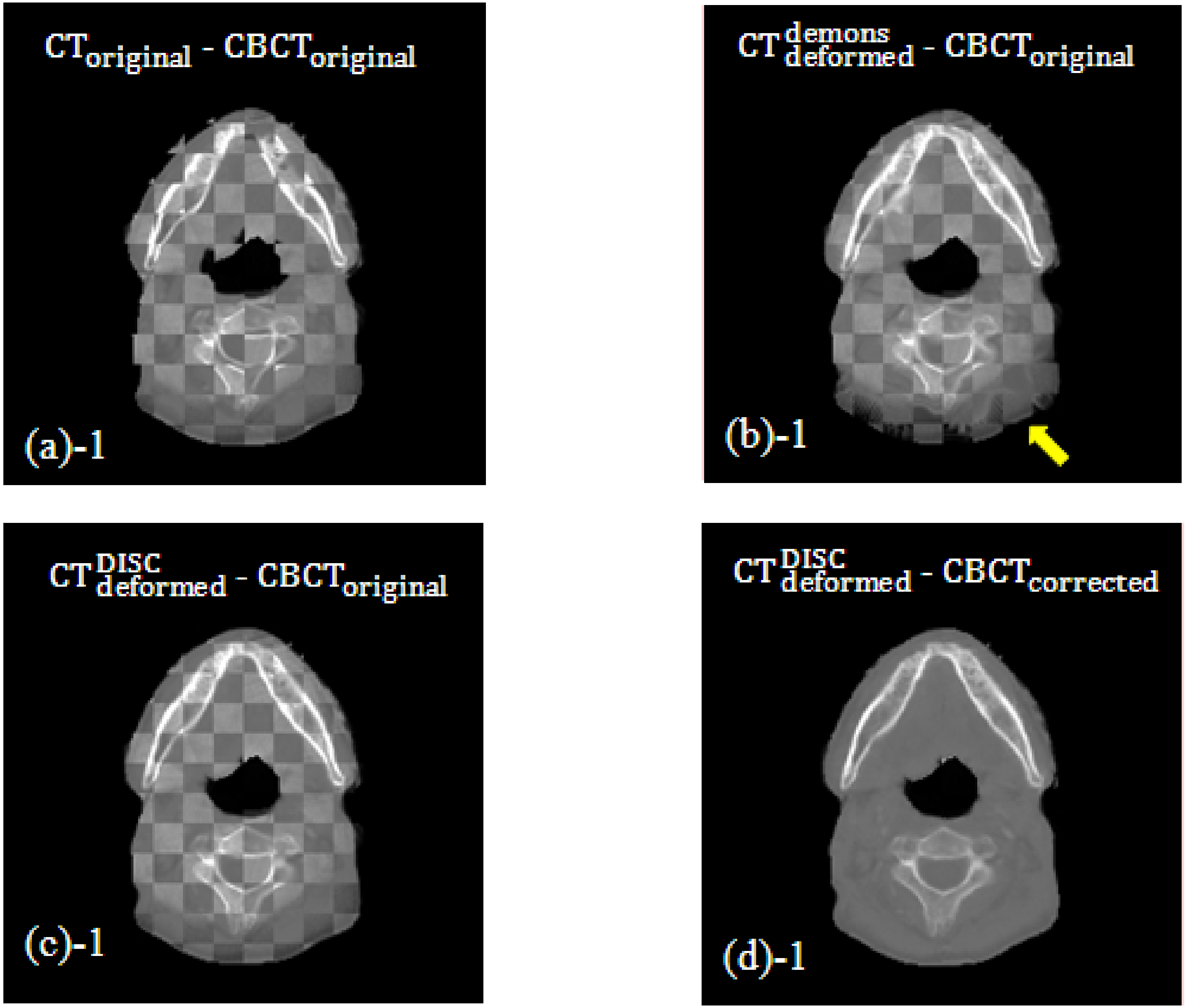


CT



CBCT

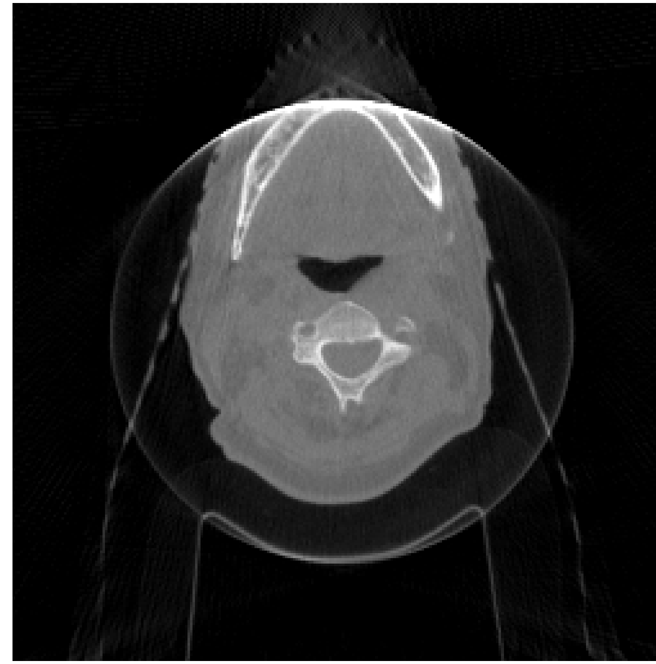

Demons: Deformed CT


$CT_{original}$ - $CBCT_{original}$
(a)-1
$CT^{demons}_{deformed}$ - $CBCT_{original}$
(b)-1
$CT^{DISC}_{deformed}$ - $CBCT_{original}$
(c)-1
$CT^{DISC}_{deformed}$ - $CBCT_{corrected}$
(d)-1

4. CT/CBCT DIR with truncation

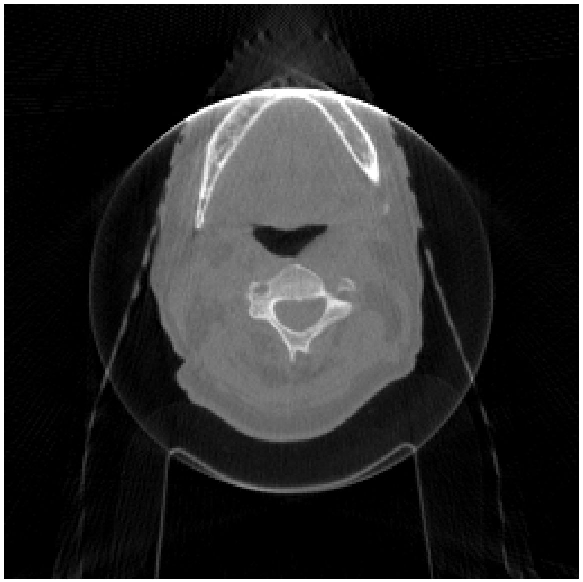
Zhen, Yan, Zhou, Jia, Jiang, *Phys Med Biol*. 58(22):7979-7993, 2013.

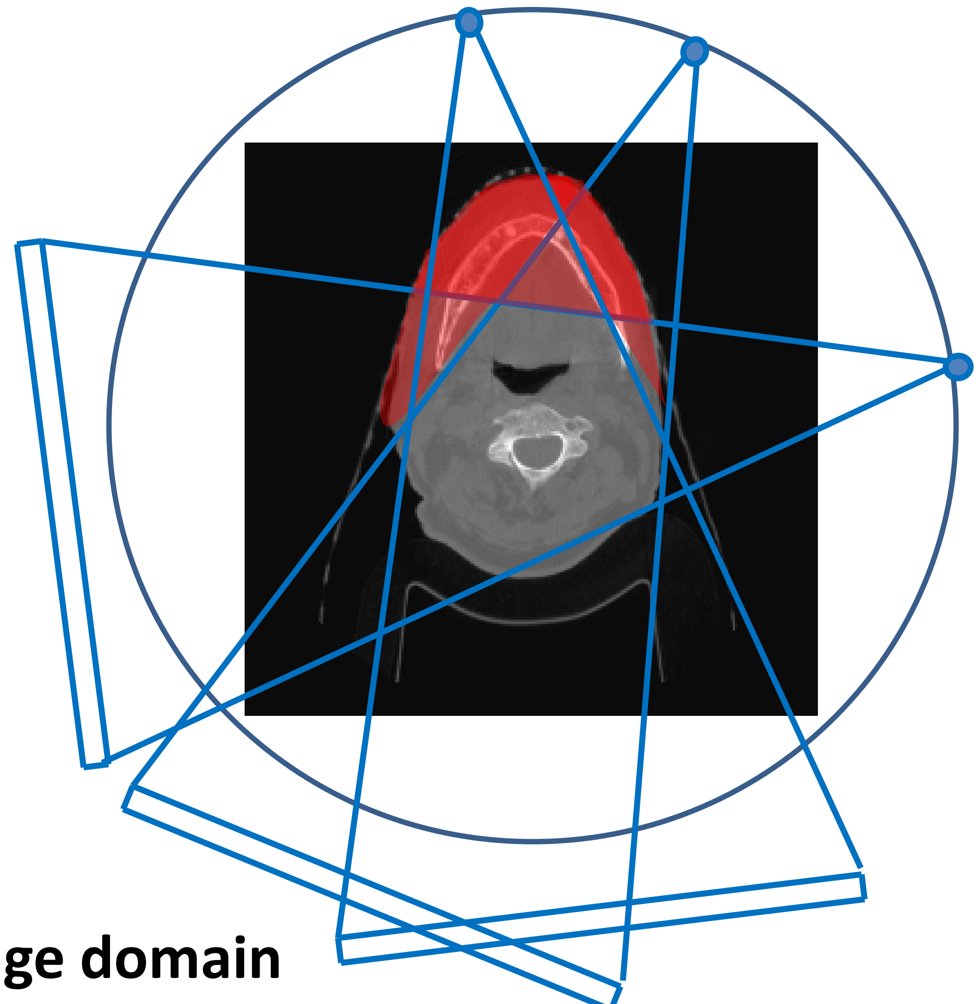
CBCT Image Truncation



- **Causes**
  - CBCT has a smaller FOV
  - Sometimes we only scan ROI
- **Problems in CT/CBCT DIR**
  - Unphysical results in/near the missing regions
  - Errors in dose calculation for ART

Rationale of Our Algorithm





Information is missing in image domain
But it still exists in projection domain

A Hybrid Reconstruction/Registration Algorithm

$$\arg\min E(x) = \frac{1}{2}\left\| Pf^0(x+v(x)) - g \right\|_2^2 + \frac{\lambda}{2}\left\| \nabla v \right\|_2^2$$

- *P:* projection operator
- f^0: moving image(CT)
- *v*: vector field
- *g*: CBCT projection

Euler–Lagarange equation:

$$\nabla f^0 \cdot P^T(Pf^0 - g) - \lambda \Delta v = 0$$

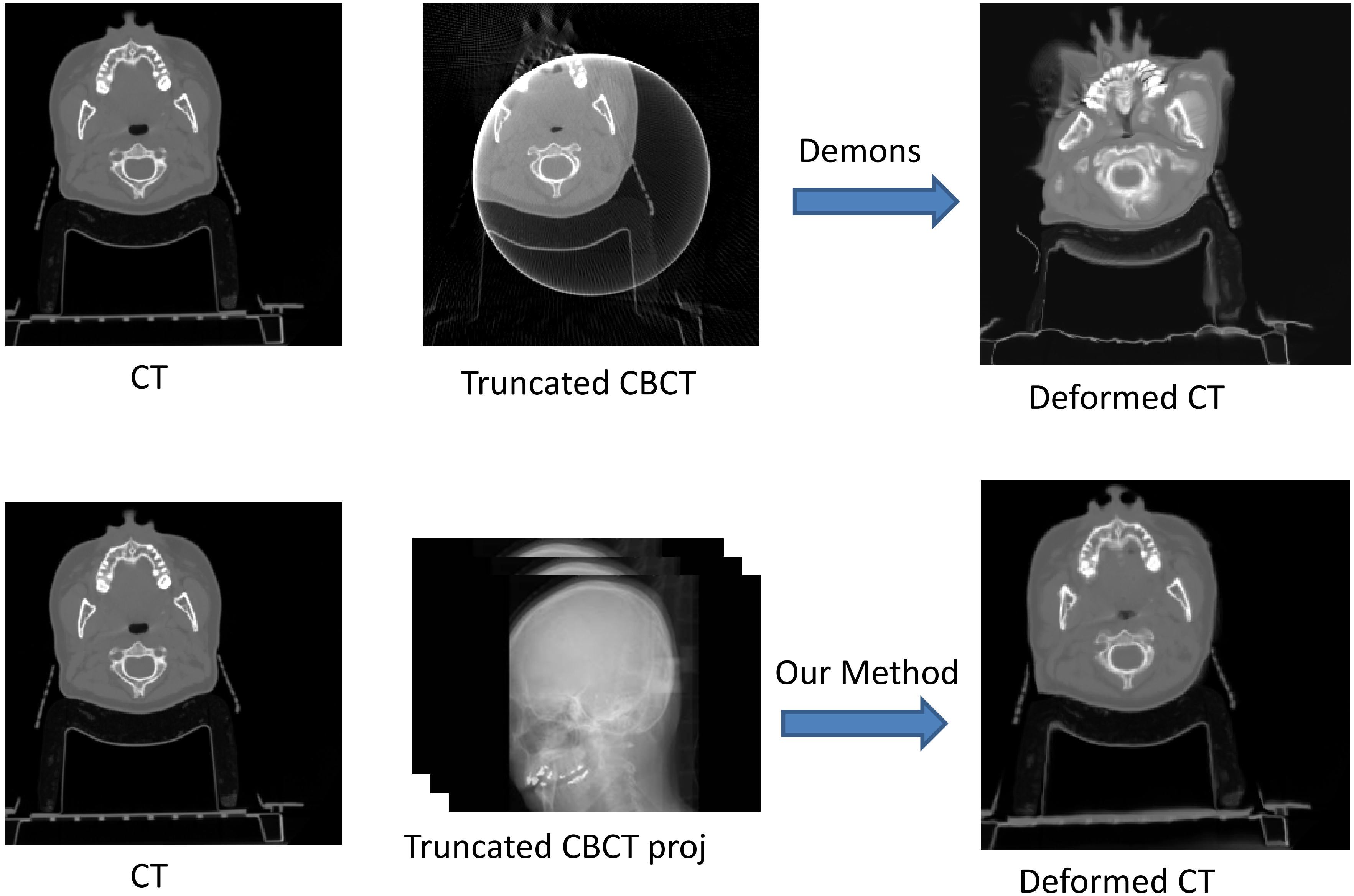
$$\nabla f^0 \cdot P^T(Pf^0 - g) - \lambda \Delta v - \nabla f^0(f^0 - s) + \nabla f^0(f^0 - s) = 0$$

$$\nabla f^0 \cdot P^T(Pf^0 - g) - \nabla f^0(f^0 - s) = 0$$

Reconstruction

$$\nabla f^0(f^0 - s) - \lambda \Delta v = 0$$

Registration

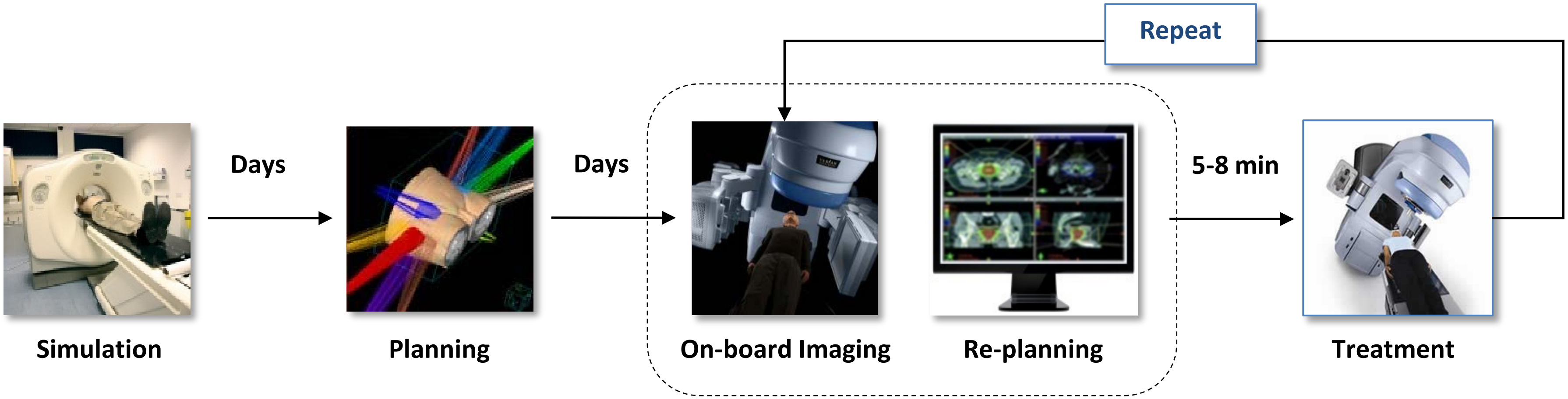

CT
Truncated CBCT
Demons
Deformed CT
CT
Truncated CBCT proj
Our Method
Deformed CT

The Use of GPU Tools

- Improve efficiency for some computational tasks in radiotherapy

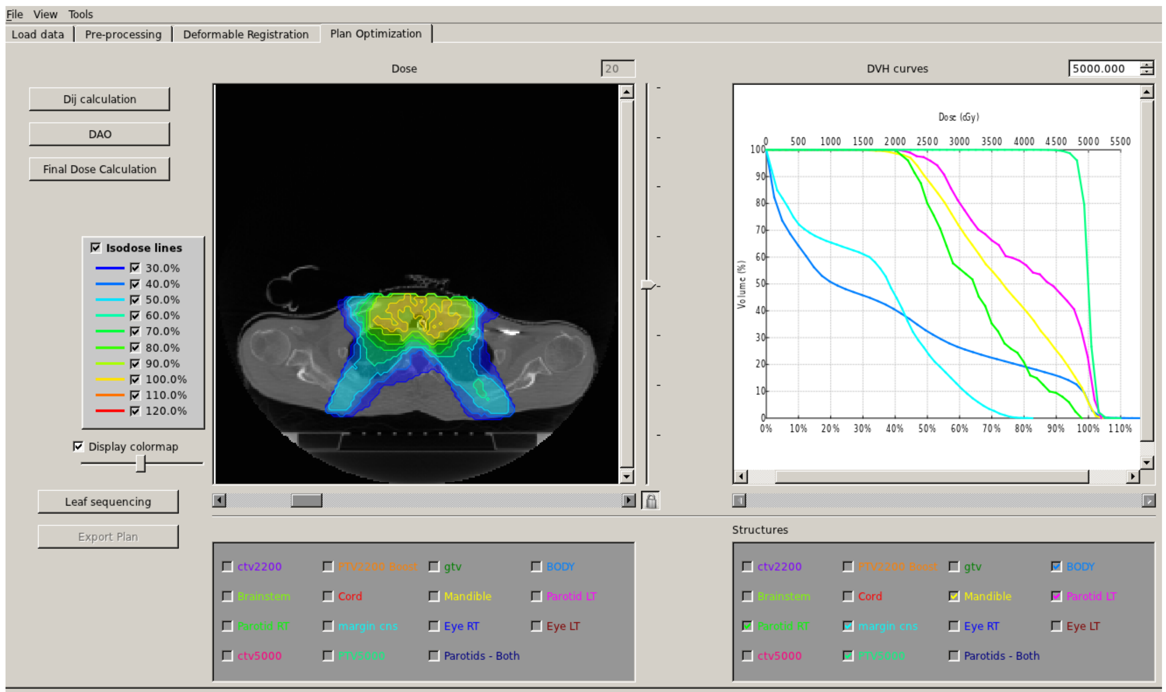
- More importantly, change the way we treat patients

Online Adaptive Radiotherapy



- ❑ Tumor volume shrinkage in response to the treatment
- ❑ Tumor shape deformation due to filling state change of neighboring organs
- ❑ Relative position change between tumor and normal organs
- ❑ Beyond geometrical changes

SCORE → <u>S</u>uper<u>c</u>omputing <u>O</u>n-line <u>R</u>e-planning <u>E</u>nvironment



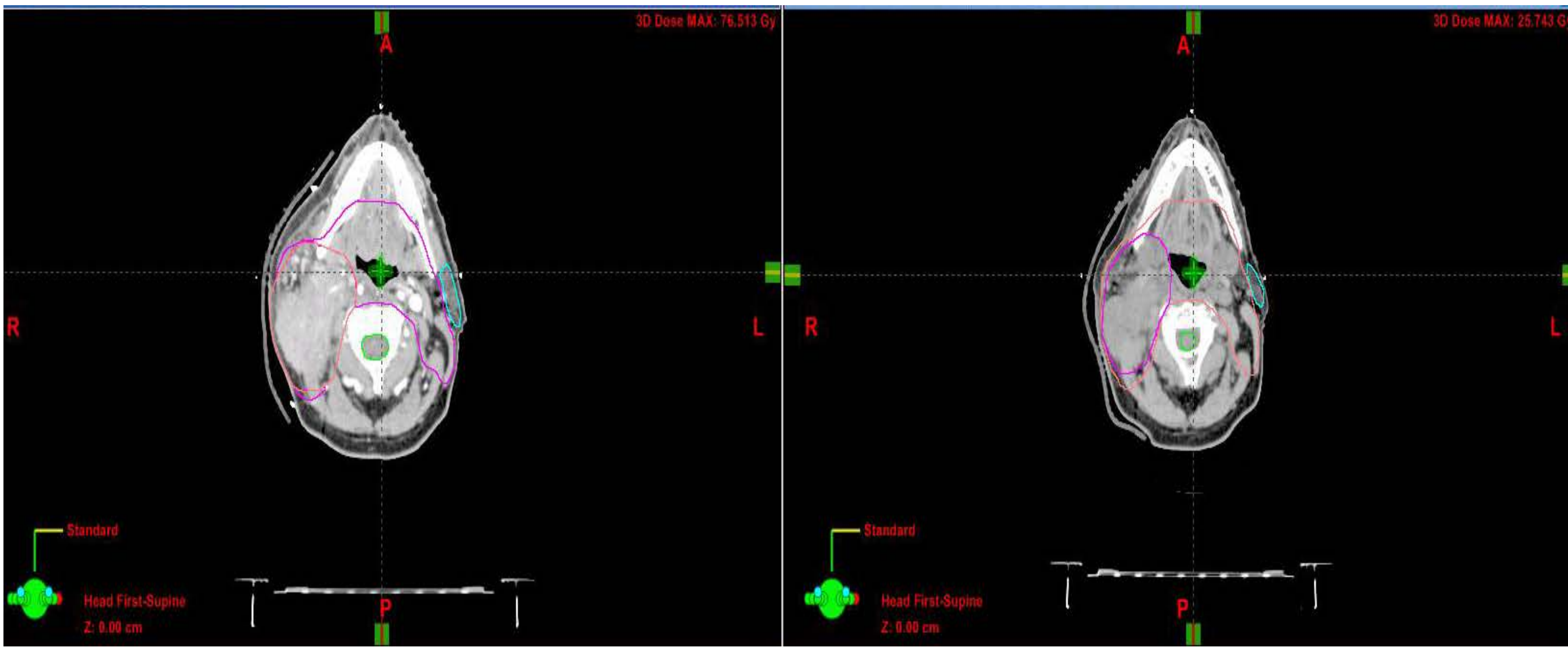
A GPU-based real-time automatic re-planning system

A research platform for online and offline ART

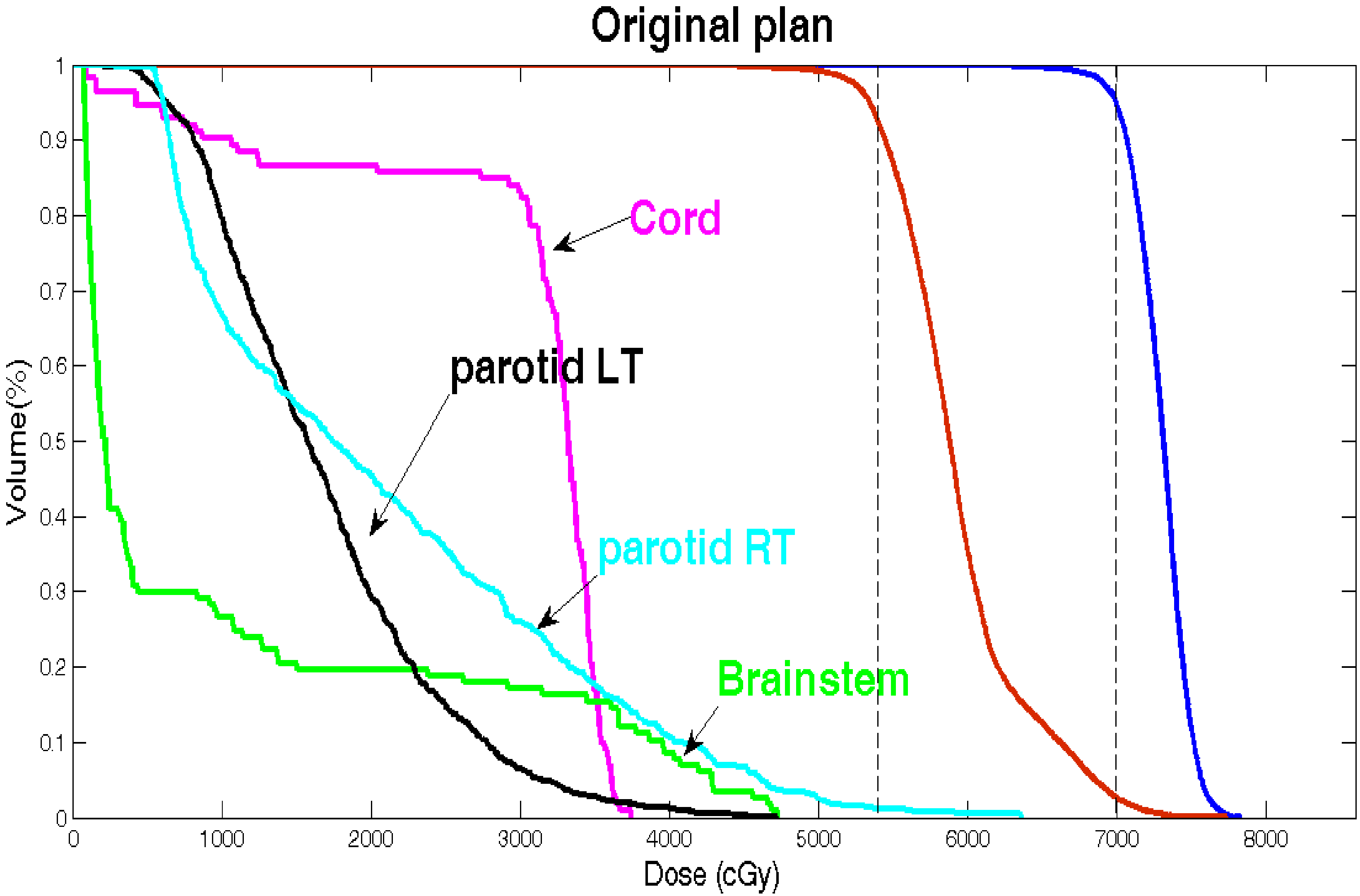
Clinical studies: H/N, pancreas, GYN, prostate, lung, *etc*

H & N Case 1

Planning CT | **Treatment CT**

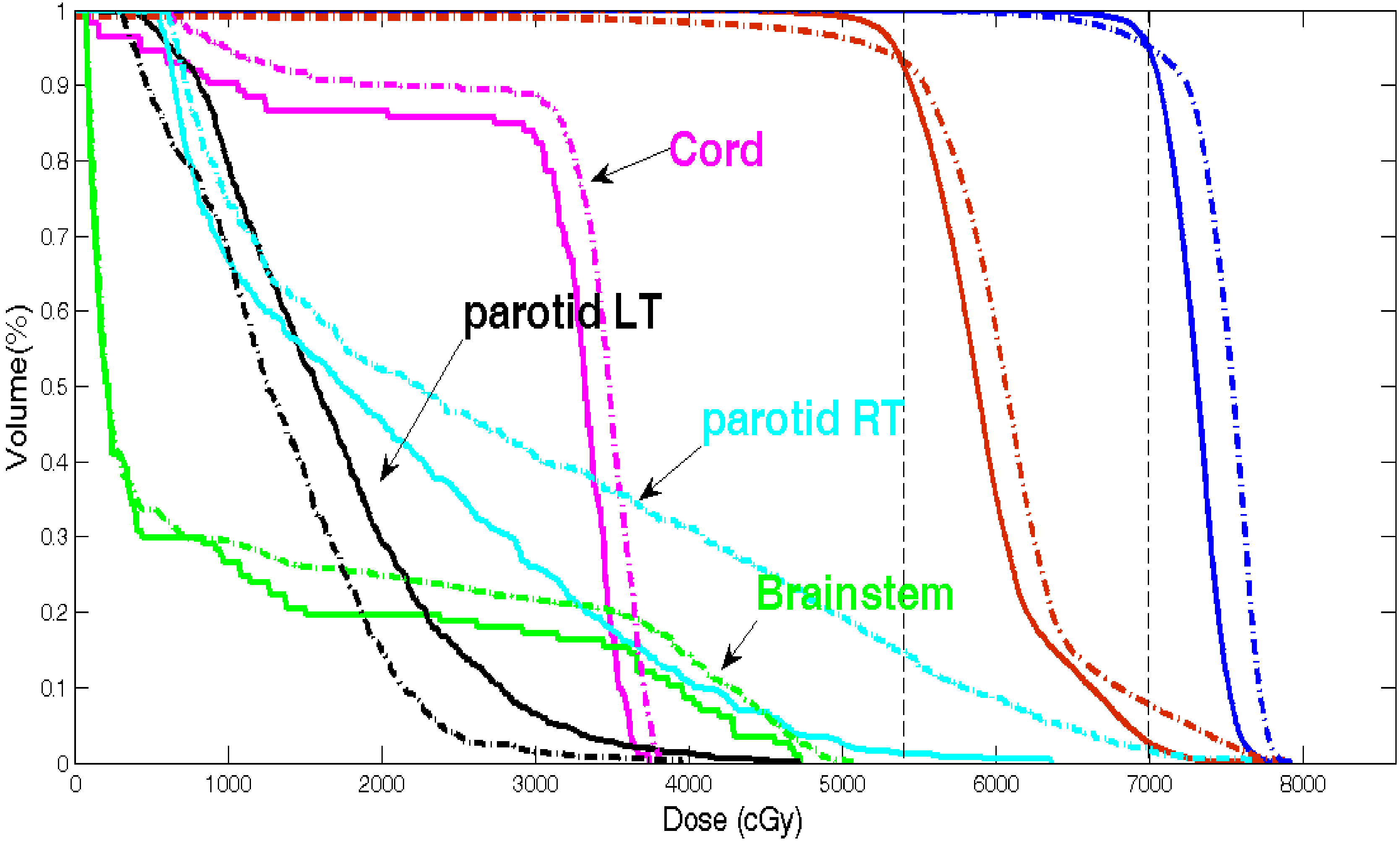


7 beams at 0, 51, 102, 153, 207, 258 and 309 degree angles

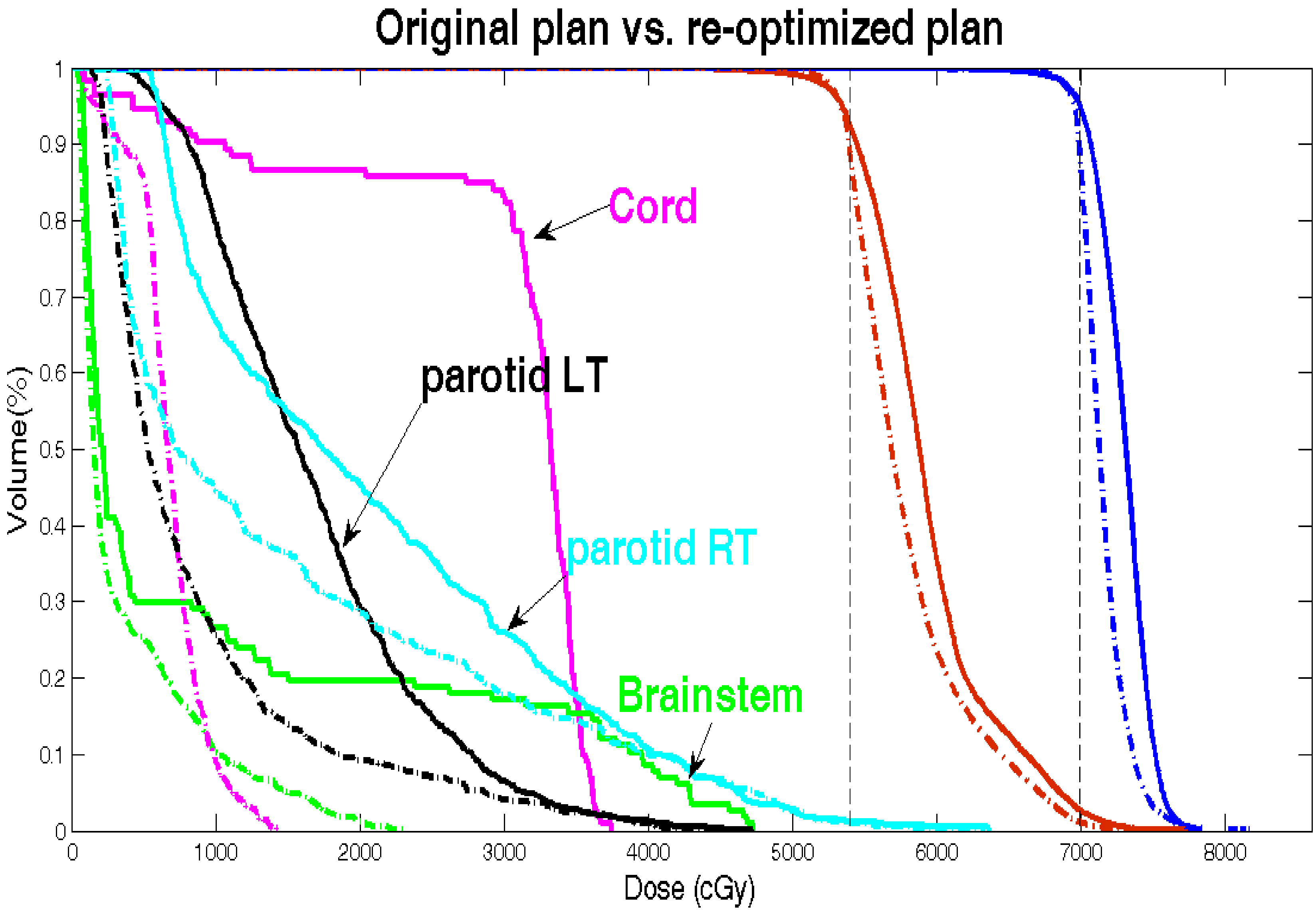


Prescription: 6996 5400 (cGy)

Original plan vs. Un-adapted plan



Prescription: 6996 5400 (cGy)



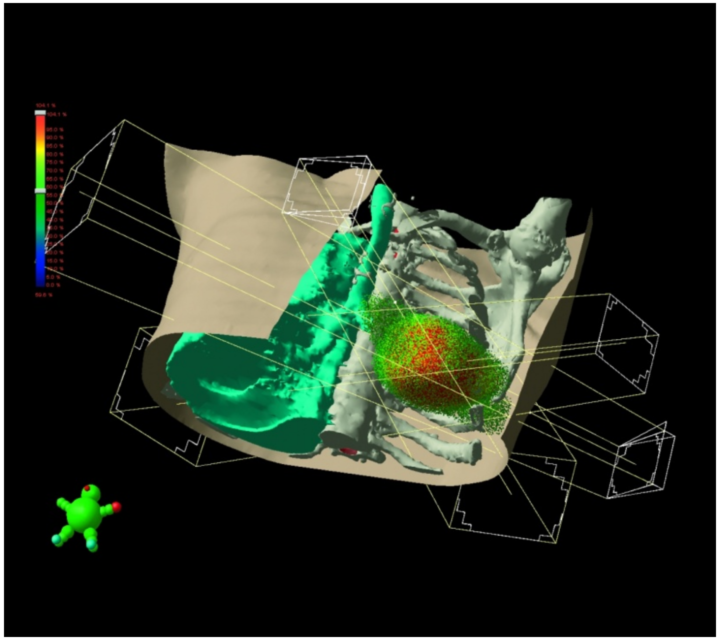
Prescription: 6996 5400 (cGy)

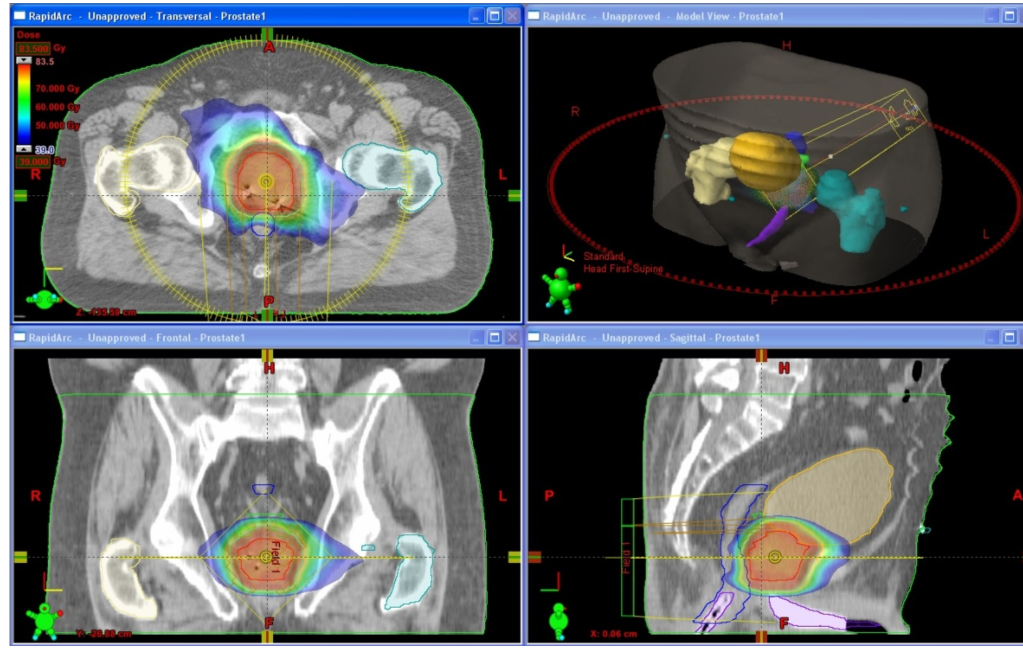
Online Re-planning - A Paradigm Shift

- **Past and current: <u>plan-centered</u>**
  - A snapshot of patient anatomy before treatment
  - A treatment plan based on this snapshot
  - Try to match this plan with the patient anatomy throughout the whole treatment course
- **Future: <u>patient-centered</u>**
  - Automatic plan re-optimization on CBCT every day
  - Setup errors and anatomical variations are considered in the new plan
  - Much smaller PTV margin and faster patient setup

From
Adaptive Therapy Re-planning
To
Next Generation Treatment Planning

Problems with Current Treatment Planning

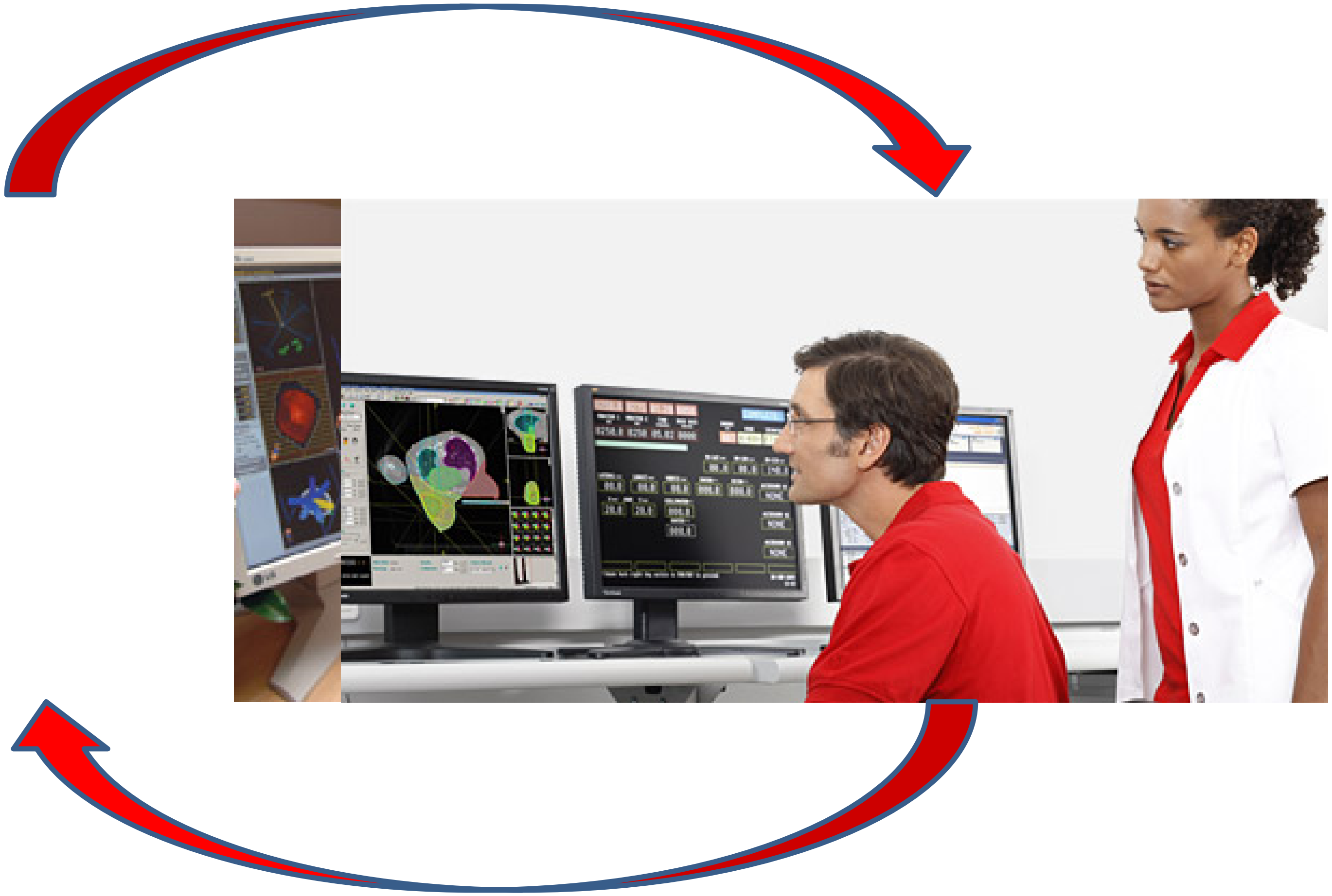




- **Large variation in plan quality** **(on paper and delivered)**
  - **Inter- and intra-institution variation**
  - **Inter- and intra-TPS variation**
  - **Inter- and intra-planner variation**
  - **Inter- and intra-attending variation**

Das IJ *et al*, J Natl Cancer Inst. 100(5):300-7, 2008.

Problems with Current Planning - Low Efficiency



The whole process may take a week !

Problems with Current Planning – High Cost

Large portion of healthcare professionals' time

(Time is money!)

Planning system purchase, installation, commissioning, maintenance, and upgrade

A dedicated data center is needed for patient data storage

Problems with Current Treatment Planning

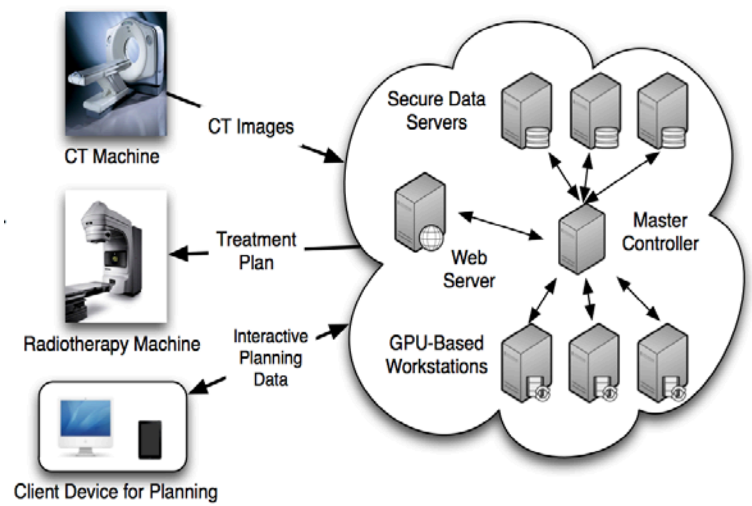
- ❑ **Difficult for cross institution collaboration**
- ❑ **Difficult for experience sharing**
- ❑ **Difficult for data sharing and mining**
- ❑ **Difficult for multi-institution clinical trials**

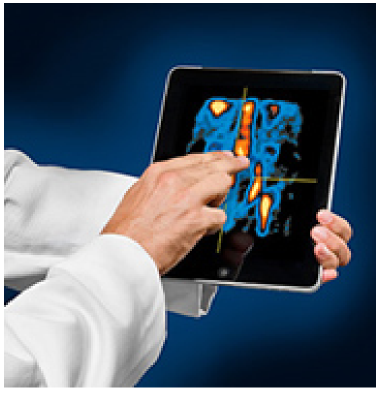
Our Vision on Next Generation TP

- Based on recent technologies
  - GPUs, cloud computing, and iPad
- Physician centered and a two step approach
- 1st step: automatic planning (Cloud computing)
  - Using delivered plans of previously treated patients as reference
  - The auto plan should be good and robust enough for clinical use for most standard cases
- 2nd step: interactive tuning (GPU and iPad)
  - Physician interactively tune the plan by dragging DVH and iso-dose curves
  - Plan re-optimization in real-time in response to any change

Proposed Process for Next Generation TP

- ❑ Upload patient CT and treatment protocol to the GPU cloud
- ❑ Automated contouring and planning in the cloud
- ❑ Clinician to review and interactively revise the contours and plan using an iPad
- ❑ Download the plan, QA, and treat





Benefits for Next Generation TP

- Higher plan quality
  - Reduced variation
  - Important for resource-limited institutions/regions
- Lower cost
  - Reduce costs in purchasing, installing, commissioning, maintaining, and upgrading TPS
  - Improved resource utilization ratio
- Higher efficiency
  - Better utilization of professional's time
  - High throughput
- Better usability and accessibility
  - Planning can be done anywhere on any device
- Faster deployment of new technologies
- Enhanced collaborative clinical trials and data mining

Optimization Guided by A Reference Plan

- Prior knowledge based optimization

- ❑ **Guided with reference DVHs**
  - — **Clinician approved trade-offs among PTVs/OARs**
  - — **Clinician approved trade-offs among dose-volume criteria for each PTV/OAR**

- ❑ **Guided with reference dose distribution**
  - — **Locations of hot/cold spot**
  - — **Shapes of iso-dose curves**

Zarepisheh et al, *Phys Med Biol.* 58(6):1869-1887, 2013.

Zarepisheh et al, *Med. Phys.* (accepted)

Where Are We?

- ❑ **Automatic contouring**
  - — **Many commercial solutions**

- ❑ **Automatic treatment planning**
  - — **Model based approaches (predicting DVH)**
  - — **Library based approaches (selecting reference patients)**
    - **Most similar patient as reference**
    - **Many patients as references**

- ❑ **Interactive plan tuning**
  - — **Approximate approaches (cutting corners)**
  - — **GPU-based approaches (exact)**

Demonstration of Some Preliminary Work

- ❑ **GPU-based brute force automatic planning**
  - — A library of 100 prostate IMRT patients
  - — Leave-one-out test
  - — 99 new plans were automatically generated for each test patient in 80 minutes on one GPU card
  - — A GUI for physician to select a preferred plan
  - — Video (YouTube) (Local)
- ❑ **SCORE for automatic planning and interactive tuning**
  - — SCORE was designed for ART re-planning
  - — It is being extended for automatic planning and interactive tuning
  - — A previously treated patient is chosen as the reference patient
  - — A plan for the new patient is automatically developed and then interactively tuned
  - — Video (YouTube) (Local)