

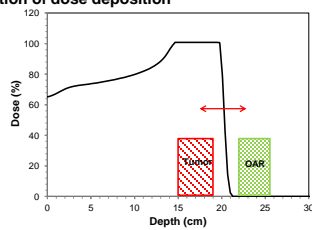
Adaptive Proton Therapy with CBCT

Kevin Teo, PhD



Sensitivity of Proton Dose Distribution

- Protons have finite range
- Change in material composition along beam path → Shift in position of dose deposition



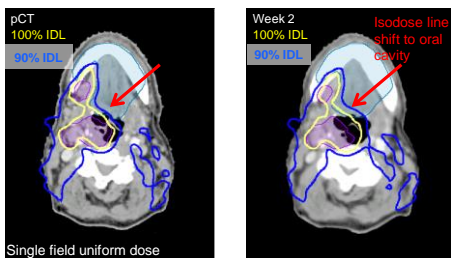
- Repeat CT imaging or in-room CBCT needed throughout treatment course to monitor anatomic change

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Impact of Anatomic Change



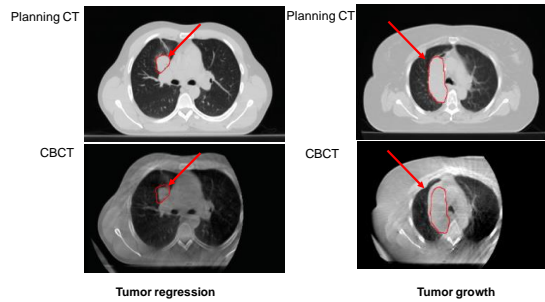
- Less optimal dose distribution- degrades with time
- OAR doses may increase eg oral cavity
- Worse with IMPT compared with single field uniform dose technique

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Lung Anatomic Change



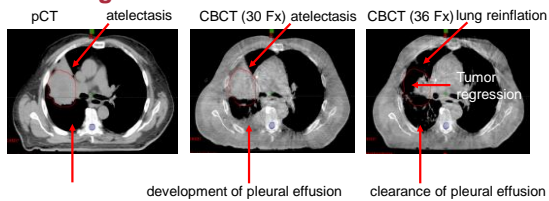
Impact on dose distribution to target and organs at risk needs to be assessed

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Lung: Pleural Effusion, Atelectasis, Tumor Regression



Anatomic change will impact proton range, periodic assessment during treatment is necessary

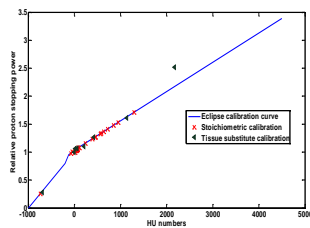
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Limitations of CBCT for Dose Calculation

- Proton dose calculation is **more sensitive** to HU accuracy than photon therapy
- CBCT **cannot** be used directly for dose calculation unless HU accuracy is verified



If CT number is off by 100 HU
Stopping power is different by 5%
For a 10cm range, error is 5 mm.

Need error in water equivalent depth << Range uncertainty of 3.5%

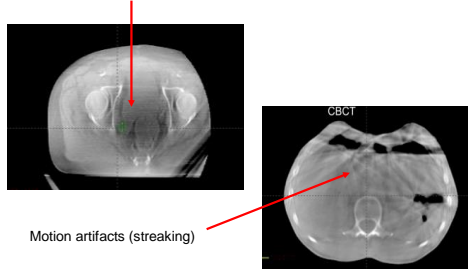
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Limitations of CBCT for Dose Calculation

- Inaccurate HUs
- Beam hardening and scatter artifacts (dark streaks between high density structures, cupping artifacts)



Improving Accuracy of CBCT HUs for Dose Calculation

1) Histogram matching method

K. Arai et al. Physica Medica 33 (2017) 68–76

2) *A priori* CT based scatter correction – More accurate correction (CBCT_{cor})

Y.-H. Park et al. Med Phys 42 4449 (2015)

Kim et al. PHYSICS IN MEDICINE AND BIOLOGY Volume: 62 Issue: 1 Pages: 59–72 JAN 7 2017

Kurz et al. MEDICAL PHYSICS Volume: 43 Issue: 10 OCT 2016

3) Deformable Image Registration (DIR) approach - Deform planning CT to geometry of CBCT (virtual CT)

C. Velga et al. LROBIP 95 549 (2016)

Velga et al. Biomed. Phys. Eng. Express 3: 015003, Feb 2017

Landry G et al. Med. Phys. 42 1354–66 2015

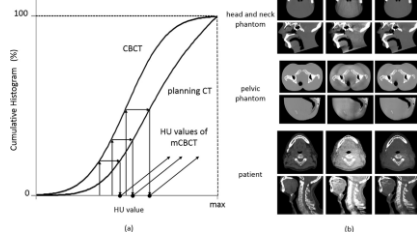
Velga et al. Med. Phys. 41 (3), March 2014 031703

..... Many others

Use one or combination of above methods

(1) Histogram Matching Method

K. Arai et al. Physica Medica 33 (2017) 68–76



- Replace cumulative value of CBCT HU histogram with SAME cumulative value of pCT histogram
- Apply rigid registration or DIR prior to histogram matching
- Scatter effects in CBCT as well as image artifacts may impact accuracy

(2) A priori CT Scatter Correction Method

$$I_{sca} = f(CF \times I_{raw} - I_{pri})$$

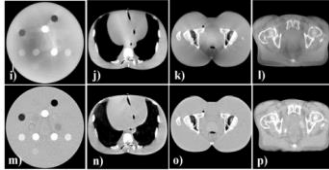
From forward projection of prior image (eg pCT)

Subtraction of primary signal (no scatter) from raw projection with scatter

$$I_{cor} = CF \times I_{raw} - I_{sca}$$

reconstruction \rightarrow $CBCT_{cor}$

Scatter corrected projection



CBCT with uniform scatter correction (traditional method)

CBCT_{cor} with a priori CT based scatter correction

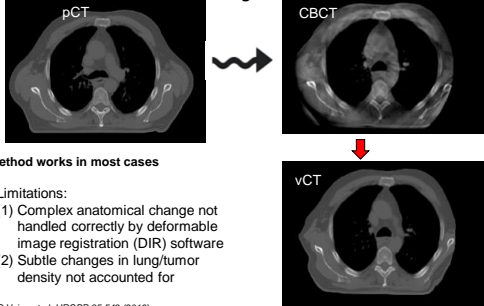
Y.K.Park et al. Med Phys 42:4489 (2015)

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(3) Deformable Image Registration Method: Virtual CT (vCT)

Deform planning CT to geometry of CBCT



Method works in most cases

- Limitations:
- (1) Complex anatomical change not handled correctly by deformable image registration (DIR) software
 - (2) Subtle changes in lung/tumor density not accounted for

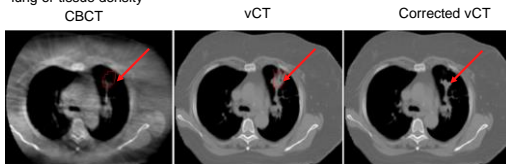
C. Velghe et al. IJROBP 95:549 (2016)

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Correction for Large Tumor Regression

Identify gross DIR errors between CBCT and vCT and replace HU with lung or tissue density



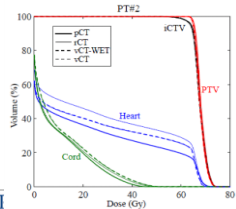
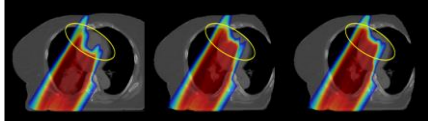
Large tumor regression

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Dose Analysis with vCT

pCT and planned dose vCT and warped dose vCT and recalculated dose

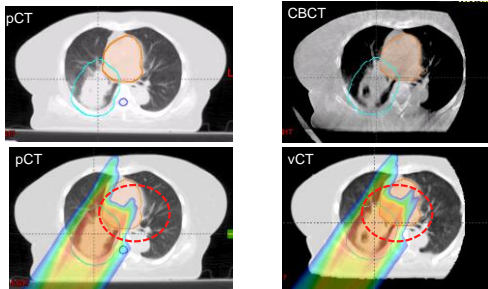


Feasible to replace evaluation CTs
with CBCT

IJROBP Veiga et al 2016

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Impact to Organ at Risk



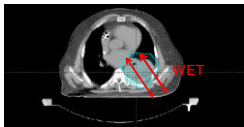
Mean heart dose 16.8Gy (pCT) vs 20.0 Gy (vCT)

Identify change in OAR dose

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Comparison of Virtual CT with Rescan CT



WET:
Water Equivalent Thickness from
entrance of beam to target

Results of 20 patient study:

Region of interest	WET _{mean} (mm)	WET _{RMS} (mm)	WET _{90%} (mm)
Distal surface	0.5±2.2	3.7±1.9	8±4
Proximal surface	0.1±1.9	2.3±1.5	4±3
PTV	0.4±2.1	3.4±2.0	7±4

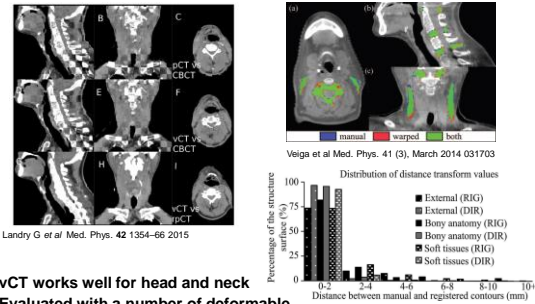
- Mean difference in WET is about 1mm
- Possible to estimate shifts in range with 2 to 3 mm accuracy

C Veiga et al, IJROBP 95 549 (2016)

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Head and Neck vCT

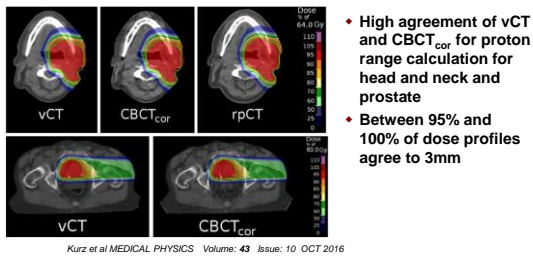


- vCT works well for head and neck
- Evaluated with a number of deformable image registration (DIR) algorithms (ANTS, Morphons, B-spline variants)

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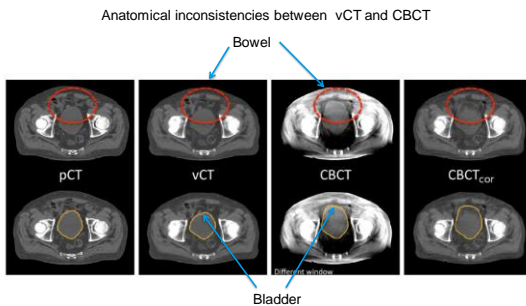
Comparison of vCT and CBCT_{cor} Dose Calculation



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Comparison of vCT and CBCT_{cor}



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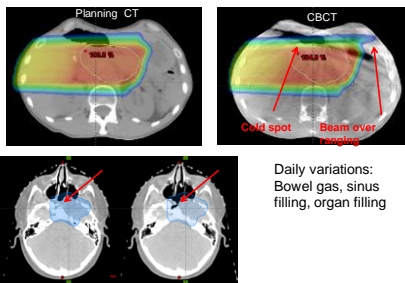
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Comparison of vCT and CBCT_{cor}

	vCT	vCT with correction	CBCT _{cor}
Head and Neck	✓✓	✓✓	✓✓
Lung	✓	✓✓	✓✓
Pelvis	✓	✓	✓✓
Prostate	✓✓	✓✓	✓✓
Contours and HU	May have some local inaccuracies	Better than vCT	Best in accuracy
Dose	May have some local inaccuracies	Fairly accurate	Fairly accurate

On-Line or Off-Line Adaptive Therapy?

- Most anatomical change especially (weight, tumor response) is gradual → offline adaptation
- In some cases, on-line adaptation would be needed but is not practical (yet)



Summary:

- Periodic monitoring of anatomy using CBCT, evaluation CT is needed for proton therapy
- Virtual CTs (deformable image registration) can be used to estimate dose
- vCTs may have local errors for large anatomical change
- Offline adaptation triggered by CBCT