"4D" IMRT Optimization Incorporating Organ Motion

Thomas Bortfeld, Alexei Trofimov, Jan Unkelbach, Timothy Chan, Benjamin Martin

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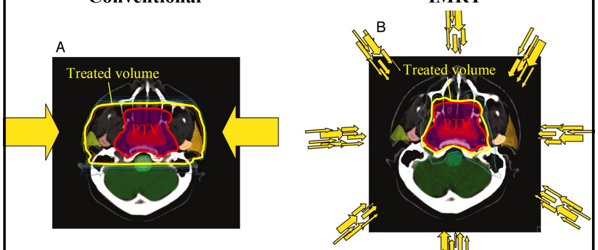
NIH: "Management of breathing effects in radiotherapy planning" (R01-CA118200)
NIH: "Multi-criteria IMRT optimization" (R01-CA103904)
BNSF US-Israel "Robust IMRT Optimization"
Siemens Medical Systems

Margin between PTV and Treated Volume

Conventional **IMRT**



From Bucci, M. K. et al. CA Cancer J Clin 2005;55:117-134.

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Can IMRT shrink the PTV?

- ICRU 62:
  PTV = CTV + IM + SM

➢ Internal motion and random setup errors lead to "dose blurring"

➢ IMRT cannot do much about systematic setup errors

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Educational objectives

1. Understand the concepts of motion blur and PDF
2. Understand the idea of de-blurring a dose distribution through "4D" motion optimization
3. Be able to discuss the relative potential and limitations of 4D motion optimization in comparison with margins and gating

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Outline

1. Dosimetric effects of respiratory motion and random setup errors
2. 4D optimization using motion probabilities
3. Uncertainties and robust optimization

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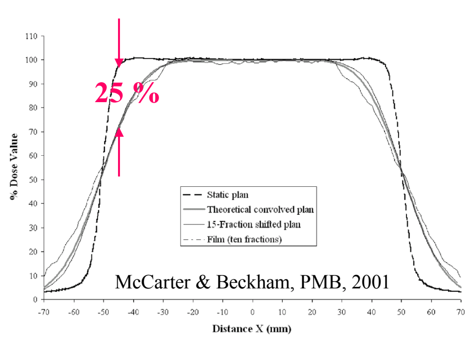
Motion blur



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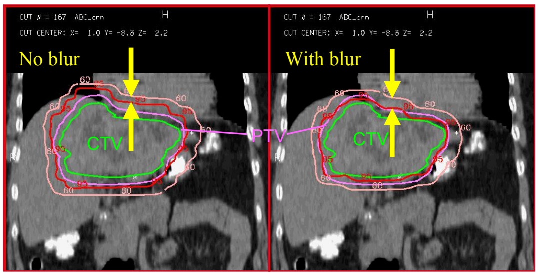
Motion blur of dose distribution

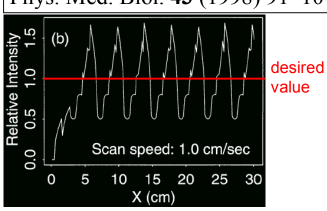


Courtesy: Randy TenHaken, Ann Arbor

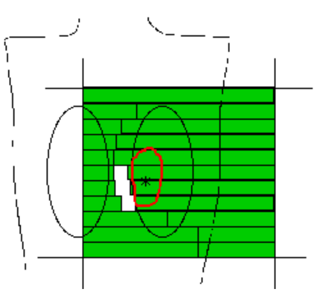
Interplay effects

Cedric X Yu, David A Jaffray and John W Wong: **"The effects of intra-fraction organ motion on the delivery of dynamic intensity modulation"**

Phys. Med. Biol. **43** (1998) 91–104.



Interplay effects between organ motion and MLC movement



JH Kung and P Zygmanski

Interplay effect in fractionated treatments

- Interplay effects tend to average out in a fractionated treatment
- Residual dose errors have a narrow Gaussian distribution
- The standard deviation (σ) is typically less than 1%

Bortfeld, Jokivarsi, Goitein, Kung, Jiang:
"Effects of Intra-Fraction Motion on IMRT . . .",
Phys. Med. Biol. 47:2203-2220, July 7, 2002

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Interplay effect in 3D

Chen-Shou Chui, Ellen Yorke, Linda Hong:
"The Effects of Intra-Fraction Organ Motion . . . ",
Med. Phys. 30(7):1736-1746, 2003

3 breast, 4 lung patients, ±3.5 mm to ± 10 mm
Simulations fully 3D

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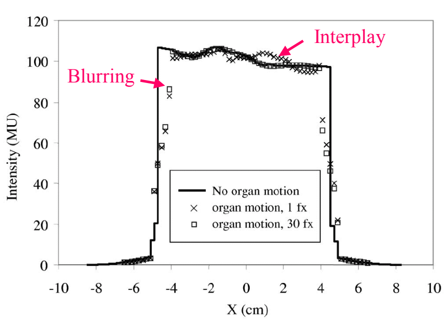
Chui et al. results: 1 fx vs. 30 fx



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Summary of effects

	how big	technique affected	where
Blurring (smoothing)	20-30%	all	field edges
Deformation (interface)	<5%	all	interfaces
Interplay	<1% standard deviation	IMRT	everywhere

Potential shortcomings of interplay studies

- Assumption that breathing is not correlated with MLC sequence
- Simulations: same motion pattern every day
- With 1% standard error there is a
  5% chance to see deviations > 2% or
  0.3 % chance to see deviations > 3% …
- Biological effect of dose per fraction variation
- Averaging may not work (well) for hypo-fractionation

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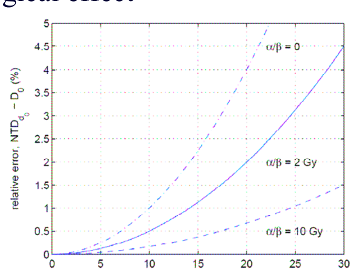
Biological effect



Bortfeld, Paganetti: "Biologic relevance of daily dose variations", IJROBP 65(3), 899-906, 2006
S. Zavgorodny: "The impact of inter-fraction dose variations", PMB 49, 5333-5345, 2004

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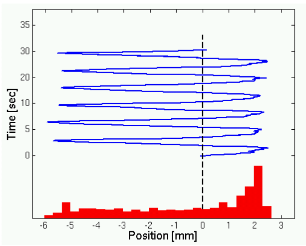
Motion probability density function, PDF



Breathing trajectory

PDF
Probability Density Function
Likelihood of a given offset

$$\langle D \rangle = \int D_s(x)\, pdf(x)\, dx$$

Outline

1. Dosimetric effects of respiratory motion and random setup errors
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Motion blur and deconvolution

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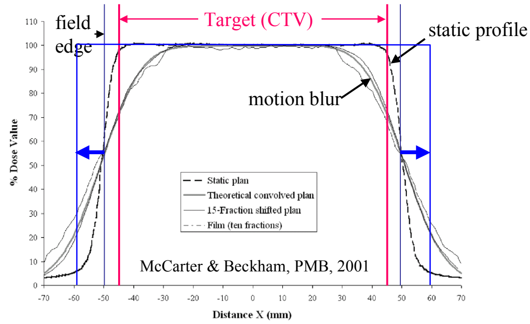
Motion blur (smoothing)



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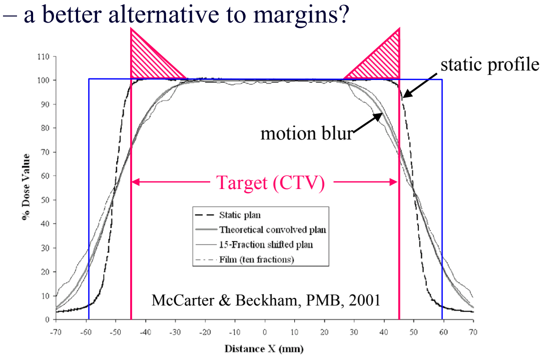
Motion compensation through "horns" – a better alternative to margins?



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Motion compensation through probability-based de-blurring

- **B. Lind et al. 1993**, "Optimal radiation beam profiles considering uncertainties in beam patient alignment", Acta. Oncol. 32:331-42
- **J. Li & L. Xing 2000**, "Inverse planning incorporating organ motion", Med. Phys. 27(7):1573-1578
- **M. Birkner et al. 2003**, "Adapting inverse planning to patient and organ geometrical variation", Med. Phys 30(10):2822-2831
- **J. Unkelbach & U. Oelfke 2004**, "Inclusion of organ movements in IMRT…probability distributions" Phys. Med. Biol. 49:4005-4029
- **A. Trofimov et al. 2005**, "Temporo-spatial IMRT optimization…", Phys. Med. Biol. 50 (2005) 2779–2798
- **D. McShan et al. 2006**, "MIGA", Med. Phys. 33(5):1510-1521
- …

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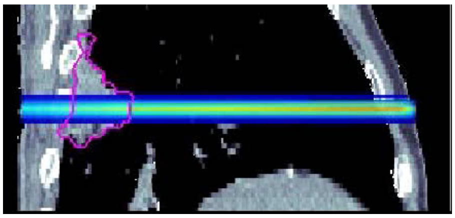
Pencil beam and organ motion



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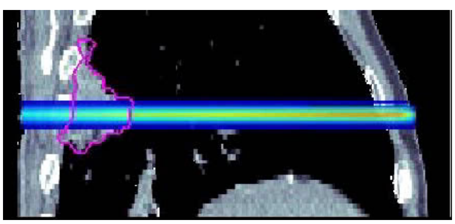
Voxels mapped back to reference geometry: Pencil beam moves



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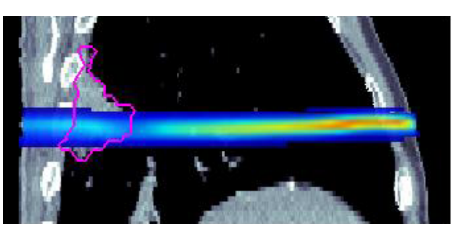
Dose delivered to a moving target over the motion cycle: Motion Kernel



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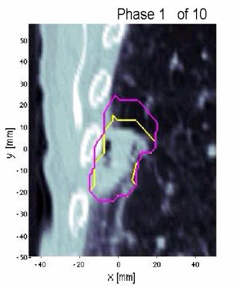
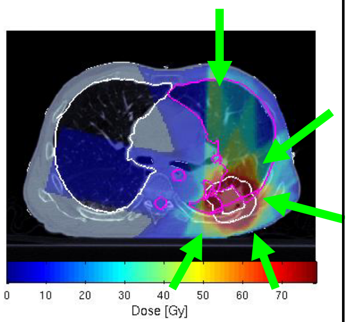
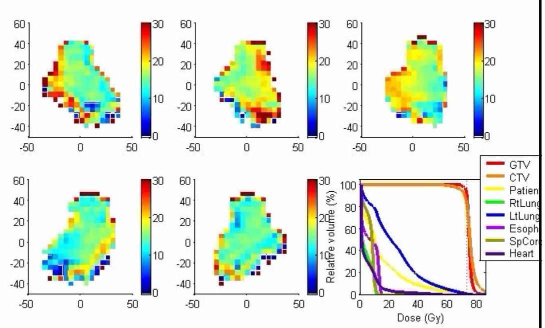
Lung example

E. Rietzel, G. Chen

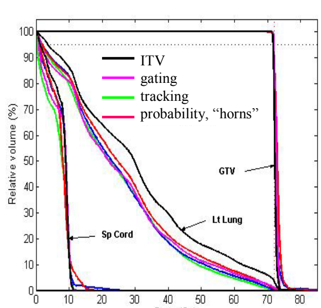




4D optimization with horns



DVH for 4 different techniques

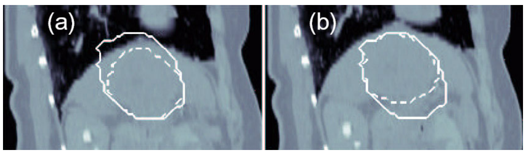


20% reduction of mean dose to left lung compared to ITV

From Trofimov et al., PMB, 2005

Liver case

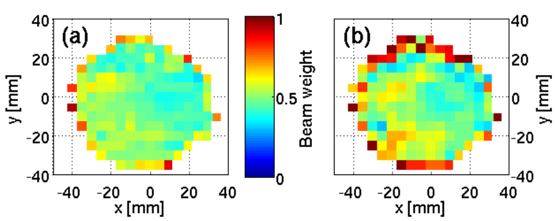
inhale exhale



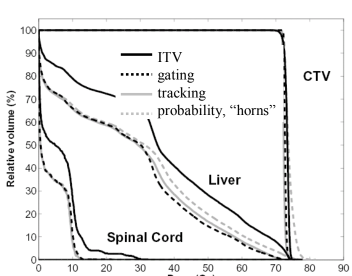
Liver case

- Intensity map for one beam

gating edge enhancement



Liver case



30% reduction of mean dose to healthy liver compared to ITV

Outline

1. Dosimetric effects of respiratory motion and random setup errors
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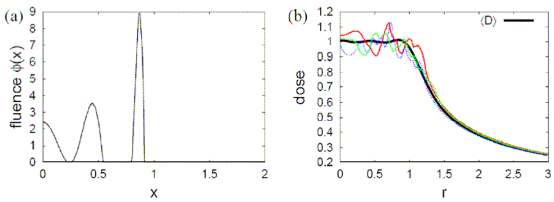
- Dose conformality of edge-enhanced IMRT with "horns" is almost as good as gating or tracking
- Is this too good to be true?

Problems with probability-based "horns"

- PDF is not precisely known
- PDF may not be fully sampled
- Horns may be difficult to deliver

PDF sampling, finite number of fractions



J. Unkelbach and U. Oelfke
"Inclusion of organ movements in IMRT treatment planning via inverse planning based on probability distributions"
Phys. Med. Biol. 49 (2004) 4005–4029

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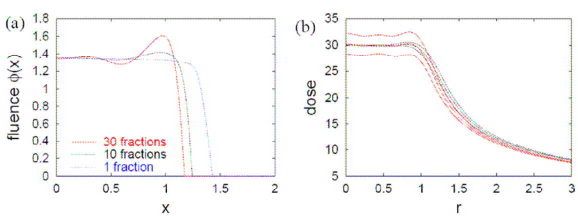
Solution: variance term in objective function



J. Unkelbach & U. Oelfke, Phys. Med. Biol. 49 (2004) 4005–4029
M. Chu, Y. Zinchenko, et al., Phys. Med. Biol. 50 (2005) 5463-5477
A. Olafsson & S. Wright, Phys. Med. Biol. 51 (2006) 5621-5642

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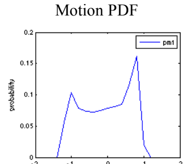
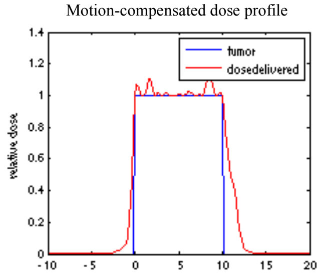
Motion compensation – ideal case

Motion PDF



Motion-compensated dose profile



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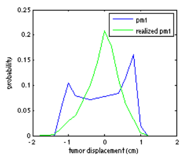
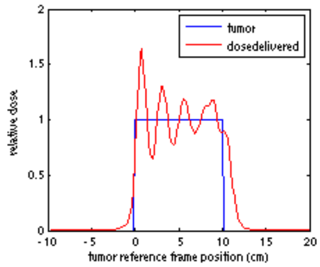
Motion compensation – what can happen

Motion PDF

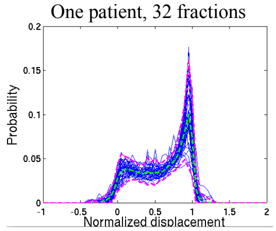


Motion-compensated dose profile

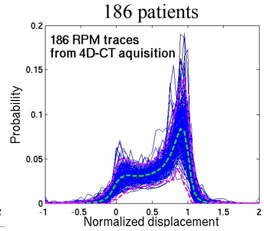


Variations of breathing PDF (from RPM data)

Inter-fractional variation
One patient, 32 fractions



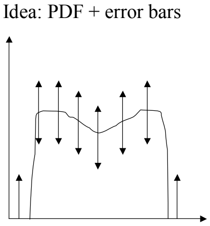
Inter-subject variations
186 patients



Uncertainty in breathing pattern

Idea: PDF + error bars

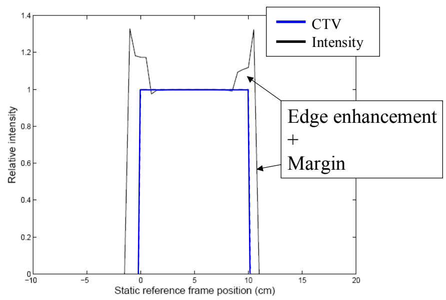
PDF



x

T. Chan et al., "A robust approach to IMRT optimization", PMB 51(2006):2567-2583

Robust edge enhanced intensity profile



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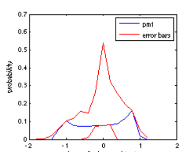
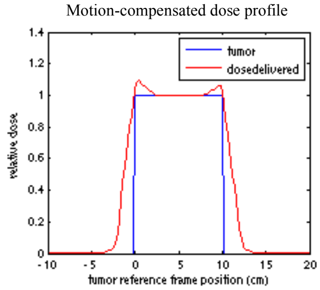
Robust motion compensation

Motion PDF



Motion-compensated dose profile



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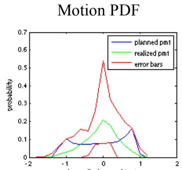
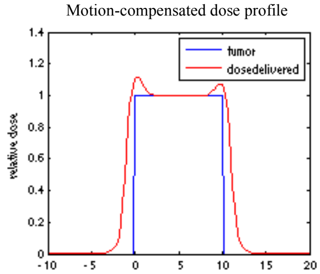
Robust motion compensation

Motion PDF



Motion-compensated dose profile



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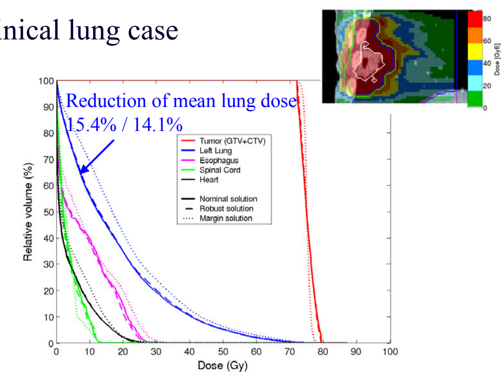
Reduction of integral dose compared to the use of conventional margins:

- “Plain” probability-based deconvolution: 15% (but target coverage not guaranteed)
- Robust solution: 9% (with guaranteed target coverage)

Vrancic et al., “Experimental …robust optimization…”, SU-FF-T-224

Clinical lung case



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Can IMRT shrink the PTV?

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Probabilistic methods and random vs. systematic errors

- So far we have addressed this problem

$$\min_x F(\langle D(x)\rangle)$$

- With systematic errors there is no dose averaging, so one can try this:

$$\min_x \langle F(D(x))\rangle = \sum_i p_i F_i(D_i(x))$$

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Probabilistic methods and random vs. systematic errors

- Lof, Lind, Brahme 1998, “An adaptive control algorithm…”, PMB 43:1605-1628
- Yang, Mageras, et al. 2005, “A new method for incorporating systematic uncertainties”, Med. Phys. 32(8):2567-2579
- Baum et al. 2006, “Robust treatment planning…coverage probabilities”, Radioth. Oncol. 78:27-35.

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Probabilistic methods for systematic errors

- No horns
- Leads to a margin-like solution without having to define the PTV

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Conclusions

- Dose blurring due to random setup errors and respiration can be partially compensated through "beam horns"
- In the case of breathing motion, this method is almost as effective as gating or tracking
- However, the method relies on very stable and reproducible breathing
- "Robustification" has recently been achieved, but leads to some loss of conformality
- It appears that robust probability-based planning can reduce high dose volume expansion needed for internal motion and random setup errors by about 50%

Thanks

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