In-Room/Beam Adaptation State of the Art

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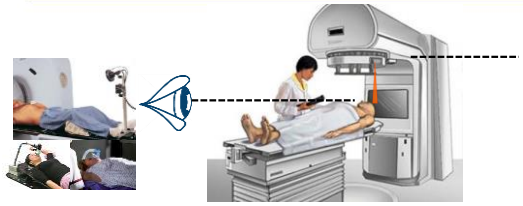
How Can We Manage Respiration?

- Compression
- Breath Hold
- Gating
- Tracking
- Couch motion

Which are beam adaptations?

- ~~Compression~~
- ~~Breath Hold~~
- Gating
- Tracking
- ~~Couch motion~~

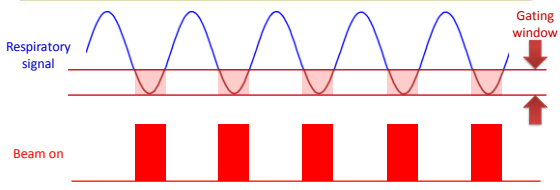
Respiratory Gating in Radiation Therapy



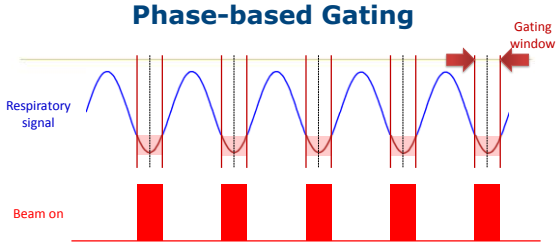
Respiratory Gating in Radiation Therapy

- Goal: reduce ITV margin volume
- Ingredients:
  - Treatment delivery device with gating capability (e.g. Varian, Elekta, Viewray, …)
  - 2x Respiratory monitoring technology (e.g. spirometry, optical …)
  - 4DCT capable simulator
  - Planning system capable of handling 4DCT
  - Time in schedule for longer Tx appointments

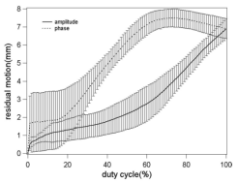
Amplitude-based Gating



Phase-based Gating



Amplitude vs. Phase Gating for 4 Lung Patients



- Could be determined for each individual patient from the 4DCT
- No commercial software solution for this task yet (idea is from 2006!)

Jiang, Steve B. "Technical aspects of image-guided respiration-gated radiation therapy." *Medical Dosimetry* 31.2 (2006): 141-151.

When Gating Does and Does not Work

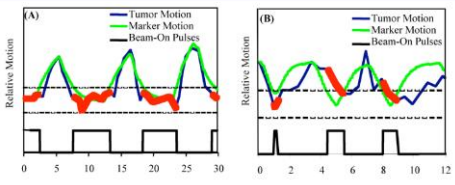


Figure 7. Comparison of external marker block motion with internal motion of the clinical target volume (CTV) for a patient with (a) no phase shift and (b) a patient with significant phase shift. The respiratory gating thresholds are set using the external marker block motion. The beam-on pulses are highlighted in red over the internal CTV position. [Reproduced from reference 227: *Int J Radiat Oncol Biol Phys*, vol 48, "Clinical experience with a commercial respiratory gating system." C. R. Ramsey, D. D. Scaperoth, and D. C. Arwood, pp. P164-165. © 2000, with permission from Elsevier.]

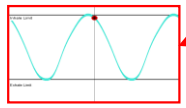
From AAPM TG-76

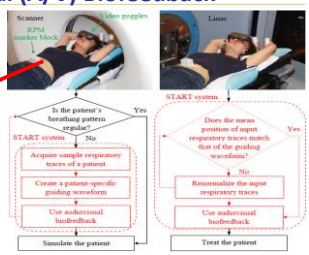
Table 4. Correlation of tumor/organ motion with the respiratory signal.

Organ/source	Respiratory signal	N patients (measurements)	Correlation range	Phase shift	Source
Diaphragm SI fluoroscopy	Abdominal displacement	5 (60)	0.82–0.95	Not observed	Vedam et al.[36]
Tumor and diaphragm, fluoroscopy	Abdominal displacement	43	0.41–0.94	Short delays observed	Ahn et al.[103]
Tumor, SI fluoroscopy	Spirometry & abdominal displacement	11 (23)	0.39–0.99	–0.65–0.5 s	Hoisak et al.[104]
Tumor, 3-D biplane radiography	Abdominal displacement	26	Respiratory waveform cycle agreed with SI and AP tumor motion	Principally within 0–0.3 s existence of >1.0 s	Tsunashima et al.[105]
Lung vessels, cine MRI	Abdominal displacement	4	SI 0.87 ± 0.23, AP 0.44 ± 0.27	--	Koch et al.[106]
Lung tumor, respiration-correlated CT	Abdominal displacement	9 where tumor SI motion > 5 mm	0.74–0.98	<1 s 4 pts <0.5 s 5 pts	Mageras et al.[100]
Lung tumor, SI respiration-correlated CT	Diaphragm position	12	0.73–0.96	<1 s 4 pts <0.5 s 5 pts	Mageras et al.[100]

3-D: three-dimensional; AP: anterior–posterior; CT: computed tomography; MRI: magnetic resonance imaging; pts: patients; s: second(s); SI: superior–inferior.

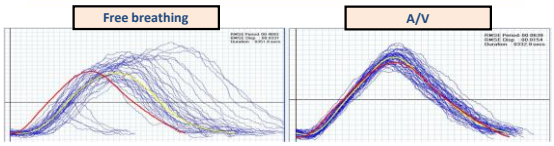
Audiovisual (A/V) Biofeedback





Venkat *et al* (PMB 2008)
Cui *et al* (JACMP 2010)

Impact of A/V Biofeedback



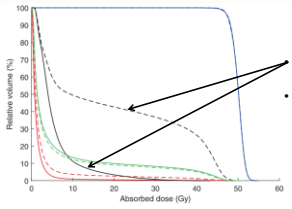
Training type	RMS var^n in displacement (cm)	RMS var^n in period (s)
Free breathing	0.56	0.78
A/V	0.21	0.20

Venkat *et al* (PMB 2008)

Motion Surrogates

- Non-Imaging:
  - Strain belts
- Non-Ionizing:
  - Point tracking (RPM)
  - Surface Imaging (Vision RT, C-Rad, …)
  - MRI (Viewray, Elekta)
- Ionizing (tracking fiducials or tumor):
  - Orthogonal kV-kV
  - Orthogonal kV-MV

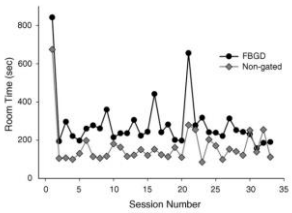
Dosimetric & health outcome impact: Breast



- Heart D_{mean}: 45% reduction (1.2 Gy)
- Excess cardiac mortality probability: 0.49 → 0.02

Edvardsson, *et al. Radiation Oncology* 10.1 (2015): 1.

Total time needed



Beam On Time
Gating takes 5.5× longer
than no gating
for a "typical" duty cycle

Fox, Timothy, et al. "Free breathing gated delivery (FBGD) of lung radiation therapy: analysis of factors affecting clinical patient throughput." *Lung Cancer* 56.1 (2007): 69-75.

Gating Pros and Cons

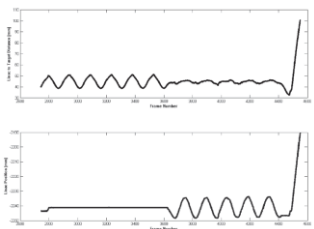
- Reduces margins ✓
- Dosimetric benefits (lower toxicity) ✓
- Patient-friendly (no compression, breath hold etc) ✓
- Increases room time by 80% and beam-on time by 5.5×

No significant impact to outcomes

CyberKnife Synchrony: Adapting the Linac

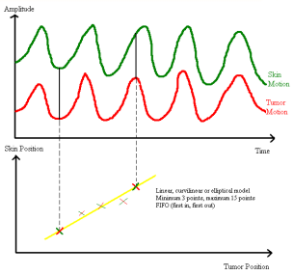
The Crux: Skin-Tumor Correlation

- **Not** an issue of respiratory pattern regularity
  (Wong et al, TCRT December 2007)
- Suspect phase shift between surface and lung motion
- 4D-CT not necessarily a good predictor of motion at time of treatment
  (Minn et al, *Am J Clin Oncol* 2009)
- Sometimes, a good correlation model is hard to establish

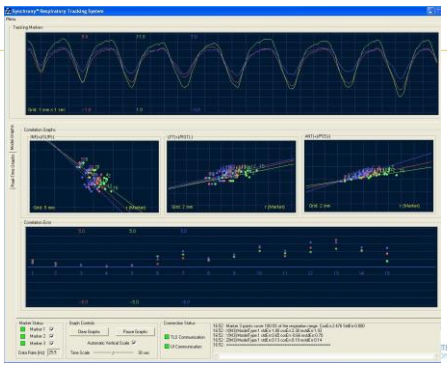


Principle of Hybrid Imaging for Tracking

- Continuous EXTERNAL imaging for respiratory motion
- Internal imaging at intervals
- Tumor and skin markers get correlated
- Skin motion predicts tumor motion
- Delivery device (robot, MLC) follows the tumor motion



Synchrony GUI



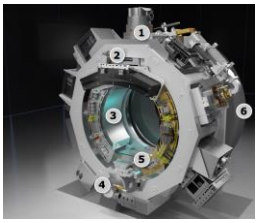
RefleXion:
Biological Guidance & Beam Adaptation

The RefleXion machine requires 510(k) clearance and is not yet commercially available.

RefleXion Machine

5 major subsystems on a wide-bore

1. 6MV LINAC
2. 64-leaf binary MLC
3. Two 90º arcs of state-of-the-art PET detectors
4. 16-slice kV fan-beam CT
5. MV X-ray detector
6. Gantry

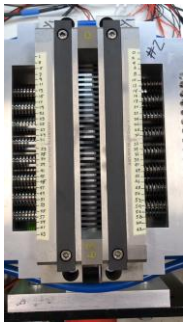


RefleXion Machine

Closed-ring gantry rotates at **60rpm**

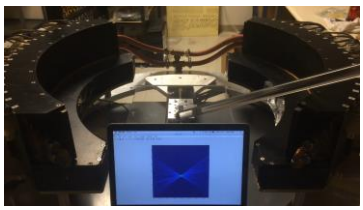
Binary MLC

- Novel pneumatic-spring-resonance design
- Leaves transition at 100 times/second allowing synchronization with LINAC pulsing and true digital delivery
- Beamlit profile 6.2mm x 10 or 20mm at isocenter
- Full field 40cm x 2cm at isocenter

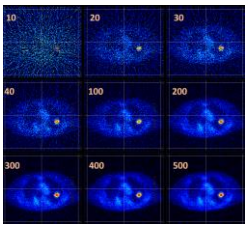


Integrated PET Detectors

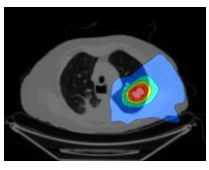
- Dual 90º arcs of PET detectors integrated into the treatment plane
- Collects LOR data that generates instantaneous line-of-sight to the tumors



BgRT principle: Just as a PET image can build up over time, BgRT builds the radiation dose over time using a real-time stream of PET emissions



PET emissions collected over time (each frame is 0.5 sec)



Radiation dose delivered

Conclusion

- Beam adaptation technologies are a solid tool in our technology toolbox
- New tumor tracking methods to increase accuracy
- Greater selection of delivery modalities
  - C-Arm linacs
  - Tomo
  - CK
  - Viewray
  - RefleXion
- Paul Keall will tell us where the future will lead us