APPLICATION OF OPTICAL AND INFRARED IMAGING SYSTEMS FOR RESPIRATORY MOTION MANAGEMENT

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AAPM 63RD ANNUAL MEETING

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DISCLOSURE

- I have no conflicts

- Prior motion management experience:
  - Varian RPM™ for 4DCT and DIBH CT simulation
  - Varian RPM™ and Respiratory Gating for treatment delivery with respiratory gating and voluntary inspiratory breath hold
  - VisionRT AlignRT® for treatment delivery with voluntary inspiratory breath hold

- Relevant prior treatment system experience:
  - Varian C-series and TrueBeam® accelerators

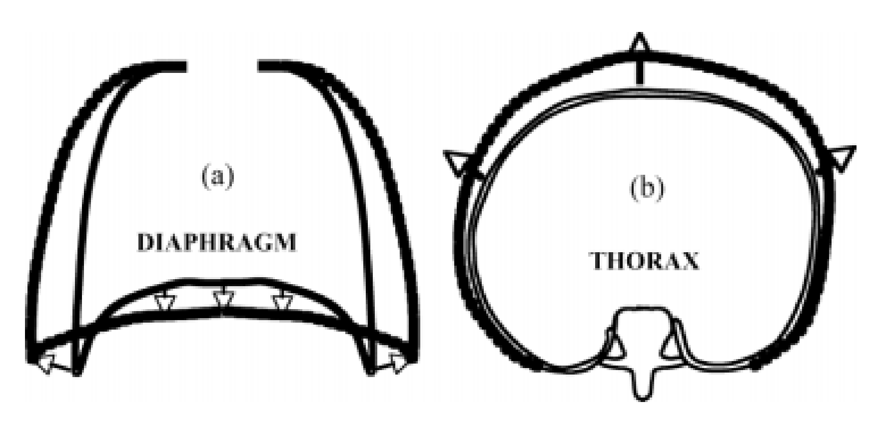
- References by name to commercially available products are for informational purposes only and do not constitute an endorsement by the speaker or the AAPM

OBJECTIVES

- Review methods to account for respiratory motion
- Review optical and infrared imaging technologies
- Discuss procedural considerations for the application of select imaging technologies for respiratory motion management

RESPIRATION

- Facilitates exchange of O_2 and CO_2 between blood and air
- Inspiration
  - Diaphragm contracts, moving inferiorly and anteriorly
  - Intercostal muscles contract, pulling ribs superiorly and anteriorly
- Expiration
  - Passive process
  - Diaphragm and intercostal muscles relax to resting position
- Hysteresis
  - Lung volume at given transpulmonary pressure is less during inhalation than during exhalation



West, JB. *Respiratory Physiology: The Essentials*. Baltimore, MD: Waverly Press, Inc, 1974.

RESPIRATORY MOTION

- 10-25% change in lung volume during respiration[1]
- Approximately 3x-4x change in lung volume at DIBH[2]
- Chest vs abdominal breathing
  - Abdominal breathing when expansion of abdominal circumference exceeds that of the chest by e.g., 10 mm[3]

1. Weiss, E, Vorwerk, H, Richter, S, and Hess, CF (2003). "Interfractional and intrafractional accuracy during radiotherapy of gynecologic carcinomas: A comprehensive evaluation using the ExacTrac system." *Int J Radiat Oncol Biol Phys* 56(1): 69-79.

2. Peters, RM. *The Mechanical Basis of Respiration*. Boston: Little, Brown, and Co., 1969.

3. Davies, SC, Hill, AL, Holmes, RB, Halliwell, M, and Jackson, PC (1994). "Ultrasound quantitation of respiratory organ motion in the upper abdomen." Br J Radiol 67(803):1096-1102.

ORGAN MOTION DURING RESPIRATION

Table 2. Lung tumor–motion data. The mean range of motion and the (minimum–maximum) ranges in millimeters for each cohort of subjects. The motion is in three dimensions (SI, AP, LR).

Observer	Direction		
	SI	AP	LR
Barnes[85]: Lower lobe	18.5 (9–32)	--	--
Middle, upper lobe	7.5 (2–11)	--	--
Chen et al.[84]	(0–50)	--	--
Ekberg et al.[26]	3.9 (0–12)	2.4 (0–5)	2.4 (0–5)
Engelsman et al.[28]:			
Middle/upper lobe	(2–6)	--	--
Lower lobe	(2–9)	--	--
Erridge et al.[101]	12.5 (6–34)	9.4 (5–22)	7.3 (3–12)
Ross[76]: Upper lobe	--	1 (0–5)	1 (0–3)
Middle lobe	--	0	9 (0–16)
Lower lobe	--	1 (0–4)	10.5 (0–13)
Grills et al.[91]	(2–30)	(0–10)	(0–6)
Hanley et al.[77]	12 (1–20)	5 (0–13)	1 (0–1)
Murphy et al.[87]	7 (2–15)	--	--
Plathow[220]: Lower lobe	9.5 (4.5–16.4)	6.1 (2.5–9.8)	6.0 (2.9–9.8)
Middle lobe	7.2 (4.3–10.2)	4.3 (1.9–7.5)	4.3 (1.5–7.1)
Upper lobe	4.3 (2.6–7.1)	2.8 (1.2–5.1)	3.4 (1.3–5.3)
Seppenwoolde et al.[67]	5.8 (0–25)	2.5 (0–8)	1.5 (0–3)
Shimizu et al.[52]	--	6.4 (2–24)	--
Sixel et al.[92]	(0–13)	(0–5)	(0–4)
Stevens et al.[66]	4.5 (0–22)	--	--

AP: anterior–posterior; LR: left–right; SI: superior–inferior.

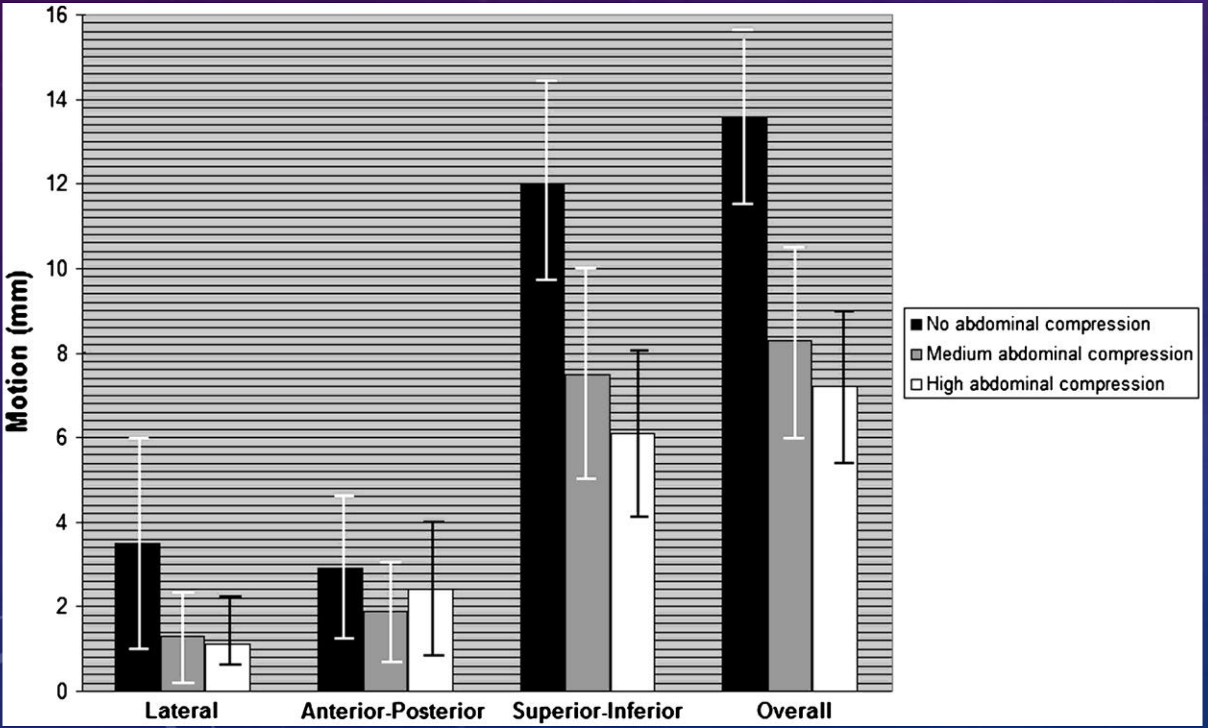
Table 3. Abdominal motion data. The mean range of motion and the (minimum–maximum) ranges in millimeters for each site and each cohort of subjects. The motion is in the superior–inferior (SI) direction.

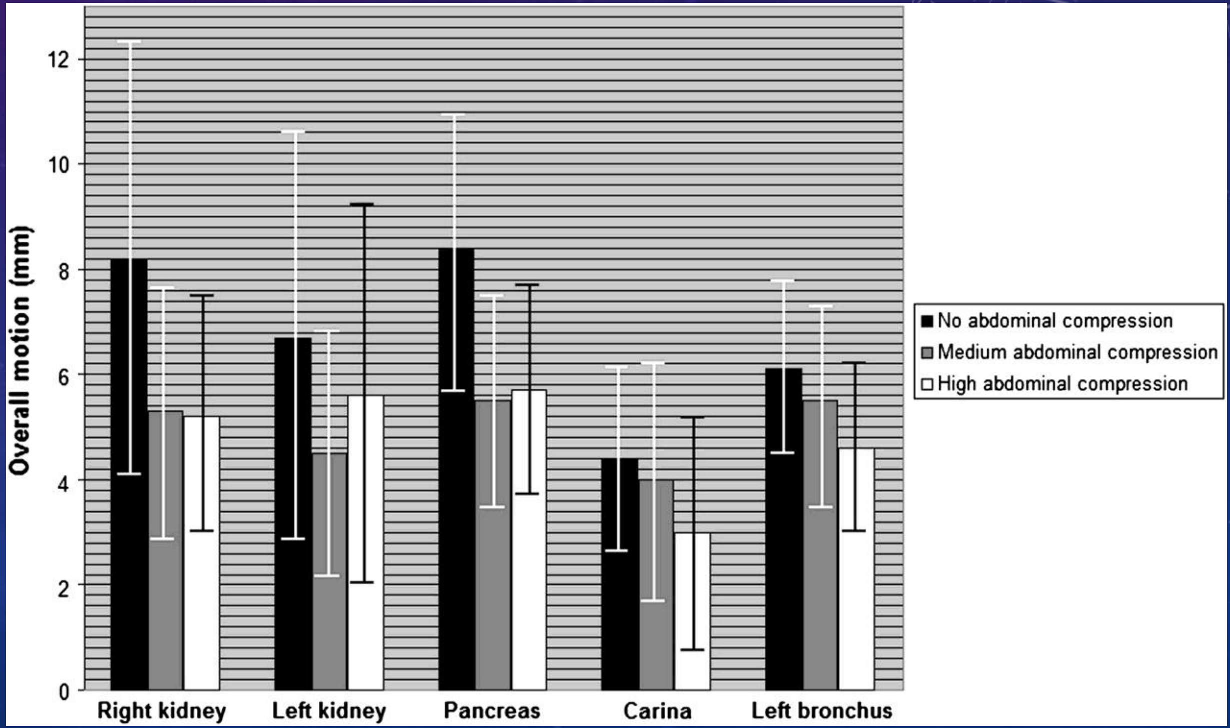
Site	Observer	Breathing mode	
		Shallow	Deep
Pancreas	Suramo et al.[74]	20 (10–30)	43 (20–80)
	Bryan et al.[75]	20 (0–35)	--
Liver	Weiss et al.[89]	13 +/– 5	--
	Harauz et al.[90]	14	--
	Suramo et al.[74]	25 (10–40)	55 (30–80)
	Davies et al.[68]	10 (5–17)	37 (21–57)
Kidney	Suramo et al.[74]	19 (10–40)	40 (20–70)
	Davies et al.[68]	11 (5–16)	--
Diaphragm	Wade[80]	17	101
	Korin et al.[79]	13	39
	Davies et al.[68]	12 (7–28)	43 (25–57)
	Weiss et al.[89]	13 +/– 5	--
	Giraud et al.[78]	--	35 (3–95)
	Ford et al.[86]	20 (13–31)	--

Tables reproduced from Keall PJ, et al (2006). "The management of respiratory motion in radiation oncology: Report of AAPM Task Group 76." *Med Phys* 33, 3874-3900.

RESPIRATORY MOTION MANAGEMENT METHODS: MOTION ENCOMPASSING

- Slow CT
- Inhale/Exhale CT
- 4DCT
- Compression to restrict motion





Heinzerling JH, Anderson JF, Papiez L, et al (2008). "Four-dimensional computed tomography scan analysis of tumor and organ motion at varying levels of abdominal compression during stereotactic treatment of lung and liver." *Int J Radiat Oncol Biol Phys* 70(5), 1571-1578.

4DCT

- Oversampled CT dataset with full 3D data at multiple respiratory phases
- Scan parameters dependent on patient respiratory pattern
- Identify free-breathing motion envelope of gross disease (ITV)

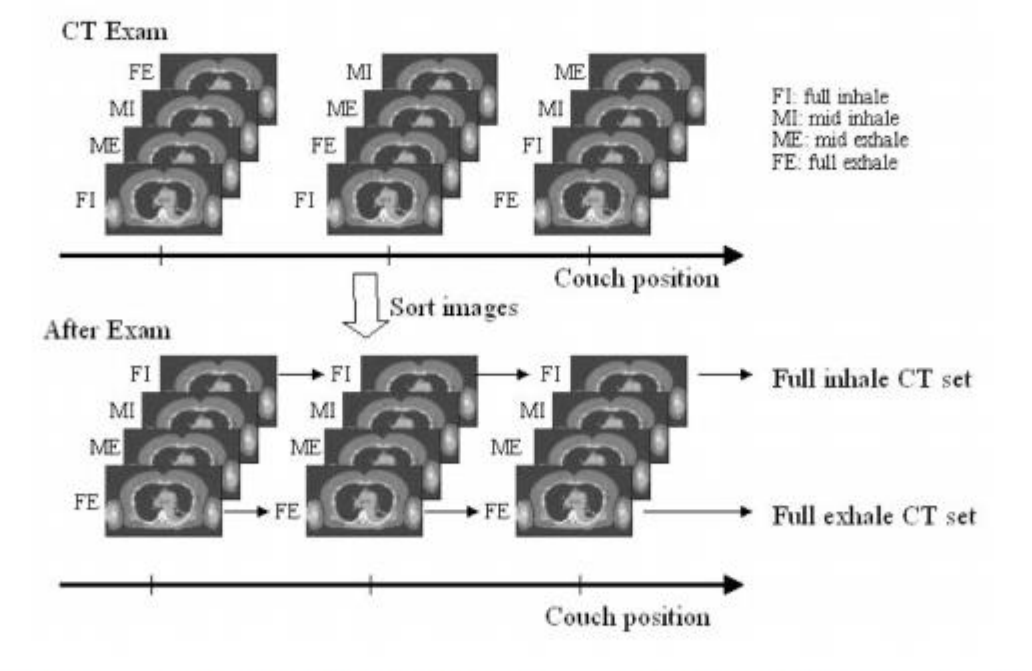


Figure 6. A schematic of the 4-D CT process using ciné acquisition. Images are acquired at each couch position for many respiratory phases. The image acquisition is time synchronized with the respiratory signal acquisition, allowing all images of a particular stage of the respiratory cycle to be concatenated into a complete 3-D CT image. All of the phases put together make up a 4-D CT data set. [Figure courtesy Dr. Sonja Dieterich.]

Keall PJ, et al (2006). "The management of respiratory motion in radiation oncology: Report of AAPM Task Group 76." *Med Phys* 33, 3874-3900.

RESPIRATORY MOTION MANAGEMENT METHODS: RESPIRATORY GATING

- Delivery of radiation during imaging and treatment synchronized with patient's breathing

- Planar radiographic imaging for prostate fiducial tracking, Gig Mageras

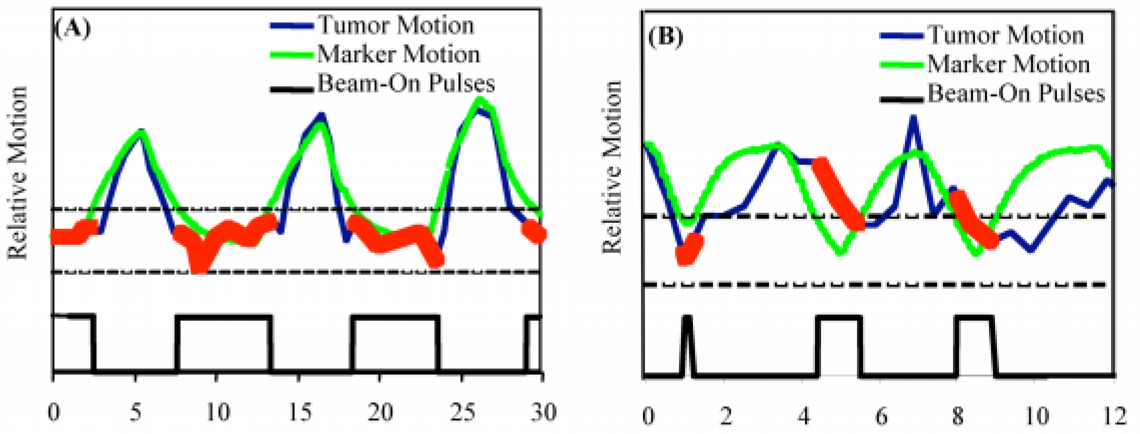


Figure 7. Comparison of external marker block motion with internal motion of the clinical target volume (CTV) for a patient with (a) no phase shift and (b) a patient with significant phase shift. The respiratory gating thresholds are set using the external marker block motion. The beam-on pulses are 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.]

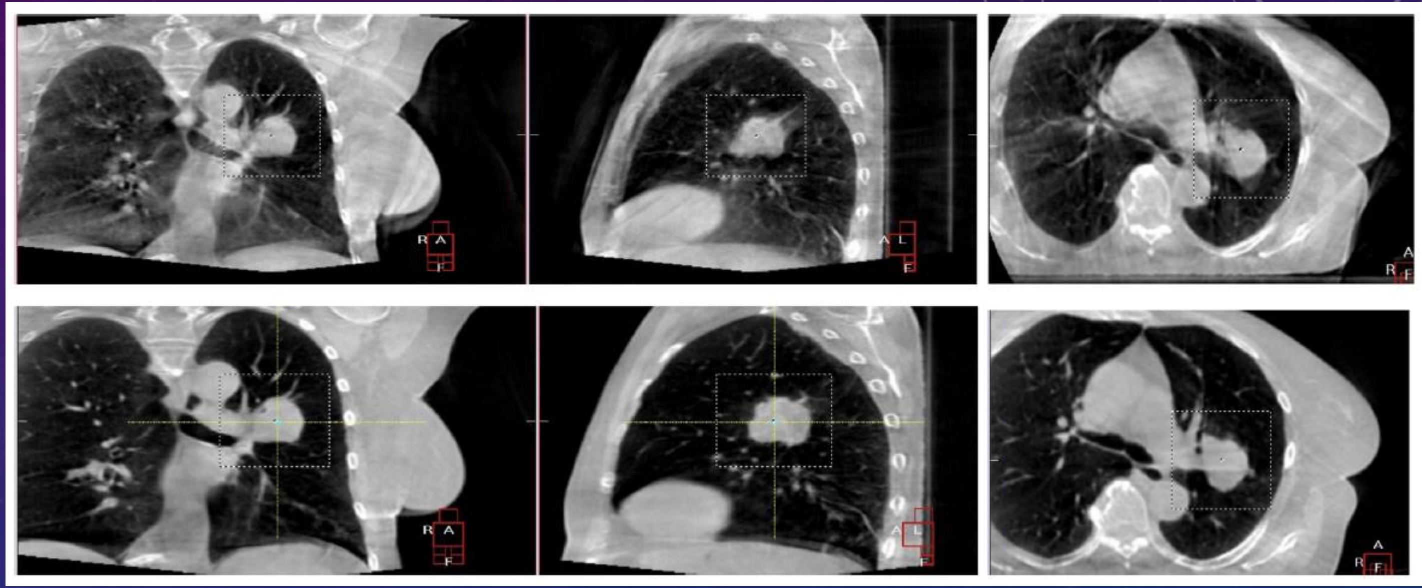
Keall PJ, et al (2006). "The management of respiratory motion in radiation oncology: Report of AAPM Task Group 76." *Med Phys* 33, 3874-3900.

RESPIRATORY MOTION MANAGEMENT METHODS: BREATH HOLD

- Compared with free breathing technique for left breast RT, DIBH[1]
  - ↓ heart V20, V40 and Dmean
  - ↓ lung V20
  - ↑ target coverage

- Compared with free breathing technique for lung SBRT, DIBH[2]
  - ↓ lung V20, Dmean
  - ↓ PTV volume

- Compared with free breathing technique for RT of advanced lung disease, DIBH was clinically correlated with[3]
  - ↓ acute pulmonary toxicity
  - ↓ late pulmonary, cardiac, and esophageal toxicity



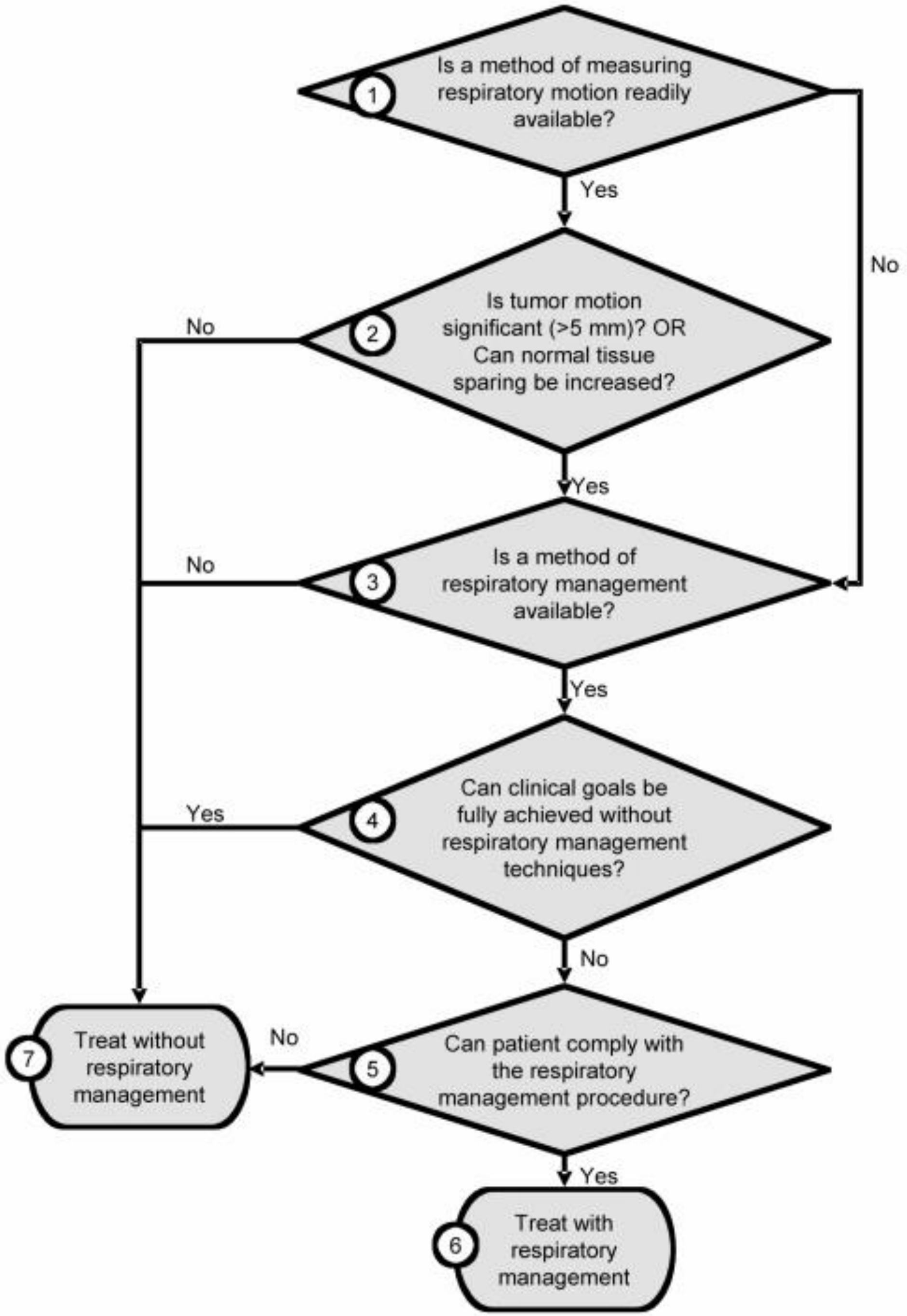
1. Nissen HD and Appelt AL (2013). "Improved heart, lung and target dose with deep inspiration breath hold in a large clinical series of breast cancer patients." *Radiother Oncol* 106, 28-32.
2. Scotti V, Marrazzo L, Saieva C et al (2014). "Impact of a breathing-control system on target margins and normal-tissue sparing in the treatment of lung cancer: experience at the radiotherapy unit of Florence University." *Radiol Med* 119, 13-19.
3. Giraud P, Morvan E, Claude L et al (2011). "Respiratory gating techniques for optimization of lung cancer radiotherapy." *J Thoracic Oncol* 6:12, 2058-2068.
4. Boda-Heggemann J, Knopf A-C, Simeonova-Chergou A et al (2016). "Deep inspiration breath hold-based radiation therapy: A clinical review." *Int J Radiat Oncol Biol Phys* 94:3, 478-492.

RESPIRATORY MOTION MANAGEMENT METHODS: REAL-TIME TUMOR TRACKING

- Field-defining aperture tracks tumor motion during treatment delivery
- MLC tracking for motion management, Emma Colvill
- Motion tracking with MLC and jaw during tomotherapy delivery, X. Allen Li

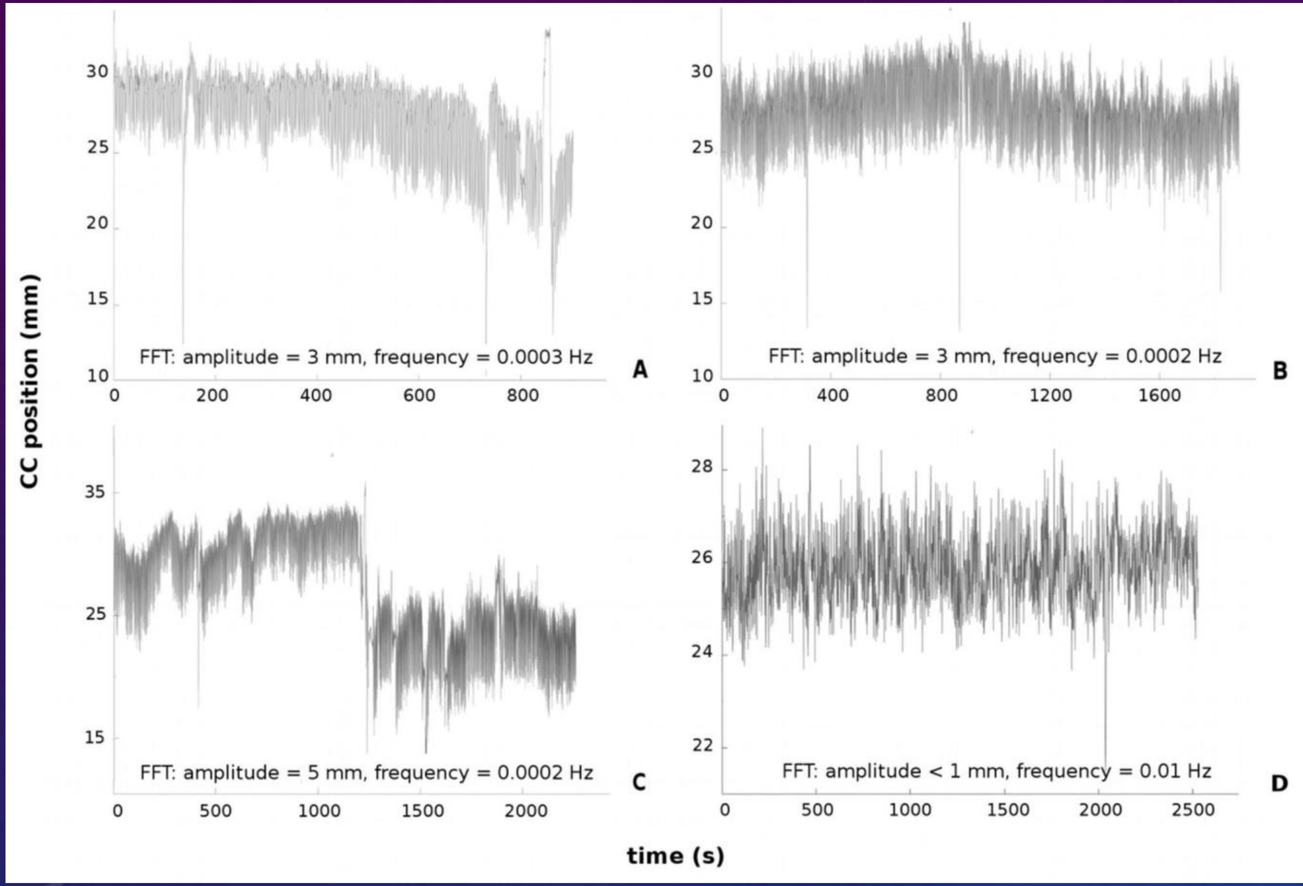
TG-76 RECOMMENDATIONS

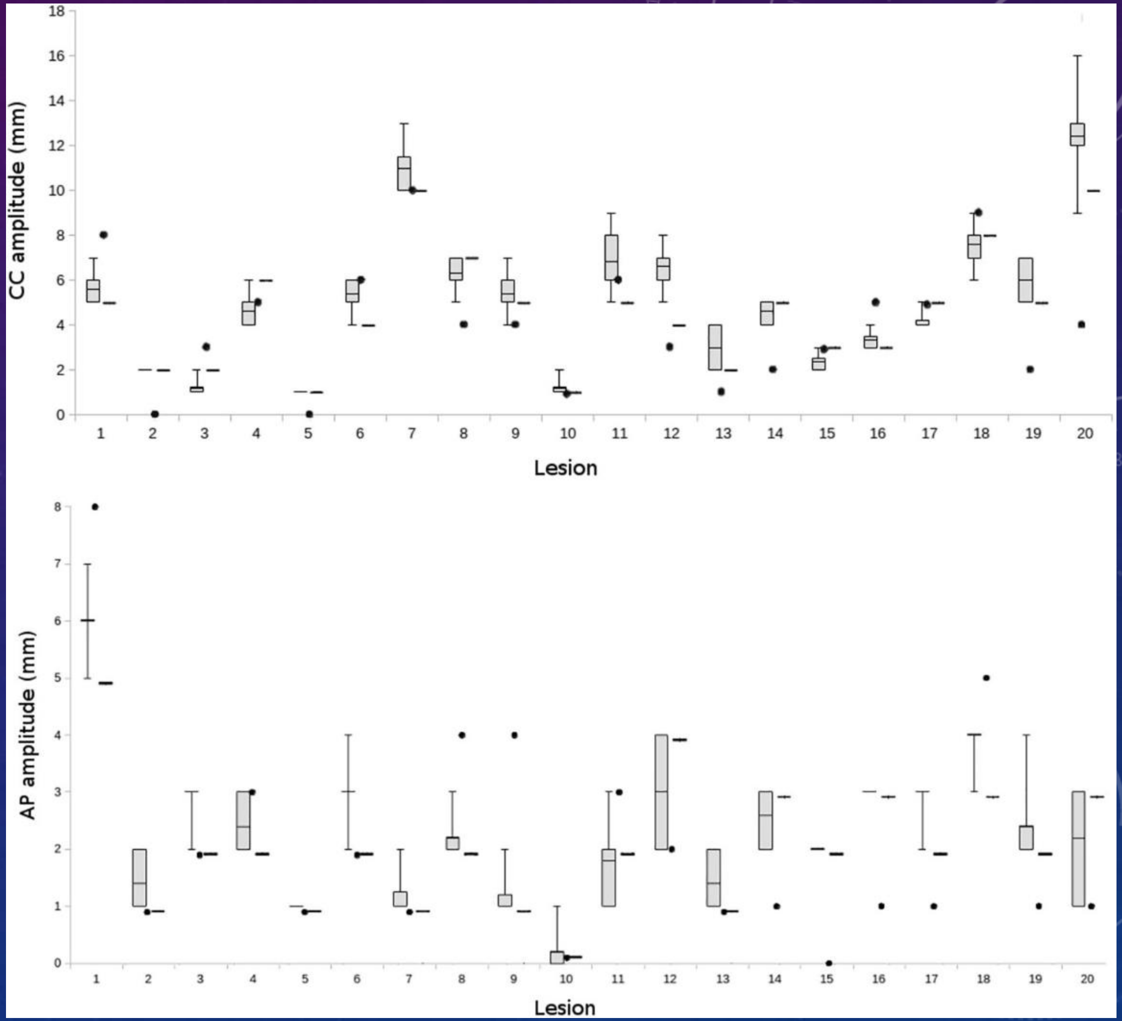
- Respiratory motion management should be used:
  - When motion exceeds 5 mm due to potential for imaging artifacts
  - When significant normal tissue sparing can be gained
- Consider possible future treatment when evaluating reduction in normal tissue toxicity
- PTV margins should consider:
  - Motion-induced imaging artifacts
  - Variability in respiratory pattern, breath-hold position, and residual motion
  - Uncertainty in relationship between tumor and surrogate position



Keall PJ, et al (2006). "The management of respiratory motion in radiation oncology: Report of AAPM Task Group 76." *Med Phys* 33, 3874-3900.

CHANGES IN RESPIRATORY PATTERN





Cusumano D, Dhont J, Boldrini L, et al (2018). “Predicting tumour motion during the whole radiotherapy treatment: a systematic approach for thoracic and abdominal lesions based on real time MR.” *Radiother Oncol* 129:3, 456-462.

OPTICAL AND INFRARED IMAGING TECHNOLOGIES

Infrared	Optical
Varian RPM™	VisionRT AlignRT®
Varian Respiratory Gating/RGSC	C-RAD Catalyst™
BrainLab ExacTrac®	Varian Identify™
Accuray Synchrony®	BrainLab ExacTrac® Dynamic

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.[70]
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.

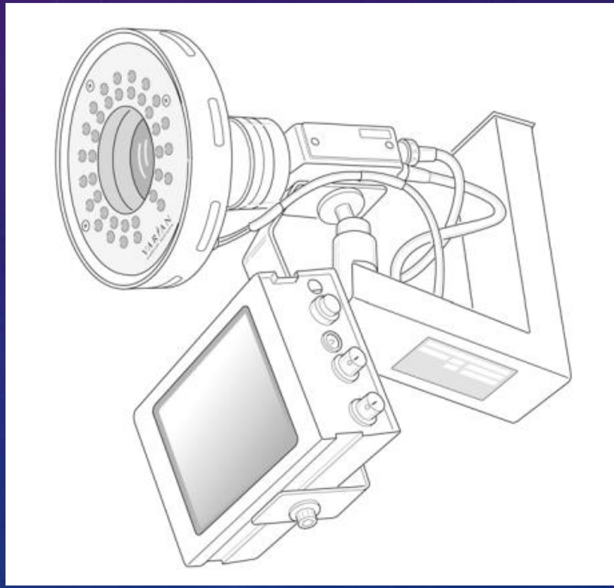
Keall PJ, et al (2006). "The management of respiratory motion in radiation oncology: Report of AAPM Task Group 76." *Med Phys* 33, 3874-3900.

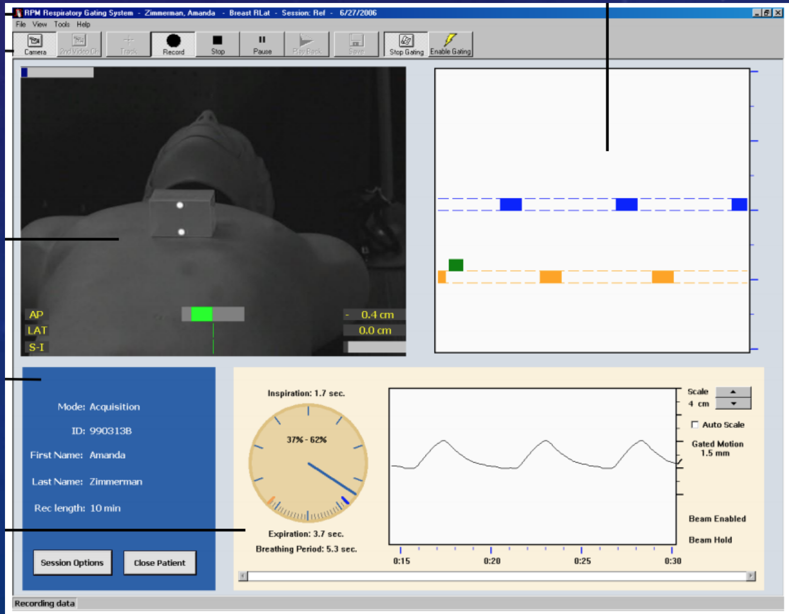
INFRARED TECHNOLOGIES

- Reflectors placed on patient surface tracked during treatment
- Fast refresh rate
- Submillimeter spatial accuracy
- Reflectors must be visible throughout treatment
  - Verify visibility for treatment with couch kicks
- Motion tracking only available at location(s) of reflector(s)

RPM™/RESPIRATORY GATING

- Marker block
- Camera
  - Monitors respiration-induced motion of block
  - 30 Hz frame rate
- Control software
  - Extracts motion data from images of marker block
  - Distance calibration based on apparent separation between reflectors
  - Threshold motion amplitude to initiate tracking
  - Defines reference (i.e., baseline) position
  - Beam control





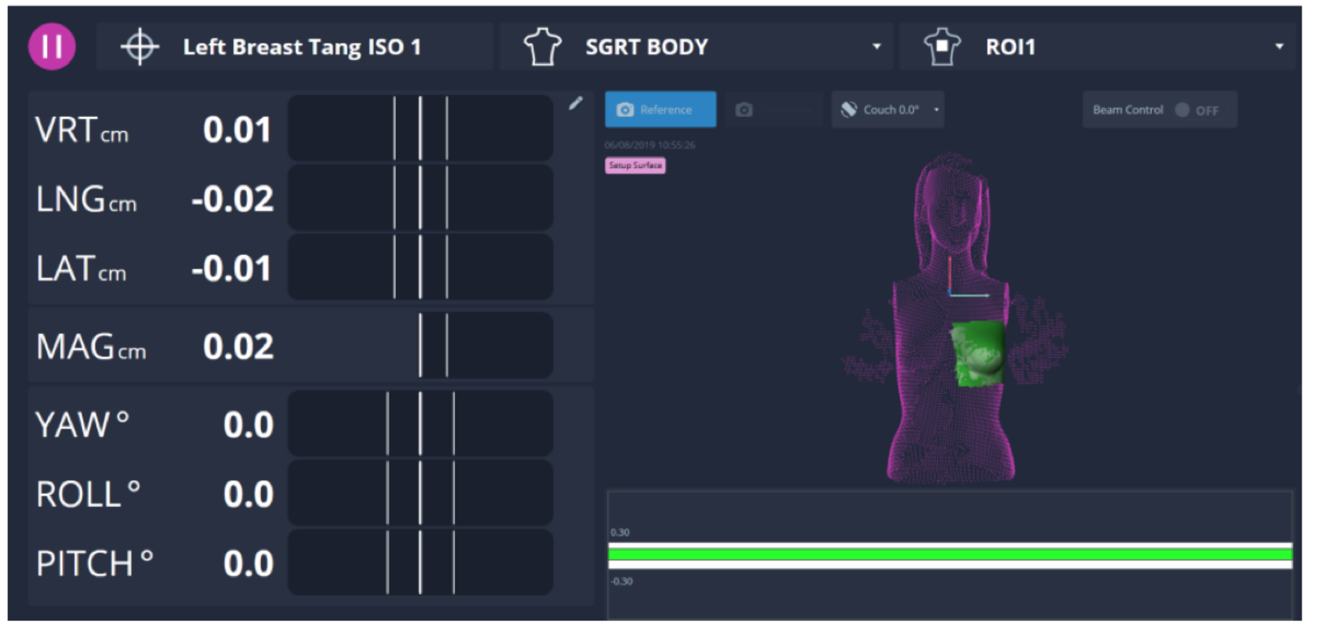
Images courtesy Varian

OPTICAL TECHNOLOGIES

- Structured light pattern or scanned laser light projected onto patient
- Cameras image reflected pattern
- Image of patient surface is registered to reference surface, and required transformations are reported
- ~5 fps
- Imaged surface must be sufficiently reflective
- Multicamera installations may have visibility impacted by treatment head or on-board imaging arms

ALIGNRT® SYSTEM COMPONENTS

- Cameras
  - Three pods, each with two stereoscopic cameras and projector
- Control software
  - Surface capture
  - ROI definition
  - Tolerance setting
  - Beam control



Images courtesy VisionRT

TG-76 QUALITY PRACTICE RECOMMENDATIONS

- Coaching and evaluation of patients (e.g., breathing regularity, breath-hold duration and consistency)
- Sanitization of devices that contact patients
- Backup planning scan at simulation if patient may not comply with motion management techniques
- Allow patient to practice breathing technique at start of treatment
- Daily imaging verification of correlation between surrogate and target to start treatment
  - No less than weekly imaging over course of treatment

Keall PJ, et al (2006). "The management of respiratory motion in radiation oncology: Report of AAPM Task Group 76." *Med Phys* 33, 3874-3900.

4DCT SIMULATION WITH OPTICAL/IR IMAGING SYSTEM

- Displacement of patient surface used as surrogate for respiratory phase
- Installation of camera on couch allows camera to move with patient
  - Mounting camera to room wall or ceiling requires separation of couch motion from respiratory motion
- Be mindful of superposition of other motion patterns (e.g., cardiac motion)
- Provide patient instruction and evaluate breathing
  - Coaching can be used to improve regularity of breathing, but must be consistent with treatment

AUDIOVISUAL COACHING

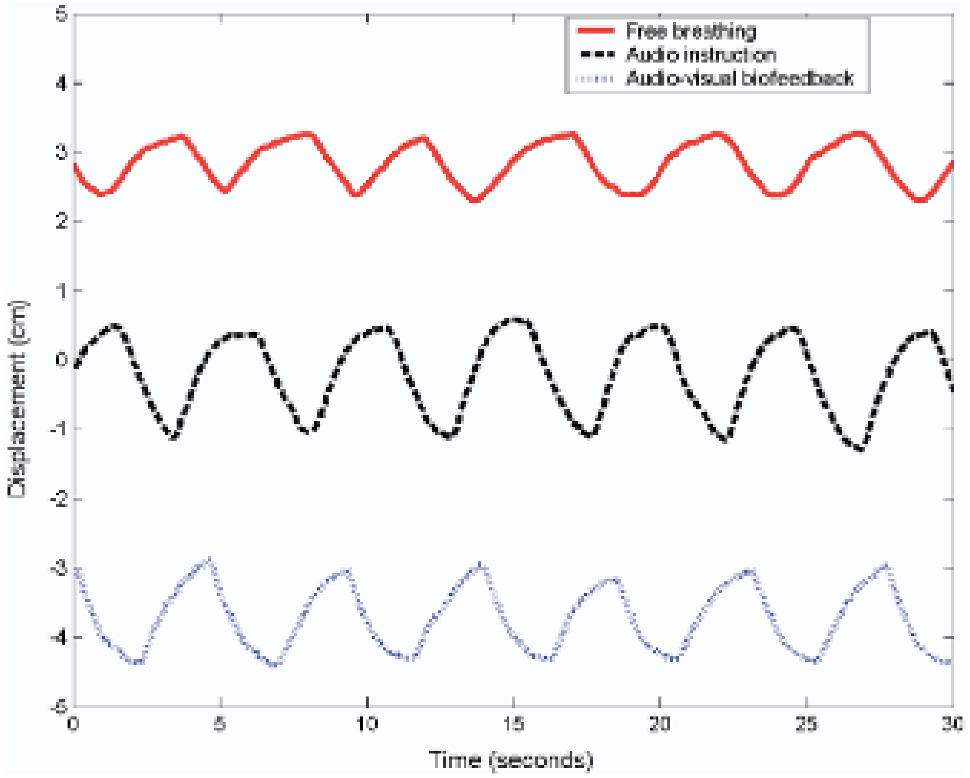


Fig. 3. Example of a respiratory trace for free breathing, audio instruction, and audio-visual biofeedback. A constant y-offset value has been added to the displacement values of each these traces to improve the clarity of the figure.

George R, Chung TD, Vedam SS, Ramakrishnan V, Mohan R, Weiss E, Keall PJ (2006). "Audio-visual biofeedback for respiratory-gated radiotherapy: Impact of audio instruction and audio-visual biofeedback on respiratory-gated radiotherapy." *Int J Radiat Oncol Biol Phys* 65(3), 924-933.

RESPIRATORY GATED TREATMENT WITH IR SYSTEM

- Set gating window to limit residual motion as determined from 4DCT
- Reproducible marker block position to limit changes to phase shift or correlation between respiratory signal and position of internal anatomy
- Daily imaging to verify correlation between respiratory signal and position of internal anatomy
  - 4DCBCT
  - Gated CBCT
  - Fluoroscopy
- Verify and monitor stability of exhale breathing position

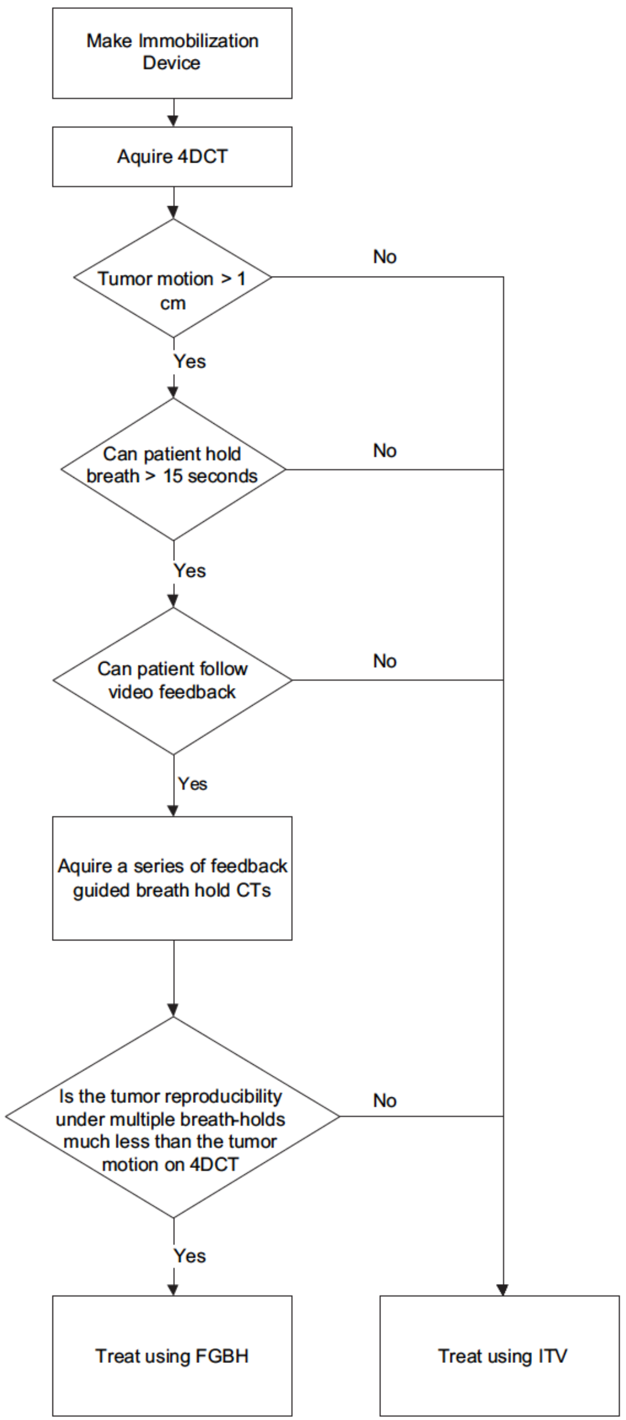
DIBH SIMULATION

- Educate patient and evaluate compliance with DIBH technique
- Position IR marker box to maximize AP motion
- IR marker box should be level with couch surface for accurate displacement measurement
  - May require adjustment of box position or patient-specific shim
- Box position should be marked for reproduction during treatment
  - Additionally document in patient's chart

Keall PJ, et al (2006). "The management of respiratory motion in radiation oncology: Report of AAPM Task Group 76." *Med Phys* 33, 3874-3900.

DIBH SIMULATION

- Evaluate patient compliance
  - Breath-hold duration and stability
  - Reproducibility of breath-hold amplitude
  - Stability of exhale
- Evaluate anatomical reproducibility over repeated breath holds for margin determination
  - Use variable breath-hold delay to evaluate motion during breath hold
  - Select mid-position scan for treatment planning



Peng Y, et al (2011). “Implementation of feedback-guided voluntary breath-hold gating for cone beam CT-based stereotactic body radiotherapy.” *Int J Radiat Oncol Biol Phys* 80(3), 909-917.

BREATH-HOLD TREATMENT

Infrared

Be mindful of monitored position if marker block differs from simulation

Verify stability of exhale breathing position

Optical

Use ROI robust to setup uncertainty and camera blockage

Verify alignment of patient to free-breathing and DIBH surfaces

- Coach patients to encourage chest breathing
- Daily imaging to verify correlation of surrogate and internal anatomy

QA: TG-142

- Monthly
  - Output constancy with gated delivery
  - Beam control
  - Gating interlock
  - Functionality of in-room system
- Annual
  - Energy constancy with gated delivery
  - Temporal accuracy
  - Calibration of surrogate
  - Interlock testing

Klein EE, et al (2009). “Task Group 142 report: Quality assurance of medical accelerators.” *Med Phys* 36(9), 4197-4212.

QA: TG-147

TABLE II. Recommended QA and frequency.

Frequency	Test	Method	Accuracy
Daily	Safety	Check interlocks and clear field of view for all mounted cameras	Pass
	Static localization	Daily QA phantom positioned at isocenter and can track movement to isocenter from offset	2 mm
Monthly (in addition to daily tests):	Safety	Machine interface: Gating termination, couch motion communication	Functional
	Static localization	Localization test based on radiographic analysis (i.e., hidden target)	2 mm/(1 mm SRS/SBRT)
	Dynamic localization	Motion table or manual couch motion of monthly phantom by known distances	2 mm or less if manufacturer spec.
Annually (in addition to all monthly tests)	Safety	Test/reset buttons, backup power supply, and emergency-off switches	Pass
		System mounting brackets (all cameras are secure)	Pass
	Integrity	Check camera settings if available	Unchanged from previous
	Stability (drift/reproducibility)	Drift Measurement (over at least 1 hour)	<2 mm over one hour
		Reproducibility (localization repeated several times)	<1 mm after stabilizing
	Static localization (extensive)	Full end-to-end tests (with data transfer check of localization accuracy, etc.)	<2 mm of isocenter (1mm SRS/SBRT)
		Translation and rotation auto correct over a clinical range of motion	<2 mm of isocenter
	Dynamic (gating system)	Using a motion phantom / check of gating system radiation dosimetry accuracy.	<2% (per TG142)
	Data transfer	From all systems in use	Functional
Commissioning: (in addition to monthly and annual tests)	Safety (integration)	Communications with EMRs/other systems	Functional
		Integration with Linac (radiation and interference)	<1 mm change in localization <1% change in expected dose
		Field of view	Per system spec.
	Stability (drift/reproducibility)	Drift measurement (over at least 1 hour)	Establish warm-up time
		Reproducibility (localization repeated several times)	<1 mm after stabilizing
	Dynamic localization	Latency test and update rates	Per spec.

Willoughby T, et al (2012). "Quality assurance for nonradiographic radiotherapy localization and positioning systems: Report of Task Group 147." *Med Phys* 39(4), 1728-1747.

SUMMARY

- Respiratory motion impacts positioning of target and critical volumes in the thorax and abdomen
- Amplitude of motion and critical organ sparing should be considered when evaluating use of motion management
- IR and optical system monitoring of patient surface can be used as surrogate for position of volumes moving with respiration

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