Four-dimensional computed tomography (4DCT)

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Disclosure

Some of the authors' work cited in this presentation was supported by a Sponsored Research Agreement with Philips Medical Systems

Questions?

- Please text questions to (713) 906-7259

Educational Objectives

At the conclusion of this presentation, the participant will be able to answer the following questions:

1. What do we mean by 4DCT?
2. Why would we need 4DCT?
3. How do we obtain 4DCT images?
4. How do we use 4DCT images?
5. How can we improve the quality of 4DCT images?

What do we mean by 4DCT?

- 4DCT is the acquisition of dynamic anatomic information via CT in which we use periodic motion to replace the time dimension with the phase dimension.

Time scales

- Typical respiratory cycle - ~4-5 sec
- Typical CT acquisition time - ~5 sec (multislice helical CT)
- How can we capture sub-respiratory cycle information given that the typical CT acquisition time is approximately equal to the respiratory cycle time?

Resolution of problem

- Take advantage of periodic nature of respiratory cycle
- Acquire small amount of information during one cycle, more information the next cycle, more information the next cycle …
- Combine information from multiple respiratory cycles
- The 4^{th} dimension becomes phase, rather than time

Why would we need 4DCT?

- 20^{th} century radiation treatment planning
  - Population-based radiation therapy
  - Account for respiratory motion by adding uniform, isotropic internal margin (IM) to clinical target volume (CTV) to generate internal target volume (ITV)

Why would we need 4DCT?

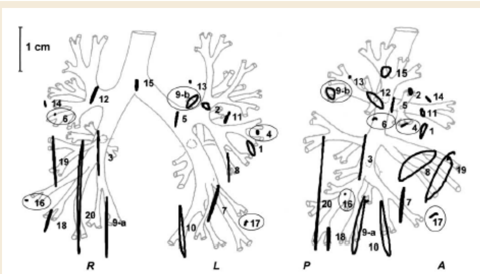
- Assumptions:
  - Lung tumors move the same amount, irrespective of patient, location, size, etc.
  - Lung tumor margins expand and contract isotropically

Why would we need 4DCT?

- Assumptions:
  - Lung tumors move the same amount, irrespective of patient, location, size, etc.
  - Lung tumor margins expand and contract isotropically
- Neither of these assumptions is true!

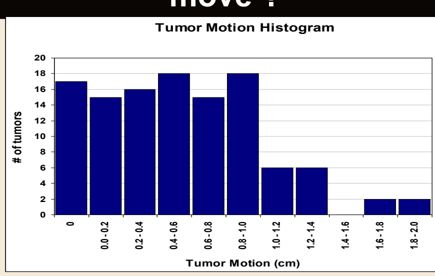
PRECISE AND REAL-TIME MEASUREMENT OF 3D TUMOR MOTION IN LUNG DUE TO BREATHING AND HEARTBEAT, MEASURED DURING RADIOTHERAPY

YVETTE SEPPENWOOLDE, M.SC.,* HIROKI SHIRATO, M.D., PH.D.,† KEI KITAMURA, M.D., PH.D.,† SHINICHI SHIMIZU, M.D., PH.D.,† MARCEL VAN HERK, PH.D.,* JOOS V. LEBESQUE, M.D., PH.D.,* AND KAZUO MIYASAKA, M.D., PH.D.†



Red Journal 53:822-834 (2002)

How much do thoracic tumors move ?



Assessing respiration-induced tumor motion and internal target volume using four-dimensional computed tomography for radiotherapy of lung cancer.

Liu HH, Balter P, Tutt T, Choi B, Zhang J, Wang C, Chi M, Luo D, Pan T, Hunjan S, Starkschall G, Rosen I, Prado K, Liao Z, Chang J, Komaki R, Cox JD, Mohan R, Dong L.

Red Journal 68: 531-540 (2007)

CT scan times

- Prior to the development of helical CT, scan times were in excess of 30 sec, encompassing several respiratory cycles
- Single slice randomly sampled respiratory cycle
  - Resulting in sloppy images

Why would we need 4DCT?

- 21st century radiation treatment planning
  - Personalized radiation therapy
  - Account for respiratory motion by adding patient-specific internal margin (IM) to clinical target volume (CTV) to generate internal target volume (ITV)

How do we obtain 4DCT images?

- Enabling technologies
  - High-speed CT – multislice helical
  - Respiratory monitoring
- Two approaches
  - Image binning [Pan, et al, Med Phys 31:334-340 (2004)]
  - Projection binning [Keall, et al, PMB 49:2053-2067 (2004)]

General approach to 4DCT image acquisition

- Acquire image data continuously during respiration
- Reconstruct the image data at specific phases in the respiratory cycle for each patient location.
- Combine image data at same phase from several respiratory cycles.
- Result: A series of 3DCT images, each representing a different phase in the respiratory cycle.

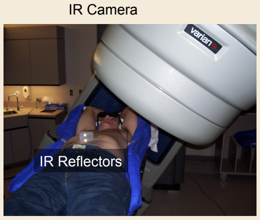
Two approaches to respiratory monitoring

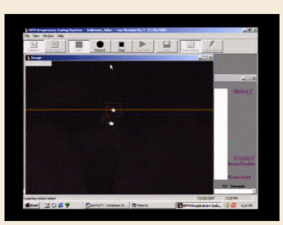
Measurement of abdominal height

Measurement of abdominal circumference

The Varian RPM® system

IR Camera



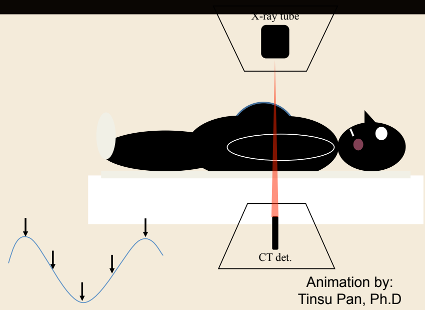


RPM software tracks the markers
Can be used to monitor patient breathing and for patient feedback

Image binning

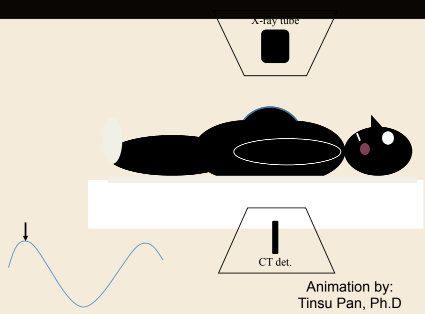
- Operate CT scanner in cine mode
- Monitor respiratory cycle
- Acquire multiple images with table in fixed position
  - Time period > 1 respiratory cycle + 2 gantry rotations
  - Ensures adequate sampling
- Index table
- Repeat image acquisition

4D-CT Data Acquisition



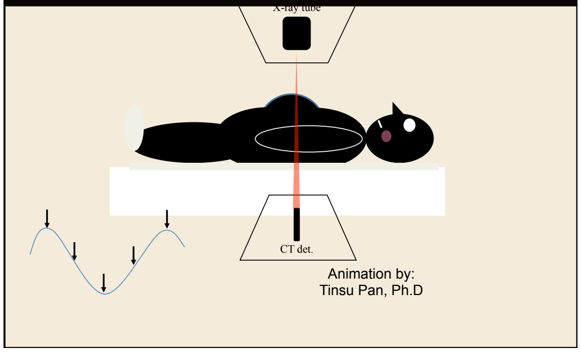
Animation by:
Tinsu Pan, Ph.D

4D-CT Data Acquisition



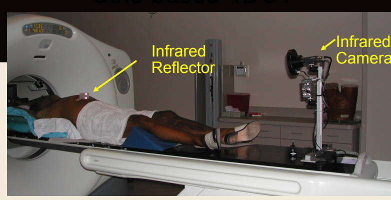
Animation by:
Tinsu Pan, Ph.D

4D-CT Data Acquisition



Animation by:
Tinsu Pan, Ph.D

Cine based 4DCT



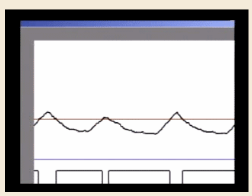
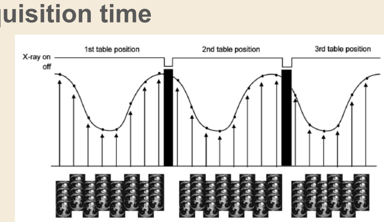


Image binning

- Obtain large number (1000-3000) of images, each figure associated with an acquisition time



Pan, et al, 2004

Image binning

- Determine acquisition times associated with corresponding phases in respiratory cycles
  - Typically 10 phases (0%, 10%, 20%, …)
- Bin images with acquisition times closest to phase acquisition time

Projection binning

- Operate CT scanner in helical mode at very low pitch
  - Table translation during one respiratory cycle < detector width
- Monitor respiratory cycle

Projection binning

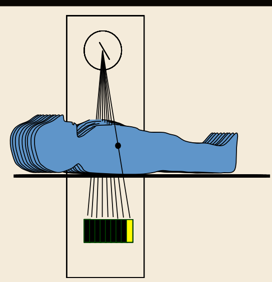
- Obtain large number of projections, each projection associated with an acquisition time

Projection binning

- Determine acquisition times associated with corresponding phases in respiratory cycles
  - Typically 10 phases (0%, 10%, 20%, …)
- Bin projections with acquisition times closest to phase acquisition time
- Reconstruct images based on binned projections

4D CT based on a Spiral CT Acquisition

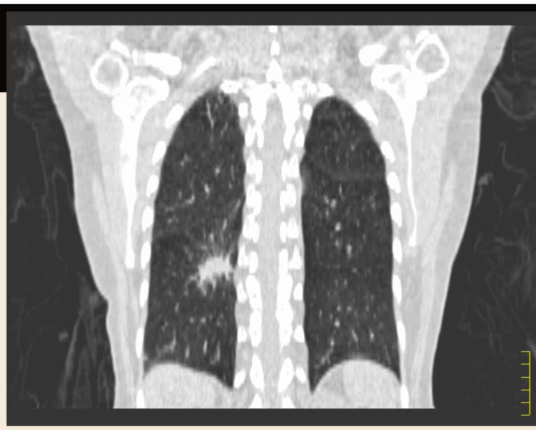
10% Phase — Sampled by detector 1



An oversimplification for demonstration of data sufficiency requirements

Result of image acquisition

- In both cases, the result is a set of several (typically 10) three-dimensional CT data sets, each data set corresponding to a different phase of the respiratory cycle.



What about patient dose?

- Li et al [Med Phys 32:3650-3660 (2005)]
  - 4DCT of chest gives dose of ~200 mSv
- Keall et al [Phys Med Biol 49:2053-2067 (2004)]
  - 250-400 mSv
- Mayo et al [Radiology 228:15-21 (2003)]
  - conventional CT dose of ~7 mSv

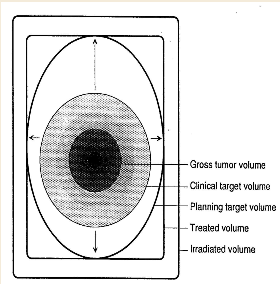
How do we used 4DCT images?

- Recall ICRU definitions
  - Gross tumor volume (GTV)
  - Clinical target volume (CTV)
  - Internal target volume (ITV)
  - Planning target volume (PTV)

ICRU 50,62

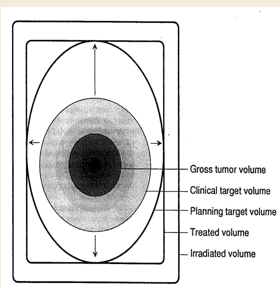
Gross Tumor Volume (GTV)

- "Gross demonstrable extent and location of the malignant growth"
  - Primary tumor
  - Involved nodes
  - Metastatic disease
- Acquire information from imaging study



Clinical Target Volume (CTV)

- "Tissue volume that contains a demonstrable GTV and/or subclinical malignant disease that must be eliminated"
- Expand GTV based on knowledge of disease spread

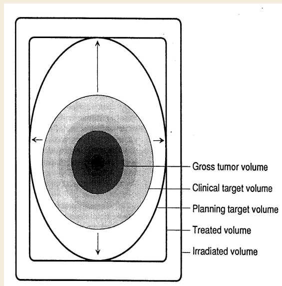


Internal Target Volume (ITV)

- CTV + internal margin (IM) to compensate for all movements
  - Respiration
  - Bladder and rectum fillings
  - Swallowing
  - Cardiac motion
  - Bowel motion
- Expand CTV based on explicit knowledge of internal motion

Planning Target Volume (PTV)

- "A geometrical concept used for treatment planning, defined to select appropriate beam sizes and beam arrangements to ensure that the prescribed dose is actually delivered to the CTV"



Planning Target Volume (PTV)

- PTV is ITV + setup margin (SM) to account for setup uncertainties
  - Expansion of ITV based on knowledge of setup uncertainties
    - Immobilization devices
    - On-line imaging

Target volumes

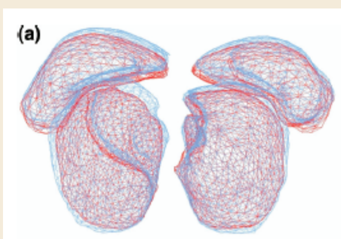
- GTV and CTV are oncological entities
  - Independent of modality of treatment
  - Define prior to planning of treatment
- ITV and PTV are treatment planning entities
  - Account for characteristics of the patient and treatment methodology
  - Relevant for targeting purposes
- The GTV and CTV belong to the radiation oncologist; the ITV and PTV belong to the medical physicist.

Explicitly accounting for motion

- The right (i.e., ICRU) way:
  - Delineate the GTV on all data sets that comprise the 4D data set
  - Can use deformable propagation to make life easier

Model-based deformation

- Represent anatomic structure as triangulated mesh
- Deform mesh to image



Model-based deformation

- Originally designed as method of automatic segmentation of CT images – deformation of library-based anatomic structure
  - Pekar V, et al, “Automated model-based organ delineation for radiation therapy planning in the prostate region,” Int J Radiat Oncol Biol Phys 60:973-980 (2004)

Model-based deformation

- Recognized application in 4D CT segmentation – use reference phase contours as "library structure" and deform to remaining phases
  - Ragan D, et al, "Semiautomated four-dimensional computed tomography segmentation using deformable models," Med Phys 32:2254-2261 (2005)

Explicitly accounting for motion

- On each phase, expand GTV to generate CTV
  - 8 mm for adenocarcinoma
  - 6 mm for squamous cell carcinoma
  - Giraud P, et al, "Evaluation of microscopic tumor extension in non-small-cell lulng cancer for three-dimensional conformal radiotherapy planning," Red Journal 48:1015-1024 (2000)

Explicitly accounting for motion

- On each phase, edit CTV to avoid regions where there is no microscopic extension
  - Chest wall
  - Across lobar boundaries

Explicitly accounting for motion

- Combine CTV from each phase to generate ITV
- Expand ITV to account for setup uncertainties to generate PTV
  - MDACC thoracic service conventions
    - 1 cm for conventional setup
    - 0.5 cm for kV image-guided setup (based on alignment of vertebral bodies)
    - 0.3 cm for CT image-guided setup (based on alignment of GTV)
- Use PTV to generate treatment portals

Explicitly accounting for motion

- Calculate dose on each phase
- Combine CTV from each phase to generate ITV
- Expand ITV to account for setup uncertainties to generate PTV
- Use PTV to generate treatment plan

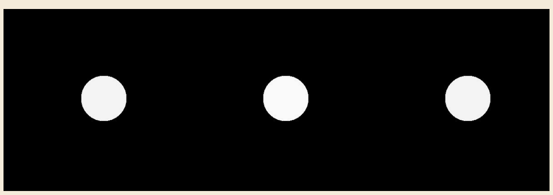
Explicitly accounting for motion

- Create 4D plan
  - Copy original trial onto all data sets in plan
- Compute 4D dose
  - Compute dose distribution on all data sets
  - Very time consuming and resource consuming
- Accumulate 4D dose
  - Deform phases of 4D dose matrix to reference phase

Explicitly accounting for motion

- The practical way:
  - Make use of observation that lung parenchyma is of lower density (~0.3) than tumor (~1)
  - Maximum intensity projection (MIP)
    - In each voxel, use maximum CT value over all phases of 4D data set

Abstractions of 4D Data: The average dataset and the maximum intensity projection (MIP) dataset.



Moving tumor

Average showing time averaging of the moving tumor

MIP showing all voxels occupied by the tumor over the respiratory cycle

Explicitly accounting for motion

- Use MIP to generate “internal gross tumor volume” (IGTV)
  - Note that this is not an ICRU term
- Expand IGTV to account for microscopic disease to generate ITV
- Expand ITV by setup margin to generate PTV
- Design treatment portals based on PTV

Explicitly accounting for motion

- Perform dose calculations on AVG data set
  - In each voxel, use CT value averaged over all phases of 4D data set

How can we improve the quality of 4DCT images?

- Common causes of artifacts on 4DCT images
  - Inadequate sampling
  - Irregular breathing

$$\text{pitch} \leq \frac{\text{gantry rotation time (typically 0.4 sec - 0.5 sec)} \times \text{resp rate} (\text{min}^{-1})}{60 \text{ sec/min}}$$

Inadequate sampling

- Helical: Table translation during one respiratory cycle must be less than detector width

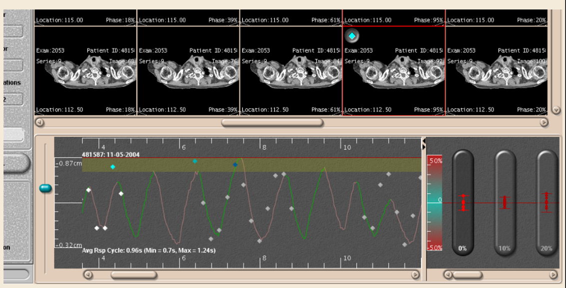
$$\text{pitch} \leq \frac{\text{gantry rotation time} (0.4\,\text{s} - 0.5\,\text{s}) \times \text{respiratory rate} (\text{min}^{-1})}{60\ \text{sec/min}}$$

- Cine: Table must be stationary for at least 1 respiratory cycle + gantry rotation

Inadequate sampling - helical

- Early versions of reconstruction software displayed gaps where adequate information was not obtained
- Newer software fills in gaps – but still may not be accurate

Inadequate sampling - cine



- Poor phase match

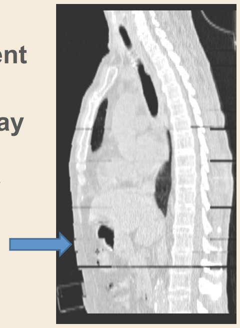
Inadequate sampling

- If appropriate pitch or table motion cannot be achieved due to slow respiration, it may be necessary for patient to increase respiratory rate.

$$\text{pitch} \le \frac{\text{gantry rotation time (typically 0.4 sec - 0.5 sec)} \times \text{resp rate (min}^{-1})}{\text{60 sec/min}}$$

Irregular breathing

- 4DCT makes the assumption that patient respiration is uniform
- Irregular breathing may result in artifacts
  - Note irregular anterior surface of abdomen



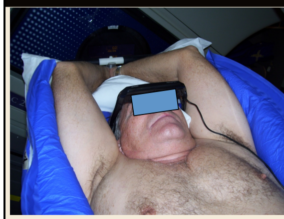
Patient training procedure in preparation of a 4D scan

- Explain to patient the nature of breathing procedure – need for consistent breathing pattern
- Monitor patient breathing pattern
- Determine respiratory rate (used to set scanner pitch) – worst case estimate
- Determine if respiration is reproducible enough to acquire a 4DCT

Patient coaching (4 approaches)

1) Do nothing – many patients breathe best by being relaxed and not thinking about breathing.
2) Pre-imaging relaxation and coaching – works for many nervous patients.
3) Audio prompting: Works best to modify breathing rate, but makes nervous patient more nervous
   - Nonverbal audio device shows promise for these patients
4) Video prompting: Helps patients who breathe irregularly in amplitude.

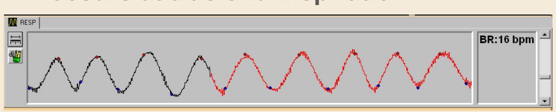
Patient Video Feedback Devices



- The patients breathing motion can be fed back to the patient along with a target amplitude to help improve the quality of 4DCT imaging.

Post-scan processing

- Respiratory trace file in RPM system indicates tags where 0% occurs
- Tags determined by predictive filter so there may be some inaccuracy
- Modify location of tags so that 0% occurs at true end inspiration



Post-scan processing

- Displacement binning
  - Bin based on displacement of tumor (or tumor surrogate) rather than equally-spaced phases
  - Can be implemented by editing respiratory trace file before binning
  - Not yet demonstrated to be advantageous
- Presently, editing of 0% tag is primary method of post-scan processing

Where do we go from here?

- Pelc (RSNA 2011) – talk on future developments in CT
  - Faster gantry speeds – 0.1 sec gantry rotation
  - Larger detectors – 512 slices (almost there now)
- True 4DCT, where 4^{th} dimension is time
- Removes issues of table translation, irregular breathing

Take-home message

- Respiratory-induced tumor motion is significant and unpredictable
- Various methods have been developed to measure the extent of respiratory-induced tumor motion
- We are now able to rationally define target volumes that explicitly account for the effect of respiratory motion
- 4DCT can become the standard of care for imaging thoracic tumors.

In 4DCT, what is the 4^{th} dimension?

11%	1. Elapsed time
0%	2. Interfractional motion
89%	3. Phase of the respiratory cycle
0%	4. Respiratory rate

In 4DCT, what is the 4th dimension?

3. Phase of the respiratory cycle

Rationale: We combine information at the same phase of the respiratory cycle from many cycles to overcome the inability to acquire adequate imaging data in a single respiratory cycle.

Reference: Starkschall G, Desai N, Balter P, *et al.*, Quantitative assessment of four-dimensional computed tomography image acquisition quality, J ApplClin Med Phys. 8(3): 1-20 (2007).

Which of the following is NOT involved in the acquisition of 4DCT images?

0% 1. Acquiring large amounts of image data during respiration

13% 2. Combining image data at the same phase from several respiratory cycles

6% 3. Reconstructing image data at specific phases in the respiratory cycle for each patient location

81% 4. Using deformable image registration to propagate the GTV among several respiratory cycles

Which of the following is NOT involved in the acquisition of 4DCT images?

4. Using deformable image registration to propagate the GTV among several respiratory cycles

Rationale: Deformable image registration is used in planning for 4D dose calculations based on 4D image data sets, and not on the acquisition of the 4DCT data sets.

Reference: Rietzel E., T. Pan, and G.T.Y. Chen, "Four-dimensional computed tomography: Image formation and clinical protocol," Med Phys 32 (4), 874 – 89 (2005).; Keall P.J. *et al.*,The management of respiratory motion in radiation oncology report of AAPM Task Group 76, Med Phys. 33 (1), 3874 – 900 (2006).

Which of the following is NOT an ICRU-defined term?

0% 1. Clinical target volume
2% 2. Gross tumor volume
91% 3. Internal gross tumor volume
8% 4. Internal target volume

Which of the following is NOT an ICRU-defined term?

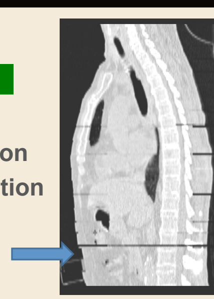
3. Internal gross tumor volume

Rationale: Some institutions have used the concept of an internal gross tumor volume (IGTV), consisting of the envelope of motion of the GTV, in the process of target delineation, but this quantity is not recognized by the ICRU.

Reference: ICRU Report 50, *"Prescribing, Recording, and Report Photon Beam Therapy"*; ICRU Report 62, *"Prescribing, Recording and Reporting Photon Beam Therapy (Supplement to ICRU Report 50)"*.

The displacements in the anterior surface of the abdomen illustrated in this figure resulted from

70% 1. Irregular breathing
10% 2. Too rapid breathing
2% 3. Too rapid gantry rotation
19% 4. Too rapid table translation



The displacements in the anterior surface of the abdomen illustrated in this figure resulted from

1. Irregular breathing

Rationale: The gaps in the figure were the result of too rapid table translation.

Reference: Starkschall G, Desai N, Balter P, *et al.*, Quantitative assessment of four-dimensional computed tomography image acquisition quality, J Appl Clin Med Phys. 8(3): 1-20 (2007).

All of the following methods have been successfully used to address the problem of irregular breathing EXCEPT

0%	1. Audio prompting
67%	2. Displacement binning
29%	3. Editing 0% tags
5%	4. Video feedback

All of the following methods have been successfully used to address the problem of irregular breathing EXCEPT

2. Displacement binning

Rationale: Although, in principle, displacement binning should assist in improving images obtained during irregular breathing, in practice this has not yet been shown to be effective.

Reference: Keall P.J. *et al.*,The management of respiratory motion in radiation oncology report of AAPM Task Group 76, Med Phys. 33 (1), 3874 – 900 (2006).


Thank you