Managing Respiratory Motion in Radiation Therapy

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I. INTRODUCTION

Intrafraction motion is an issue that is becoming increasingly important in the era of image-guided radiotherapy. Intrafraction motion can be caused by the respiratory, skeletal muscular, cardiac and gastrointestinal systems. Of these three systems, most of the research and development to date has been directed towards accounting for respiratory motion. The management of respiratory motion in radiation oncology is the subject of this presentation.

It is important to note upfront that respiratory motion is just one potential source of error in radiotherapy. Other important errors, particularly for lung tumors, are gross tumor volume (GTV) and clinical target volume (CTV) definition variations and set-up errors. Large inter-physician GTV variations for lung cancer[1-4] and CTV variations for breast cancer[5,6] have been published. Some of these errors are almost an order of magnitude larger than that of respiration-induced motion. Also, set-up errors for lung[3,7-13] and breast[14-21] cancer are of the same or a higher order than that of respiratory motion.

Specific issues addressed by this presentation are:
- The magnitude of respiratory motion.
- The problems that respiratory motion causes during the imaging, planning, and delivery of radiation therapy.
- A description of the methods that have been used to explicitly account for this motion.
- Recommendations for clinical implementation of methods that explicitly account for respiratory motion.
- Recommendations for radiotherapy to sites affected by respiratory motion, both in the presence and absence of methods that account for this motion.
- Recommendations of the types and frequency of QA procedures for methods that account for respiratory motion.
- Recommendations for research studies that address currently unresolved or disputed issues.

Methods used in the management of respiration motion in radiation oncology that are covered in this presentation include:
- Respiratory gated techniques.
- Breath-hold techniques.
- Forced shallow breathing methods.
- Real-time tumor tracking methods.

It is recognized that most facilities currently do not have access to methods that explicitly account for respiratory motion, and, thus, guidelines for treatments at these facilities are also included.

II. PROBLEMS OF RESPIRATION MOTION DURING RADIOTHERAPY

A. Image acquisition limitations

If respiratory motion is not accounted for during image acquisition, as is the case when conventional radiotherapy techniques are applied in thoracic and abdominal sites, the motion causes artifacts during image acquisition. These artifacts cause distortion of the target volume and incorrect positional and volumetric information.[22-33] These motion artifacts occur because different parts of the object move in and out of the CT slice window during image acquisition. Motion artifacts are commonly seen with thoracic CT images. An example of the difference between a gated and non-gated CT scan for a patient and sinusoidally moving sphere are shown in Figure 1. Artifacts from CT scans manifest themselves not only as target/normal tissue delineation, but also negatively affect dose calculation accuracy.

B. Treatment planning limitations

During treatment planning, margins need to be large enough to ensure coverage of the target for most of the treatment delivery. Generally, for CT-planned lung cancer treatments, the GTV [34,35] is outlined, from which a margin is added to include the suspected microscopic spread (which added to the GTV creates the CTV). Thus, using ICRU 62 [35] nomenclature, to obtain the planning target volume (PTV) from the CTV involves the addition of the margins to account for intra-fraction motion (due to respiration) and inter-fraction motion as well as set-up error. Accounting for respiratory motion by adding treatment margins to cover the limits of motion of the tumor is clearly undesirable, because this increases the volume of healthy tissues exposed to high doses. This increased treated volume increases the likelihood of treatment-related complications. However, if the margins are not sufficiently large, part of the CTV will not receive adequate dose coverage. Because of the artifacts observed in CT images in which respiratory motion has not been accounted for, the magnitude of margin to allow for respiratory motion is difficult to quantify, particularly for individual patients in which a wide range of tumor motion is observed.[36,37]

C. Radiation delivery limitations

Radiation delivery in the presence of intra-fraction organ motion causes an averaging or smearing of the dose distribution without motion over the path of the motion. This displacement results in a deviation between the intended dose and the dose actually delivered. Assuming a static beam, it is the composite vector of internal (e.g., tumor-bone) and external (bone-treatment room) displacements that determine the total positional error affecting the dose. Thus, for conventional (non-IMRT) treatments, in which the dose gradient in the center of each individual field can be assumed to be fairly small, the effect is manifested by a blurring of the dose distribution by the anatomy moving near the beam edges,

in effect increasing the beam penumbra. This effect is though to be exacerbated during IMRT delivery due to the interplay between motion of the leaves of a multileaf collimator* and the component of target motion perpendicular to the beam, which can lead to motion artifacts in dose distributions. This effect was demonstrated using theoretical models by Yu et al[38], yielding dose variations for 'clinically relevant parameters' of up to 100%. Keall et al[39] experimentally showed dose variations of up to 20% for a single field. However, more recent articles[40-44] show that though variations may exist for single fractions, for multiple field and multiple fraction treatments these over- and underdose variations tend to average out, yielding similar averaging artifacts as conventional treatments. Care, particularly with hypo-fractionated IMRT treatments should still be taken (further discussion of IMRT effects is given in a previous continuing education session at this meeting, *The Effects of Motion on IMRT*).

III. MAGNITUDE AND MEASUREMENT OF RESPIRATORY MOTION

A. Measuring respiration motion

The lungs, esophagus, liver, pancreas, breast, prostate, and kidneys, are known to move with breathing. The impact of this motion on CT and MR image quality, as well as on radiotherapy dose planning and delivery, has prompted medical physicists and clinicians to study the motion using a variety of imaging modalities. We provide here a survey of published observations on organ motion due to respiration and other influences. The survey is not exhaustive, but is intended to provide guidelines for accommodating the motion during treatment.

B. Motion observations

Generally, abdominal organ motion is in the superior/inferior (SI) direction, with no more than 2-mm displacement in the AP and right/left (RL) directions.[45,46] However, in some individuals, the kidneys show more complex patterns.[45] Lung tumor motions generally show a much greater variation in the trajectory of motion.

The amount by which a lung tumor moves can vary widely. Stevens et al[36] find that out of 22 lung tumor patients, ten subjects showed no tumor motion at all. Of the remaining 12 subjects, the average IS displacement was anywhere from 3 to 22 mm (mean 8 +/- 4 mm). They found no correlation between the occurrence or magnitude of tumor motion and tumor size, location, or pulmonary function, suggesting that tumor motion should be assessed individually.

Barnes et al[47] found the average motion of tumors in the lower lung lobe to be significantly greater than that in the middle lobe, upper lobe, or mediastinal tumors (18.5-mm vs. 7.5-mm average IS displacement). This observation has generally been corroborated by other observations,[17] although the individual ranges of motion are such that some individuals will show less motion in the IS direction than others will show in the AP and LR directions.

The most detailed lung tumor motion data reported in the literature are the measurements of Seppenwoolde et al,[37] who measured 3D tumor trajectories for 20 patients via dual real-time fluoroscopic imaging of a fiducial marker implanted in the tumor. They observed hysteresis in the tumor trajectories of half the patients, amounting to 1- to 5-mm separation of the trajectories during inhalation and expiration. This indicates that where high accuracy is required in dose alignment, a real-time tracking or gating process based on surrogate breathing signals should not only correlate the

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* Motion artifacts in dose distributions may be encountered with both DMLC and SMLC IMRT delivery.

tumor's motion along each axis with the breathing signal, but should also recognize the relative phase for the time series describing each component of motion, because this phase difference is what leads to the hysteresis effect. In Figure 2, tumor motion trajectories during gated radiotherapy of lung tumors, measured using implanted gold markers, are depicted.[37] The amount of motion ranges from 1-mm displacement to more than 2-cm displacement. Furthermore, it can be seen that the motion is non-linear (i.e., it follows semi-circles rather than a line) for most of the tumors. The majority of tumors (78% in this study) move with less than 1-cm peak–peak displacement. Similar results, based on portal imaging studies, have been reported.[48]

IV. RADIOTHERAPY IN THE PRESENCE OF RESPIRATORY MOTION WHERE NO METHODS THAT EXPLICITLY ACCOUNT FOR RESPIRATORY MOTION ARE AVAILABLE

Most radiotherapy facilities do not currently have methods that explicitly account for respiratory motion, the problems of which were outlined in section II. In the current section we give the imaging and treatment planning guidelines for tumor sites affected by respiratory motion. As tumor motion throughout the entire respiratory cycle will be present during radiation delivery, it is important that this is accounted for during CT imaging and planning.

A. CT Imaging

Three techniques for CT scanning are possible that include the entire range of tumor motion for respiration (at least at the time of CT acquisition) are slow CT, inhale and exhale breath hold CT and 4D CT. These are listed in order of increasing workload. For all of these techniques it is important to understand that the breathing patterns, and hence tumor motion will change between simulation sessions and treatment sessions.

1. Slow CT scanning

One solution to obtain representative CT scans is slow scanning.[49-51] In the slow scanning method, the CT scanner is run very slowly and/or multiple CT scans are averaged such that, on average, multiple respiration phases are recorded per slice. Hence the image of the tumor (at least in the high contrast areas) should show the full extent of respiratory motion that occurred during the time the anatomy was scanned. This technique yields a tumor-encompassing volume, with the limitation that the respiration motion will change between imaging and treatment, and thus additional margins are required to account for these variations. A further advantage of slow scanning over standard scanning is not only anatomic delineation but also the dose calculation is performed on a geometry which is better representative of that during the entire respiratory cycle, as occurs during treatment. For slow CT scanning, one CT scan is obtained, so the overall treatment process does not increase.

2. Inhale and Exhale breath hold CT

Breath-hold[52-55] and respiration gated CT scanning[23] are potential solutions to reduce image distortion induced by respiration. An important aspect to consider, however, is whether the obtained scans will be representative of the lesion's position during treatment. On average, the distortion of the free-breathing scans is zero, and this is the reason why free breathing scans are nowadays used for treatment planning. However, a gated CT scan would typically be taken during the time when the lesion speed would be minimal, i.e., after breath-out. This position deviates from the mean tumor position and will introduce a patient group systematic error if not taken into account. Voluntary breath-hold CT scans are even worse in the sense that deep breathing will lead to larger displacements than free breathing, and very large systematic errors may be introduced. Active breathing control[56] potentially allows the respiration to be

stopped in the average tumor position, but care should be taken to verify that the respiration pattern does not deviate from free breathing when using this system for imaging only.

3. 4D CT/Respiration Correlated CT

A promising solution for obtaining high quality CT data in the presence of respiration motion is 4D CT or respiration-correlated CT (conventional and cone0beam approaches).[30,31,57-63]. Here, 4D data that can be analyzed to determine the mean tumor position, tumor range of motion and the actual tumor motion itself can be acquired. A limitation of 4D CT is that this technique is strongly affected by variations in respiratory patterns during acquisition. Breathing training techniques have been developed,[64] however even with these techniques artifacts can be observed.[63]

B. Treatment planning

The effect of all geometrical uncertainties is a displacement of the target relative to the dose distribution. Considering the target as static and the dose distribution as mobile allows one to sum the dose delivered over the time period of all fractions. When there are many fractions, the random errors can be accurately described as a blurring of the dose distribution.[65] The blurring is described as a convolution of the dose distribution with the probability distribution function of the total displacement vector of the target versus the treatment machine.[66,67] A convolution is not completely correct to describe the dose changes (see for example [68,69]) but is quite accurate in practice.[70] Systematic errors cannot be accounted for by this approach. The following components contribute to the target displacement:

- Respiration motion and heartbeat,[37] which are periodic functions of time.
- Variation of mean respiration depth, a random function with unknown distribution. Some data appear in ref. [37].
- Variations caused by the changing volumes of hollow organs. These are unknown for organs in the lung or upper abdomen, but probably fairly small.
- Patient setup error: typical 3-mm (1SD)[11,48]

Note that gated radiotherapy or breath-hold techniques not only impact the accuracy of target localization, but also can play a role in normal tissue sparing.[71,72] Finally, it is important to notice that fast tumor shrinkage occurs quite often in lung radiotherapy, which may give rise to systematic delivery errors.[48]

The distortion of the planning CT is an important source of systematic error that should be combined with other sources of systematic error to estimate the required margin.

V. METHODS TO EXPLICITLY ACCOUNT FOR RESPIRATION MOTION IN RADIOTHERAPY

The methods that have been developed to explicitly account for respiration motion in radiotherapy can be broadly separated into four major categories: respiratory gating techniques, breath-hold techniques, forced shallow breathing techniques, and respiration synchronized techniques. These methods are discussed in this section.

A. Respiratory gating methods

Respiratory gating involves the administration of radiation (both during imaging and treatment delivery) within a particular portion of the patient's breathing cycle, commonly referred to as the "gate". The position and width of the gate within a respiratory cycle are determined by monitoring the patient's respiratory motion, using either an external respiration signal or internal fiducial markers. The ratio of the time spent by the signal within the "gate" to the overall treatment time is referred to as the duty cycle, and is a measure of the efficiency of the method. To date the only commercially available respiratory gating method is the Varian RPM system.

B. Breath-hold methods

1. Deep inspiration breath-hold

A reproducible state of maximum breath-hold (deep inspiration breath-hold or DIBH) is advantageous for treating thoracic tumors, because it significantly reduces respiratory tumor motion and changes internal anatomy in a way that often protects critical normal tissues. Several methods for implementing DIBH have been developed and are described in this report. All the methods require patient compliance, active participation and, often, extra therapist participation. This section focuses on a spirometer-monitored technique that was developed and clinically implemented—primarily for conformal radiation treatments of nonsmall-cell lung cancer (NSCLC) at the Memorial Sloan-Kettering Cancer Center (MSKCC).[71,73,74]

2. Active Breathing Control

Active Breathing Control (ABC) is a method to facilitate reproducible breath-hold without requiring the patient to reach maximum inspiration capacity [56,75]. The ABC method was developed at William Beaumont Hospital and is currently commercialized by Elekta, Inc. as the Active Breathing Coordinator. The ABC apparatus can be used to suspend breathing at any pre-determined position along the normal breathing cycle, or at active inspiration. The device consists of a digital spirometer to measure the respiratory trace, which is in turn connected to a balloon valve. In an ABC procedure, the patient breathes normally through the apparatus. When an operator "activates" the system, the lung volume and the phase (i.e., inhalation or exhalation) at which the balloon value will be closed are specified. The patient is then instructed to proceed to reach the specified lung volume, typically after taking two preparatory breaths. At this point, the valve is inflated with an air compressor for a pre-defined duration of time, thereby "holding" the patient's breath. The breath-hold duration is patient dependent, typically 15-30 seconds, and should be well tolerated to allow for repeated (after a brief rest period) breath-holds without causing undue patient distress. Figure 3 shows the display of the Elekta's ABC system, where the appearance of a green color shade serves to indicate both activation of the balloon valve and the lung volume at which it will close to maintain breath-hold. A timer display counts down remaining breath-hold duration in seconds.

3. Self-held breath-hold

As the name "Self-Held Breath-Hold Techniques" implies, the patient is being asked to independently hold their breath at some point in the breathing cycle. During a breath-hold, the beam is turned on, and dose is delivered to the tumor. Depending on the patient's ability to hold his/her breath, multiple breath-holds may be required in order to deliver the requisite dose for a given field. In order to effectively gate a radiotherapy beam to the breath-hold, an effective control system for the accelerator must be developed. Such a system, developed[47,76] for the Varian Linac (Varian Medical Systems, Palo Alto, Ca), makes use of the "Customer Minor (CMNR)" Interlock available on all of the Varian C Series accelerators. In this particular design, the patient is given a hand-held switch that is connected

to the CMNR interlock circuit. When the switch is depressed, the CMNR interlock is cleared at the console, which then allows the therapist to activate the beam. When the switch is released, the CMNR interlock is active, which turns the beam off and disables any further delivery until the switch is depressed again. It should be noted that although the therapist is the ONLY person who can turn the beam on, both the therapist and the patient can turn the beam off. Since this makes use of the existing interlock circuitry, there are no modifications required to the beam-delivery system or any of the safety features of the accelerator. Further details of the exact setup procedure are given in the "Treatment" section below. Studies have shown that the most reproducible position tends to be at deep inspiration or deep expiration, although neither was significantly better than any other position. This, along with the potential dosimetric advantages of increasing the lung volume,[48,49] has meant that deep inspiration is generally chosen as the preferred point for breath-hold. Therefore, the discussion in earlier sections regarding the advantages of DIBH with other gating techniques would be similar to the advantages with this method.

4. *Self-held breath-hold using an External Marker*

This breath-hold technique requires patients to manually hold their breath during a specific phase of the respiratory cycle. One of the key advantages of this technique is that the simulation and treatments can be delivered more efficiently than free breathing techniques because the radiation may be delivered continuously during the breath-hold. For example, 100 MU can be delivered in a short 10 second breath-hold using 600 MU/min dose rate. The same 100 MU would take 30 seconds to deliver using a free breathing technique with a 33% duty cycle and 600 MU/min. An additional advantage of this technique is that the user may constantly monitor the patient's breath-hold using an external fiducial tracking system that will automatically create a beam-hold condition if the patient does not hold their breath during the proper phase.

C. **Forced shallow breathing methods**

Forced shallow breathing (FSB) was originally developed for stereotactic irradiation of small lung and liver lesions by Lax and Blomgren at Karolinska Hospital in Stockholm.[77-79] These techniques have been shown to reduce the magnitude of intra-fractional motion.[46,80-82] This technique employs a stereotactic body frame with an attached pressure plate that is pressed against the abdomen in a reproducible fashion. The applied pressure to the abdomen is administered to minimize diaphragmatic excursions, thereby reducing the volume of gases exchanged during normal respiration while still permitting limited normal respiration. Elekta Instruments, Inc. commercially produces the body frame and the pressure plate system. The accuracy of the reproducibility of both the body frame and the pressure plate has been evaluated by several groups, with the most comprehensive and careful assessment of this device being published by Negoro *et al*. from Kyoto University School of Medicine.[83]

D. **Real-time tumor tracking methods**

Arguably, the best means of accommodating respiratory motion is to dynamically shift the dose in space so as to follow the tumor's changing position during free breathing. However, to date there is limited clinical experience with this technique. This will be referred to as respiratory-synchronized or real-time tracking. Under ideal conditions, continuous real-time tracking can eliminate the need for a tumor motion margin in the dose distribution, while maintaining a 100% duty cycle for efficient dose delivery. To succeed, this method should be able to do four things: (1) identify the tumor position in real time; (2) anticipate the tumor motion to allow for time delays in the response of the beam positioning system; (3) reposition the beam; and (4) adapt the dosimetry to allow for changing lung

volume and critical structure locations during the breathing cycle. This section will address current techniques to accomplish each of these tasks, discuss known and potential difficulties, and recommend development efforts to address them.

VI. QUALITY ASSURANCE

Quality assurance has a crucial role in all aspects of radiation oncology, as outlined in the report of AAPM Task Group 40.[84] In this section, QA techniques used in the management of respiratory motion are described. This section is divided into general descriptions and recommendations common to all methods accounting for respiratory motion and specific descriptions for each mode of accounting for respiration motion.

A. Respiratory gating

Dynamic feedback in gating systems is established by correlating the signal from a respiration-monitoring device with the internal location of the target. Because respiratory gating is a dynamic feedback process, existing static test phantoms and tools cannot be used to fully evaluate a gating system. In order to test *in vivo* dosimetry and target localization for gating systems, dynamic test phantoms that simulate respiration are needed. Such test phantoms are needed for acceptance testing, commissioning, and ongoing QA of clinical respiratory gating treatment programs.

Several important factors should be taken into consideration when designing dynamic test phantoms for respiratory gating: 1) The test phantom should be capable of producing cyclical and/or random motion similar to human respiration. 2) The gating feedback mechanism must be able to detect test phantom motion. 3) The phantom should be constructed of low-density material for CT and X-ray compatibility. 4) The device should be large enough to allow detectors, such as ion chambers or diodes, to be attached during motion. 5) The phantom should also be reliable and cost-effective. Several commercial and custom-built phantoms have been made to meet these criteria.[85]

B. Breath-hold methods

1. Deep inspiration breath-hold

a)   Patient-related QA

A primary QA issue is the achievement of reproducible inspiration levels in the patient. This in particular affects the self-consistency of a CT scan that spans multiple respiratory cycles or breath-holds, and the reproducibility of patient anatomy between simulation and treatment. Changes in the latter may occur because of changing respiratory health or increasing familiarity with the DIBH procedure.

b)   Equipment-related QA

The spirometer is calibrated with a three-liter syringe for flow rates between approximately 0.5 and 3 L/s. The linearity of spirometer vs. actual (syringe) volume is checked over a range of 0 to 3 L in either flow direction; typical linearity is within 2%. The constancy of the calibration is checked at approximately two- month intervals.

2. *Active breathing control*

a) Patient-related QA

As with DIBH, the primary concerns of ABC for individual patients involve reproducibility and duration of breath hold. Early studies indicate a difference in short- and long-term reproducibility, thus potentially indicating the need for integration of ABC with routine image-guided adjustment of setup.

It is essential that the function of this system be well understood prior to use. The process for establishing a breath-hold at a given state (e.g., exhale, inhale, deep inhale) should be documented and tested. If different patients are to exercise a breath-hold at different relative states, appropriate procedures and documentation are necessary. A standard set of patient instructions for communication with the ABC operator and for emergency actions to re-establish breathing is recommended. All of the ancillary components will require both inventory and maintenance procedures. It is important at the outset to understand the use of consumable items (nose clips, filters, gas canisters, etc.), establish a hygienic procedure for cleaning reusable items (e.g., rubber mouthpiece), and establish possible failures of the system from the use of ancillary equipment so that a proper set of use and maintenance procedures can be implemented.

3. *Self-held breath hold QA*

a) Patient Related QA

The most important quality assurance issue is patient specific QA in terms of insuring accurate setup and breath hold stability. Patient selection is a key to delivering a high quality treatment. Only those patients that are able to benefit from this technique, and can reproducibly hold their breath should be enrolled.

b) Equipment Related QA

With the self held breath hold technique, there is minimal QA required for the equipment it self. Every time it is used there is visual confirmation on the Clinac screen that the CMNR interlock is operational. Since a standard Varian interlock is being used with this design, it should be sufficient to test dose reproducibility annually to ensure that interrupting the beam does not cause a change in output.

C. Respiratory synchronized methods

Continuous real-time beam tracking to compensate breathing motion is still in an investigatory stage, with only a few sites conducting clinical trials. Therefore the necessary QA procedures are still under development. These procedures must address two fundamental sources of potential error in dose delivery: (1) determination of the tumor position as a function of time and (2) calibration of the spatial relationship between the tracking coordinate system and the beam delivery coordinate system.

VII. SUMMARY AND RECOMMENDATIONS

A. Clinical Process Recommendations

For patients in which respiratory motion may be a concern, that the flowchart in Figure 4 be followed. Box 1 of Figure 4 asks if a method of measuring motion is available. EORTC guidelines[86] recommend that 'An assessment of 3D tumor mobility is essential for treatment planning and delivery in lung

cancer'. When measuring tumor motion, the motion should be observed over several breathing cycles. It is important to note that respiratory patterns change over time. If no method exists for measuring motion, for example with a standard respiratory gated CT procedure, then the prudent approach is to assume that motion is significant, and treat with respiratory management (box 6) as outlined in section V. If a method of measuring motion, such as fluoroscopy, is readily available (box 1), then it can be worthwhile measuring the motion for two reasons. First, if the magnitude of the motion is significantly small (see following paragraph) relative to other errors in radiotherapy, then the extra effort of using respiratory management techniques is unwarranted (box 2). Second, if a patient specific tumor motion measurement is made, then this information can and should be used in the CTV to PTV margin used for treatment planning. If a respiratory management device is not used, the entire range of motion should considered when establishing the internal margin.[35] If respiratory management devices are used, then only the motion expected during the radiation treatment delivery should be considered when establishing the respiratory motion component of the internal margin.

B. Treatment Planning Recommendations

When deriving CTV-PTV margins for treatment planning the following factors specific to respiratory motion should be taken into account:

- The distortion of the planning CT due to respiratory motion-induced artifacts is an important source of systematic error.
- If a surrogate structure, such as the chest wall or diaphragm, is used to as a surrogate for tumor motion for the purpose of breath hold, beam gating or tracking, without observing the tumor directly during treatment, there will be uncertainties in the displacement and phase relationship between the surrogate and the tumor.
- There are variations within and between respiratory cycles.

Other factors such as set-up error and tumor changes during the course of radiotherapy are common to all sites.[35] An obvious problem is that the errors listed above have yet to be adequately quantified, and thus informed guesses as to the magnitude of these area need to be made. In areas where knowledge is lacking, the next section details a list of recommendations for further investigations to full the knowledge gaps.

C. Personnel Recommendations

It is recommended that, due to the complexity of the management of respiratory motion problem and the technology used, a physicist be present at all imaging sessions in which respiratory management devices are used and also for at least the first treatment for each patient. A physicist should also be available for consultation during the treatment planning process and all treatment sessions. The physicists involved with the procedures should have appropriate understanding of the equipment, and have attended, where possible, training on the specific device(s) used.
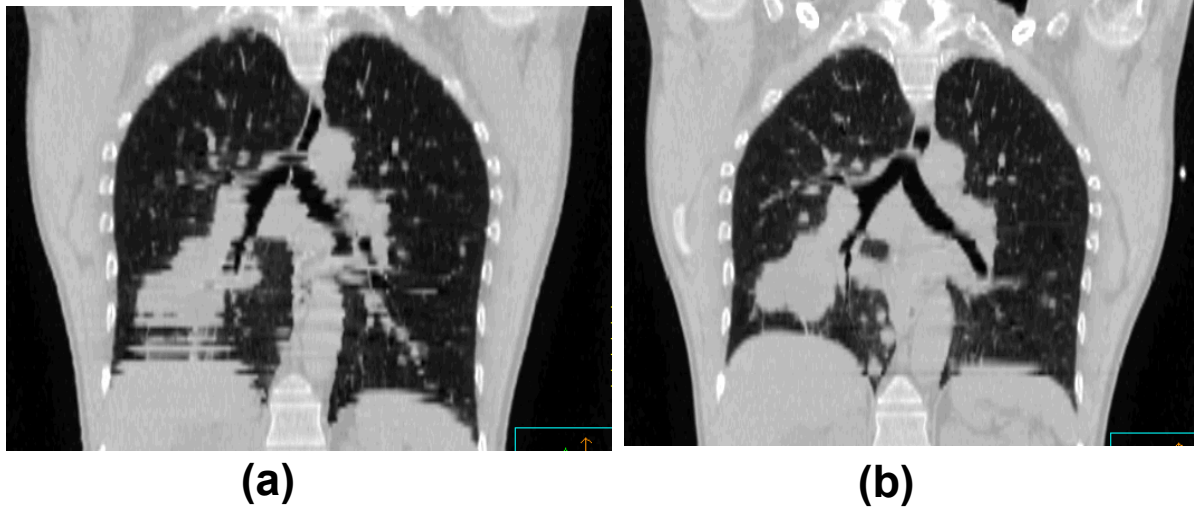
(a)

(b)

Figure 1. Coronal views of CT scans of the same patient taken (a) during free breathing and (b) with respiratory gated scanning at exhale. From Ref. [27].
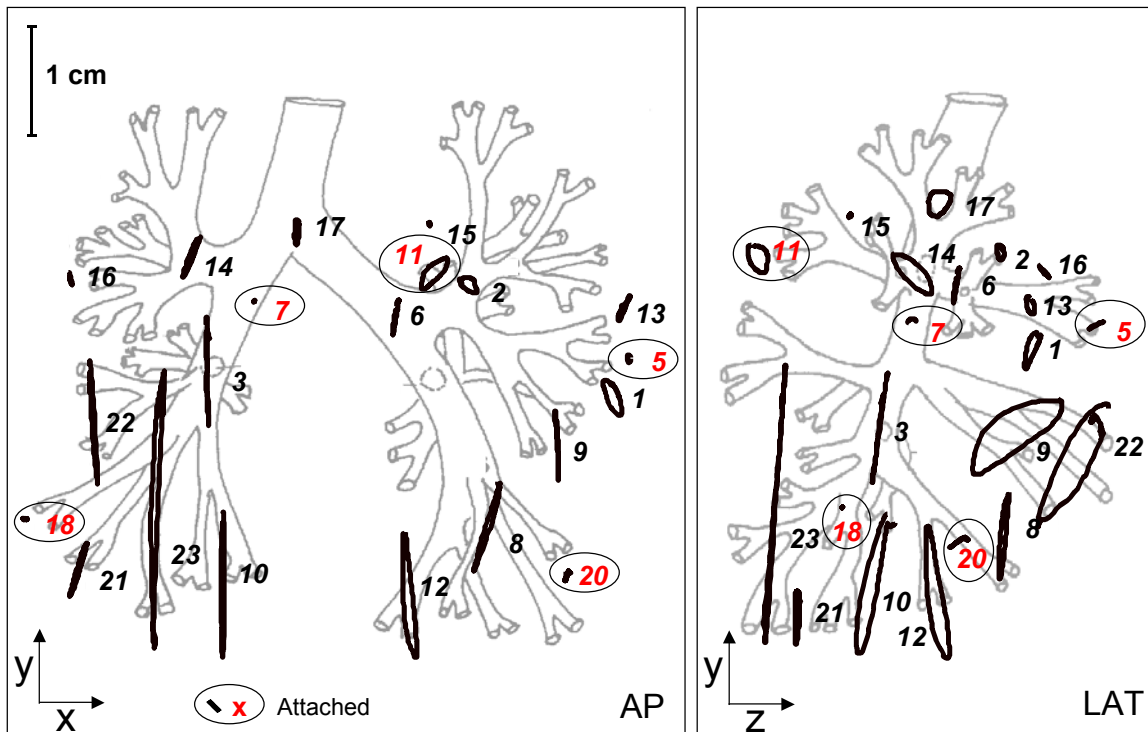

Figure 2. Measured tumor trajectories (not to scale) in 23 lung tumor patients measured using implanted markers and real-time stereoscopic fluoroscopy.
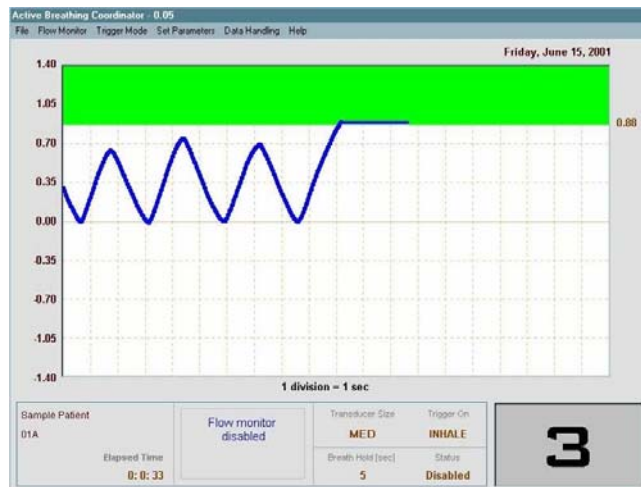
Figure 3. The screen display of the ABC system. The blue waveform is the ventilation signal converted from the digital flow-meter. The green shade indicates that the system is activated and also the lung volume for breath-hold. The bottom right display counts down the remaining duration of breath-hold in seconds. Note that this example does not show the large lung volume at mDIBH.
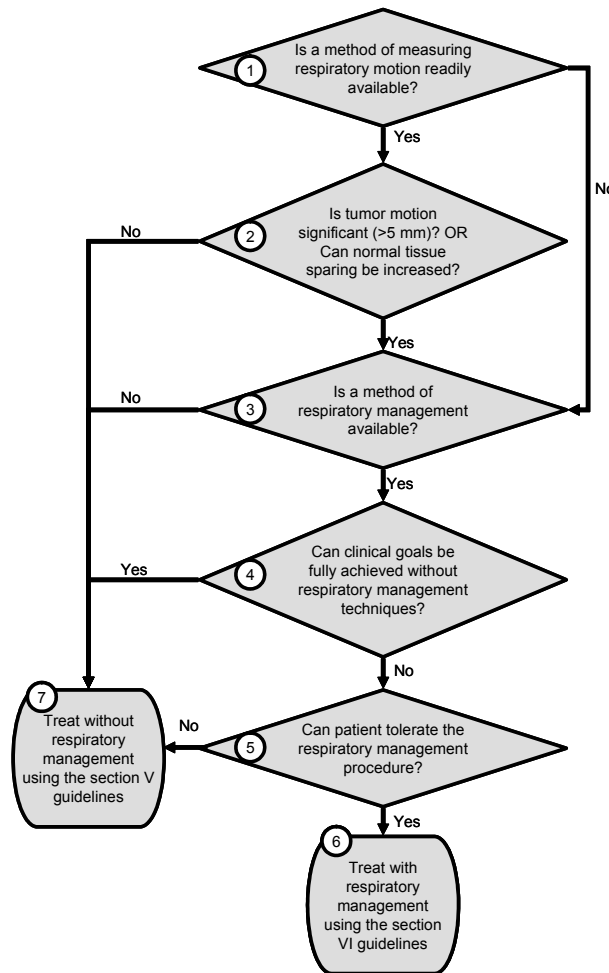

Figure 4. Recommended clinical process for patients for whom respiratory motion during the radiotherapy process is a concern.

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