A SYSTEMATIC APPROACH TO 4D RADIATION THERAPY – INTEGRATION OF 4D MEDICAL IMAGING INTO 4D RADIATION THERAPY

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ABSTRACT

Historically, the evolution of radiation oncology, commonly known as radiation therapy, has been closely linked to the advances in medical imaging. Recent breakthroughs in imaging technology, particularly 4D medical imaging, have injected new momentum into radiation oncology, shedding new light on revitalizing this century old treatment modality. This eventually led to the creation of a primitive form of 4D radiation therapy (4DRT). 4DRT can be defined as a combination of using 4D imaging to guide radiation treatment planning, correcting for daily set-up errors through either patient repositioning or plan adaptation, and controlling radiation delivery based on internal or external fiducial markers that can be continuously tracked. 4DRT introduces the time dimension into the 3DRT in order to compensate for patient motion/changes occurring either during a single fraction (intra-fractional) or between successive fractions (inter-fractional). The major advantages of 4DRT are high-precision dose conformity, minimized normal tissue complication probability, and possible further dose escalation to the target. To maximize the potential benefits of 4D medical imaging and promising improvements in patient survival and quality of life, an integrative and systemic approach to 4DRT is essential. Without such an integrated multi-disciplinary strategy, 4DRT would only remain as an ideal concept. Here, we propose a comprehensive approach that integrates 4D medical imaging into each of the key steps in 4DRT, including 4D simulation, 4D treatment planning, and 4D treatment delivery.
Keywords: 4D, radiation therapy, medical image, tumor motion, internal target volume.

4D RADIATION THERAPY

A major goal in radiation therapy is to deliver a high radiation dose to the perceived tumor volume while minimizing the dose to surrounding normal tissues. However, there are many sources of patient motion, such as respiratory, cardiac, digestive, and muscular motion, during the course of radiation therapy treatment planning and delivery process. Consequently, 3D imaging often produces images with motion artifacts. A fast imaging technique, such as single-slice CT, may only span a small portion of the respiratory cycle. Moreover, each slice may be acquired at different phases, resulting in image deformation artifact. For a slow imaging technique, such as PET, data acquisition is usually at a rate of 3-7 minutes per field of view (FOV). Therefore, signals from all phases of the breathing cycle are averaged, causing image blurring artifact. In order to remove such motion artifacts, various techniques have been developed and implemented clinically, including patient immobilization, breath holding, breath coaching, respiratory gating, and respiratory motion tracking. The latter two approaches are frequently applied in 4D imaging techniques for both motion correction and motion control, which eventually led to the formation of the concept of 4D radiation therapy – the inclusion of temporal changes to patient anatomy. Without such a motion control, radiation beam may either irradiate more normal tissue than necessary or miss the tumor at certain phases of a motion cycle, leading to a situation called the geometric miss. This could potentially cause local failure or increased side effects.

4D SIMULATION

The 4D imaging modalities, including 4DCT, 4DMRI, 4DPET, and 4DSPECT, should be used to provide needed clinical information. In addition, 4D multi-modality imaging techniques, such 4D CT/PET and 4D CT/SPECT, should also be used to minimize errors in image registration. Lung and liver tumors present a particularly unique challenge due to the effect of respiratory motion. More than 2.5 cm tumor movement has been observed during a free breathing cycle (Shirato, 2004). To provide a time-stamped indication of the motion stage (amplitude or phase), external or internal fiducial markers should be used for monitoring patient motion in 4DCT imaging (Figs. 1a-b). With this tracking information, image acquisition can be prospectively gated and the acquired images can be retrospectively sorted into image bins reflecting the different respiratory phases. One of the three respiratory tracking techniques should be considered: (1) optical tracking methods using an infrared laser with reflectors placed on thorax or abdomen, (2) use of a spirometer to measure tidal ventilation volume, (3) use of Bellows pressure sensor below diaphragm for monitoring anatomical volume change.

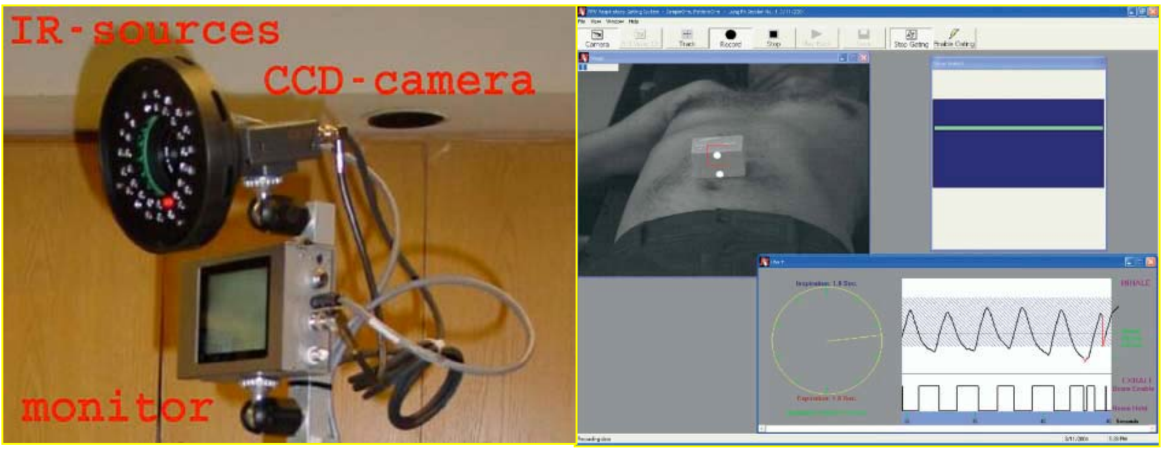

Fig.1a. Varian infrared laser tracking device. Fig.1b. Patient during 4DCT scanning mode.

4D TREATMENT PLANNING

An internal target volume (ITV) with more precise margin covering the moving clinical target volume (CTV) should be delineated on either 4DCT or 4DMRI. In addition, PET or SPECT 3D images should also be employed to accurately determine the true extent of the CTV. A full 4DCT image (multiple 3DCT images) acquired at each of the respiratory phases (at least eight) should be used to create an independent treatment plan for each phase. Or maximum intensity projection (MIP) images that can accurately trace the trajectory of a moving lung tumor should be used to generate ITV (Underberg, 2005, Bradley, 2006). In the case of a pancreatic cancer or a lung cancer that has low attenuation component or invades the surrounding airways, minimum intensity projection (MinIP) may be the optimal techniques for defining the ITV (Salles, 2007).

The physician contoured target and organs at risk (OAR) should be preserved through deformable image registration. Plans should be computed using adaptive dose calculation technique. Figures 2a-c show three orthogonal images of dose distribution of a lung patient, whose PTV was delineated based on the ITV from both the MIP images and PET/CT fused images.

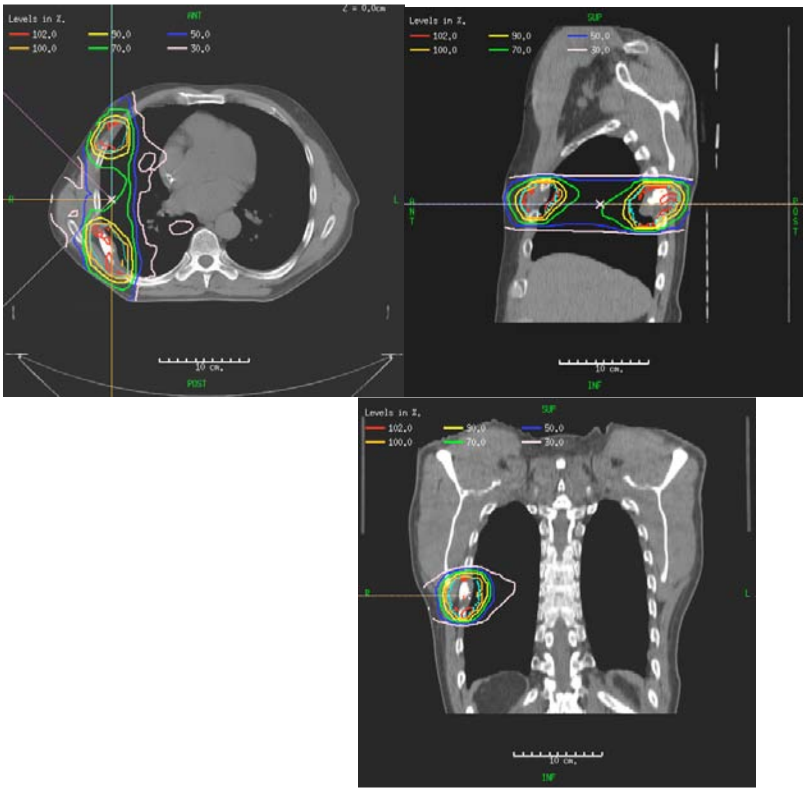

Fig. 2a. Axial image Fig. 2b. Sagittal image Fig. 2c. Coronal image

4D TREATMENT DELIVERY

On-site Imaging for Patient Setup: The 2D/3D/4D imaging of the patient in the treatment position should be used to improve setup accuracy. These include multiple 2D x-ray imaging (Figures 3a-c), optical 3D superficial imaging, kV cone-beam CT (CBCT) imaging (Figs. 4), helical MVCT imaging, and 4DCT imaging.

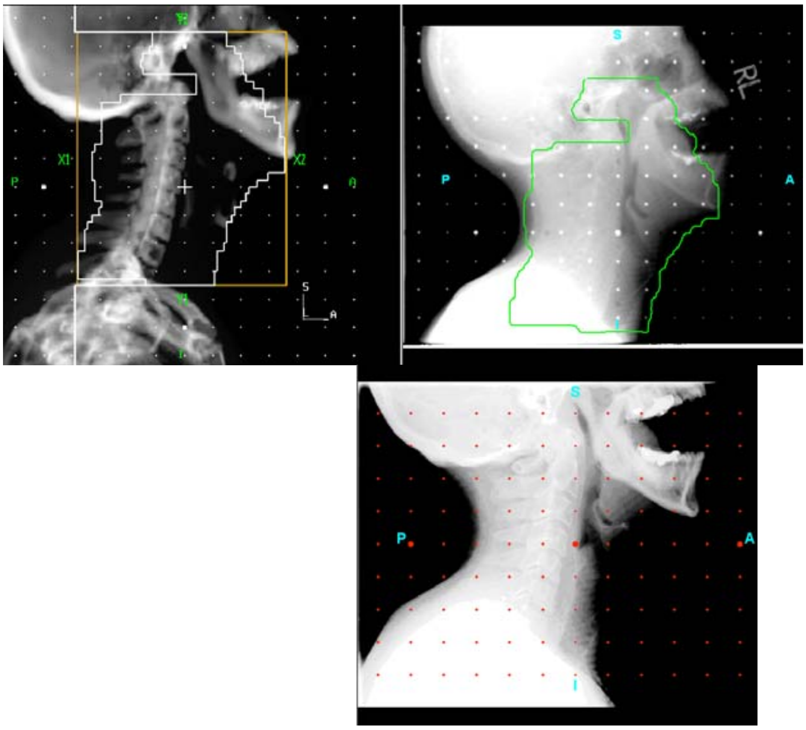

Fig. 3a. DRR from TPS Fig. 3b. Weekly PV field Fig. 3c. Daily KV imaging

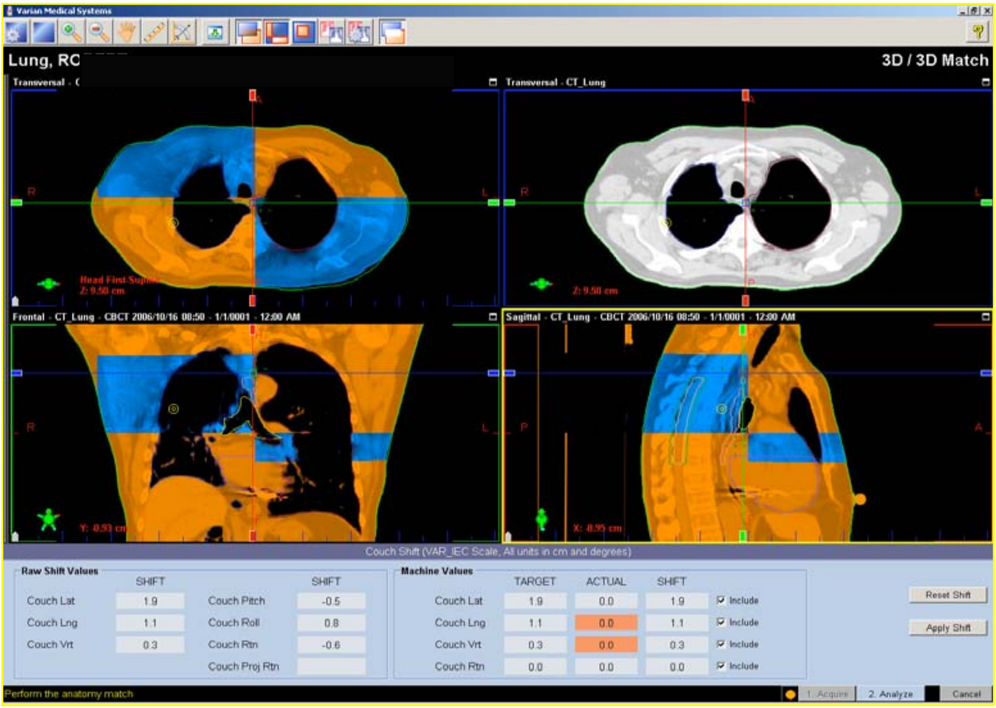

Fig. 4. 3D image registration of referenced CT and CBCT.

Real-time Target Tracking: Superficial motion tracking and external surrogates are useful in determining the extent of respiratory motion, but are not sufficient for tracking tumor motion and change in volume and shape. Therefore, internal fiducial markers should be implanted into or around the target to precisely deliver radiation to the tumor (Figures 5a-b).

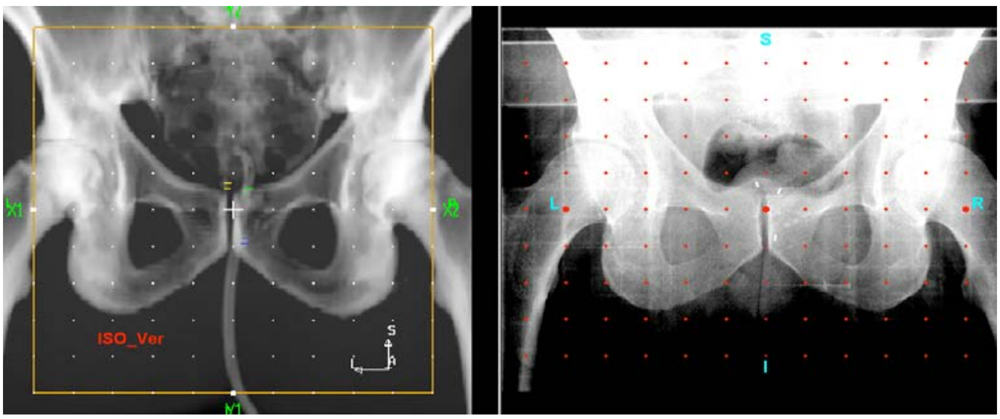

Fig. 5a. AP view - prostate implanted with 3 gold seeds.

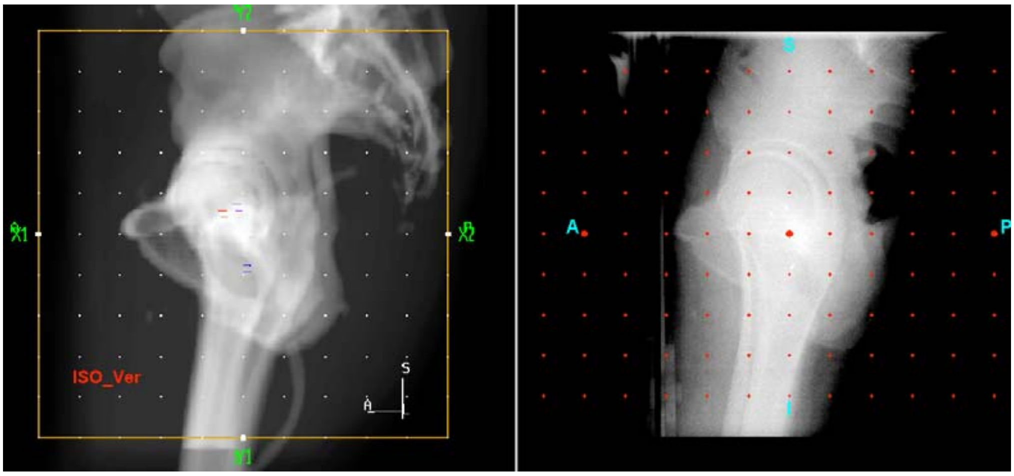

Fig. 5a. Left lateral view - prostate implanted with 3 gold seeds.

Real-time Dose Delivery: Real-time treatment delivery should be guided by a target tracking feedback system. Currently, this has not been feasible in most of the clinics. The key is the combination of the individual 4DRT components to form a clinically feasible approach.

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