International Journal of
Radiation Oncology
biology • physics

www.redjournal.org

Physics Contribution

A Four-Dimensional Computed Tomography Analysis of Multiorgan Abdominal Motion

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Received May 24, 2010, and in revised form Mar 10, 2011. Accepted for publication Jun 13, 2011

Summary

We quantify the four dimensional motion of multiple organs in the abdomen during respiration. The motion is described in terms of center of mass motion of each organ as well as the bounding box that characterizes motion extrema. Our results are critically compared with other studies using a variety of modalities and metrics. Abdominal organ motion is highly patient specific; gating near exhale substantially reduces the range of motion.

Purpose: To characterize and quantify multiorgan respiration-induced motion in the abdomen in liver and pancreatic cancer patients.

Methods and Materials: Four-dimensional computed tomography scans were acquired for 18 patients treated for abdominal tumors. Contours of multiple abdominal organs were drawn by the radiation oncologist at one respiratory phase; these contours were propagated to other respiratory phases by deformable registration. Three-dimensional organ models were generated from the resulting contours at each phase. Motions of the bounding box and center of mass were extracted and analyzed for the clinical target volume and organs at risk.

Results: On average, the center of mass motion for liver clinical target volumes was 9.7 mm (SD 5 mm) in the superior−inferior direction, with a range of 3 to 18 mm; for pancreatic tumors, the average was 5 mm (SD 1 mm) m with a range of 3 to 7 mm. Abdominal organs move in unison, but with varying amplitudes. Gating near exhale (T40−T60) reduces the range of motion by a factor of $\sim$10.

Conclusion: We have used deformable registration to calculate the trajectories of abdominal organs in four dimensions, based on center of mass and bounding box motion metrics. Our results are compared with previously reported studies. Possible reasons for differences are discussed.

Keywords: Abdominal organ motion, Liver, Pancreas, Four-dimensional computed tomography, Deformable registration

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Supported by Award Number P01CA021239 from the National Cancer Institute.

The content of this article is solely the responsibility of the authors and does not necessarily represent the official views of the National Cancer Institute or the National Institutes of Health.

Conflict of interest: none.

Acknowledgment—The authors thank Brian Napolitano for assistance in volume calculations and Paul Burkard for assistance in figure preparation.

0360-3016/$ - see front matter
doi:10.1016/j.ijrobp.2011.06.1970

Introduction

Precise knowledge and control of the dose distribution within the patient is essential in accurate radiotherapy. For moving targets, this begins with detailed knowledge of organ motion. In the abdomen, the primary source of organ motion is respiration. Knowledge of patient-specific motion is needed when designing a treatment plan (*e.g.,* aperture, beam angles, gating). Motion can change the radiologic depth from entrance surface to the target; its effect on photon therapy dose of moving lung tumors is small (1), whereas the potential effect on charged particle beam can be large (2, 3). Because critical organs adjacent to liver and pancreas tumors may be overirradiated by beam overshoot (particularly with proton or other charged particle beams), understanding respiratory-induced motion of abdominal organs may improve treatment planning of tumors within these organs.

Abdominal organ motion studies have been previously reported, using different imaging modalities, breathing protocols, and analysis metrics. One of the seminal papers on organ motion (before the availability of four-dimensional computed tomography [4DCT] and four-dimensional magnetic resonance imaging [4DMRI]) was written by Langen and Jones (4). More recently, 4D imaging modalities have been used in addition to helical CT, MRI, fluoroscopy, and ultrasound (2, 5−13). Organ motion has been reported in terms of center of mass (COM) motion, edge (bounding box) motion, and points of interest motion (fiducials). Organ motion data have been acquired under a variety of breathing conditions, including free breathing, breath hold, and deep inspiration breath hold. Data have been acquired from one breath cycle to ∼15 cycles. The various approaches affect both the values reported and the interpretation of their comparison.

In this analysis, we present our study of abdominal multiorgan motion of pancreatic and liver tumor patients. 4DCT data are used for the analysis, and the focus is primarily on the COM and bounding box motions. We compare our results with studies previously reported.

Methods and Materials

Patients studied

Eleven patients with liver cancer and 7 with pancreatic cancer treated with proton beam therapy were sequentially selected for this retrospective study. The image data were analyzed under a protocol approved by the institutional review board to retrospectively analyze anonymized 4DCT data. The patients included 11 men and 7 women (liver: 7 men and 4 women; pancreas: 4 men and 3 women). Two of the liver patients had two lesions each. After initial analysis, 2 patients were excluded because of irregular breathing, which resulted in severe image artifacts.

Four-dimensional computed tomography

Each patient received a 4DCT scan (Lightspeed RT16, GEMS, Waukeshau, WI) for treatment planning. Scans were acquired during (*1*) quiet breathing, without breath coaching, (*2*) respiratory monitoring (RPM, Varian Medical Systems, Palo Alto CA), and (*3*) in the supine position with both arms up. Field of view was typically 50 cm, with pixel size approximately 1 mm × 1 mm and slice thickness 2.5 mm. The 4DCT data were binned into 10 respiratory phases (T00−T90) wherein T00 was defined at end inhalation and T50 at end exhale.

Organ segmentation

The analysis relies on contours of an organ at each respiratory phase. Manual contouring of multiple structures at each phase is tedious. We therefore apply deformable registration (14) to aid contouring, as has been used by other investigators (2, 5). The deformable registration software propagates the physician-drawn contours at one respiratory phase to all other phases.

One physician (T.H.) contoured organs of interest on CT scans of liver and pancreatic tumor patients. Multiple structures contoured typically included the gross tumor volume, clinical target volume (CTV), liver, left and right kidneys, stomach, duodenum, large and small bowel, porta hepatis, superior mesenteric artery , and radiopaque clips if present. In most patients, contours were defined at the T30 respiratory phase (15). The choice of the midrespiration phase was dictated by the protocol because, for internal target volume (ITV) based treatment, it most closely approximated the average tumor position during the full respiratory cycle (16). In cases of larger tumor motion, gating was used in a respiration window between T40 and T60. In this scenario, contours of targets and normal structures were drawn on the T50 phase and propagated to T40 and T60. Scans of 2 patients treated with a gated beam were in the patient cohort.

Deformable registration validation

Deformable registration was performed using a three-stage multiresolution B-spline method, with a mean-squared error cost function and a minimum grid spacing of 25 mm. The B-spline method has been validated for lung 4DCT (17), and our current estimate of mean landmark accuracy in the lungs is 1.41 mm (18). In addition, we have validated the method for contour propagation in the thorax and have found that Dice coefficient values were within 2% of the interrater variability (19). To assess the accuracy of this method in the liver, we visually inspected the contours of the liver and kidneys on every axial slice and every breathing phase for 2 patients We observed differences as great as 2 cm in the axial view between the propagated contours and the soft tissue image, at the most superior images of the liver. These deviations arise from 4D imaging artifacts at the dome of the liver stemming from irregular breathing. In regions other than the superior liver−lung interface, the propagated contours typically agreed with grey level assessment of the liver border within 1 and 3 mm. To test the sensitivity of this inaccuracy on COM assessment, the noncongruent superior liver contours (on 1−2 slices) were manually redrawn and COM was recalculated. Changes in COM liver motion were minimal (∼1 mm).

We also performed a controlled phantom experiment to test the trajectory analysis software. Spheres were moved under known conditions to simulate respiration motion The peak-to-peak motion, was 3 cm with periodicity 3 seconds near the extrema of observed organ motion (20). Our software-derived trajectory was in agreement with ground truth by 1 mm in eight respiratory phases and within 3 mm for nine of the 10 phases.

Organ motion metrics

Three geometric parameters for each organ were quantified using in-house developed software, including COM motion, edge