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Fast MVCT: A rapid imaging method for total body or marrow irradiation in helical tomotherapy

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Abstract

Purpose—Megavoltage computed tomography (MVCT) imaging has been widely used for three-dimensional (3-D) setup of patients treated with helical tomotherapy (HT). One drawback of MVCT is its very long imaging time, owing to slow couch speeds of approximately 1 mm/s, which can be difficult for the patient to tolerate. We sought to develop an MVCT imaging method allowing faster couch speeds, and to assess its accuracy for image guidance for HT.

Methods and Materials—Three cadavers were scanned four times with couch speeds of 1, 2, 3, and 4 mm/s. The resulting MVCT images were reconstructed using an iterative reconstruction (IR) algorithm with a penalty term of total variation, as well as with a conventional filtered back projection (FBP) algorithm. The MVCT images were registered with kilovoltage CT images, and the registration errors from the two reconstruction algorithms were compared. This fast MVCT imaging was tested in three cases of total marrow irradiation as a clinical trial.

Results—Three-dimensional registration errors of the MVCT images reconstructed with the IR algorithm were smaller than the errors of images reconstructed with the FBP algorithm at fast couch speeds (2, 3, 4 mm/s). The scan time and imaging dose at a speed of 4 mm/s were reduced to 30% of those from a conventional coarse mode scan. For the patient imaging, faster MVCT (3

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Conflict of interest statement

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mm/s couch speed) scanning reduced imaging time and still generated images useful for anatomical registration.

Conclusions—Fast MVCT with IR algorithm is clinically feasible for large 3-D target localization, which may reduce overall time for treatment procedure. This technique may also be useful for calculating daily dose distributions or organ motion analyses in HT treatment over a wide area. Automated integration of this imaging is at least needed to further assess its clinical benefits.

Keywords

Megavoltage computed tomography; Fast scan; Iterative reconstruction; Registration; Tomotherapy

INTRODUCTION

Helical tomotherapy (HT) (Accuray™, Madison WI, USA) has been widely used for intensity-modulated radiation therapy (IMRT) (1,2). The treatment couch is moved at a fixed rate through the gantry as the radiation source rotates around the patient. Because the maximum couch translation distance is 160 cm in the superior-inferior (SI) direction (3,4), HT enables the delivery of highly conformal dose distributions to large and complex targets while simultaneously reducing doses to organs at risk (OARs). There have been several studies of HT in large targets such as total body irradiation, total lymphoid irradiation, and total marrow irradiation (TMI), with favorable outcomes (4-12).

Megavoltage computed tomography (MVCT) has been used for daily 3-D target localization before each treatment fraction, calculation of daily dose distribution, and/or organ motion analysis (13,14). Although MVCT is suitable for targets localization, the scan time of MVCT is very long for large targets such as bone marrow. It takes more than 800 seconds for a 100 cm scan length even in coarse scan mode (1.2 mm/s). Reducing MVCT scan time will be essential to successfully implement routine clinical use of body-wide treatment with HT.

Recently, 2-D orthogonal images from MVCT detector data were developed for patient setup (15,16), which also led to a reduction in imaging time. In particular, XXXXXX et al. (16) showed how whole-body MVtopo imaging can be generated and utilized for rapid whole-body 2-D localization before TMI treatment delivery. Although, MVtopo images can help to gain a coarse estimation of patient position, volumetric anatomical information cannot be ascertained in this 2-D imaging. Three-dimensional MVCT is used not only for patient setup and daily organ motion analysis, but also for actual dose estimation and adjustment using deformable registration techniques to monitor changes in target morphology and volume. However, conventional 3-D MVCT requires very long scan time, adversely affecting patient comfort and impairing worldwide acceptability of TMI. Therefore, to overcome the limitations of the previously used two imaging modalities, we report here the feasibility of a new “Fast MVCT” imaging system.

It has been reported that an iterative reconstruction (IR) algorithm (17–19) can maintain the CT image quality even with a limited number of projections. Unlike the conventional filtered back projection (FBP) algorithm, the IR algorithm can easily handle incomplete data. In this study, we investigated fast 3-D MVCT imaging in two steps. First, using cadavers, we developed an MVCT reconstruction method with faster couch speeds based on the IR algorithm, and compared the registration accuracy with that of the conventional FBP algorithm. Second, we implemented this optimized model in a clinical setting to assess the feasibility of this approach in routine use.

METHODS AND MATERIALS

Data Acquisition

Approval for use of cadavers was given by the University Anatomy Bequest program in accordance with the XX. Patient studies were approved by the University Institutional Review Board (XXXXXXX).

In this study, images of three cadavers were acquired using 3-D MVCT. The rationale for using cadavers is to mimic as closely as possible the physical characteristics of a patient. Cadavers were taken for the study within 12–24 h of their deaths to obtain fresh tissue characteristics. We used a stereotactic body frame (SBRT) and Vaclok such that the external shape and position were fixed. Each cadaver was additionally aligned on the couch by a skin marker with a laser system, and scanned four times with couch speeds of 1, 2, 3, and 4 mm/s (The couch speed of conventional MVCT scanning is 0.4, 0.8, and 1.2 mm/sec for fine, normal, and coarse modes, respectively). All MVCT sinogram data were acquired with the following settings: 0.05 mm jaw size, all multileaf collimators open, 10 s/gantry rotation. The compression factor was set to 1 (no compression) with imaging accelerator output mode and detector sampling rate of 80 Hz. The detector sinograms were collected from the data server, and converted to a binary file using proprietary software (TDAT®, Accuray™, Madison WI, USA). In this study, 528 (the 65th–592nd) xenon gas-filled detector cells were used for the reconstruction. Using in-house software, the sinogram data was normalized with air scan data to correct nonuniform detector cell response (20).

Three images of TMI patients with 3 mm/s couch speed were also acquired using the same settings.

Reconstruction Algorithm

The 3-D MVCT images were generated using an iterative reconstruction (IR) algorithm constrained total-variation minimization, as has been reported (17–19). We have briefly summarized the practical equations in this section. The image $\hat{I}$ was reconstructed based on a penalized log-likelihood-based objective function as follows:

$$\hat{I} = \underset{I}{\operatorname{argmax}} \{ \ln(p(n|I)) - wTV(I) \}, \quad (1)$$

where $p(n|I)$ is a conditional probability that n photons are observed at the detector when reconstructed image I was acquired, $TV(I)$ is a penalty term with total variation (TV), and w is a weight for $TV(I)$ (here, we employed $w = 0.01$). In this study, we defined $p(n|I)$ as a Poisson distribution as follows:

$$p(n|I) = \prod_{i=1}^M \frac{\left(n_0 e^{-\sum_j a_{ij} I_j^*}\right)^{n_i}}{n_i!} e^{-n_0 e^{-\sum_j a_{ij} I_j^*}}, \quad (2)$$

where n_0 is the initial number of photons incident on to the i -th detector cell from the source, a_{ij} is the path length traversed by the photon passing through the j -th voxel (so-called system matrix element), I_j^* is the expectation value of the linear attenuation coefficient of the j -th voxel, n_i is the number of observed photons at the i -th detector, and M is defined as the product of the number of detector cells and the number of projections used for reconstruction (800 projections over 360° were used to reconstruct each slice). In this study, the following 2-D total variation was used as a penalty term (19):

$$TV(I) = \int_{\Omega} |\nabla I| dx dy \approx \sum_{m,n} \sqrt{(I_{m,n} - I_{m+1,n})^2 + (I_{m,n} - I_{m,n+1})^2}, \quad (3)$$

where Ω is 2-D image plane, ∇I is the gradient of image I , m and n are the voxel numbers in the x and y directions in the reconstructed image I . Eq (1) was iteratively solved (21), and the reconstructed images were output after 200 iterations. For comparison, the MVCT data were also reconstructed based on the conventional FBP algorithm using a Shepp-Logan filter (21).

Imaging Dose Measurement

The MVCT imaging doses at various couch speeds were measured using a 0.053 cc ionization chamber (A1SL®, Standard Imaging™, Madison WI, USA). The ionization chamber was inserted 0.5 cm inferior to the center of a cheese phantom (TomoPhantom®, Accuray™, Madison WI, USA).

Registration Accuracy Validation

MVCT images acquired at the various couch speeds were registered to kilovoltage computed tomography (kVCT) images acquired with a Philips Big Bore® CT scanner (Brilliance Big Bore®, Philips™, Eindhoven, the Netherlands). Three-dimensional translational shifts were calculated based on commercialized registration software (RayStation®, RaySearch Laboratories AB™, Stockholm, Sweden). All kVCT and MVCT images had a matrix size of 512×512 and a pixel size of 1.17 mm. Please note that the field of view (FOV) was extended to 60 cm from the conventional FOV of the HT system (40 cm). Section thickness was 6.0 mm for MVCT (same as coarse mode) and 5.0 mm for kVCT, which were used for our routine clinical practice. Registration error was defined as the difference between the couch movement associated with setup corrections at each couch speed and that of the slowest couch speed with the FBP algorithm.

RESULTS

Comparisons of Various Couch Speeds

Figs. 1(a) and (b) show a kVCT image and a coarse mode MVCT image of a cadaver, respectively. The conventional MVCT could not reconstruct the arm regions because of the more limited field of view (FOV) (40 cm). The scan time of the coarse mode MVCT was 833 seconds for a 100 cm scan length, which was the fastest scan in the conventional MVCT mode.

Table 1 shows a scan-time and imaging dose comparison among various couch speeds. The scan distance was set at 100 cm in the superior/inferior direction in this study. If a couch speed of 4 mm/s was used, both scan time and imaging dose were shortened to 30% of those of coarse mode. Figures 2 shows MVCT images reconstructed with the algorithms. Soft tissues (e.g., liver, kidney) are clearly visualized in the images with IR algorithm even in the 4 mm/s couch speed. Although it was impossible to completely reconstruct arm regions because of the narrower FOV of the HT, the visible arm regions were better visualized using the IR algorithm than with the FBP algorithm. Figure 3 shows the convergence properties of the IR algorithm. The convergence properties are almost the same for each couch speed. In addition, the effects of the reconstruction algorithm and increased couch speeds were quantified by the signal to noise ratio (SNR), contrast to noise ratio (CNR), and HU constancy value in supplemental Figure S1. The images reconstructed by the IR algorithm had a better SNR, CNR, and HU constancy than the images reconstructed by the FBP algorithm. Comparing the couch speeds, there are no consecutive trends.

Registration Accuracy

Figure 4(a) shows registration accuracy for the FBP algorithm. The registration error increased in the superior/inferior direction as couch speed increased. Figure 4(b) shows registration accuracy using MVCT reconstructed with the IR algorithm. The mean registration error was < 3 mm in all directions. Although the weight w for the total variation term in Eq. (1) and the number of iterations for the IR algorithm were empirically set to 0.01 and 200, respectively, the influence of those two parameters on the reconstructed images was tested in the supplemental Figure S2. As a result, the registration errors were <3.5 mm with the parameters shown in the supplemental Figure S2.

Imaging Trial in TMI patients

Figure 5 shows an example of a TMI patient kVCT, conventional MVCT with a fastest scan mode in the HT system (1.2 mm/s couch speed), and fast MVCT images reconstructed using the IR algorithm. In this study, we chose a 3 mm/s couch speed for the first clinical trial. The mean registration errors of right-left, inferior-superior, and posterior-anterior directions were -0.4, -1.6, and -0.4 mm for conventional MVCT, and -0.5, 1.2, and 1.6 mm for fast MVCT, respectively. Maximum registration error was < 5 mm in both conventional and fast MVCT results. In our limited samples of patient imaging in TMI, we observed that the fast imaging was equally effective as conventional imaging for target localization. Moreover, the scan time and imaging dose at the 3 mm/s couch speed were reduced to 40% of those of the conventional (coarse mode) scan.

DISCUSSION

The very long imaging time needed for patient localization, particularly for long targets in HT, has been an issue, adversely affecting patient comfort and impairing worldwide acceptability of TMI. Using a cadaveric translational model and fast MVCT image reconstruction with IR image processing, we reduced the imaging time significantly without degrading image registration accuracy. This 3-D fast imaging development further improves upon our previously established 2-D imaging-based (16) methodology to measure rigid body motion and organ deformation. This information is essential for actual dose estimation and may allow adjustments to enhance TMI dose delivery precision.

The IR algorithm maintained registration accuracy even with fast couch speeds. Although the FBP algorithm has been widely used to reconstruct CT images, our results showed a larger registration error than those with the IR algorithm at faster speeds. The main reason for the registration error seen in FBP is poorer CT resolution in the SI direction. As the couch speed increased, the top of the head and shoulders were less clear, as seen in Fig. 2(a). Such a situation does not occur with use of the IR algorithm, which can produce higher-quality images with the limited projection data. Using the IR algorithm allowed for a faster scan technique that shortened the patient setup time without sacrificing registration accuracy when imaging a long target. Although the IR algorithm used in this study was created by an in-house code, there are many open source codes available to the public. Moreover, this imaging development effort is a part of a global health initiative of the international consortium of total marrow irradiation “ICTMI.” Therefore, our next step will be to share the source code and recruit patients in participating centers.

As shown in Fig. 5, the entire body outline was visualized by the IR algorithm. However, monitoring of daily translational motion or deformation by the MVCT scans is feasible for the organs located inside the FOV. In our clinical experience, almost all pediatric patients and adult patients of smaller size fit within this FOV. The arms in large adult patients, though, stay outside the FOV, limiting the MVCT scan. However, the arms were fixed within a specific mold and held fixed with a vest at the chest level indexed within the stereotactic body frame. Thus, for large patients, a planning kVCT image has been used to supplement gaps in the information for arms, etc., outside the FOV to calculate the daily dose distribution in the current system (Planned Adaptive ® software, Accuray™, Madison WI, USA). In this case, the dose distribution cannot correctly calculate if the arm and/or shoulder is moved or deformed. Instead of using kVCT, by reconstructing the MVCT images based on the proposed method with an extended FOV, nonlinear movement and deformations of the arm/shoulder can be visualized. However, our method still has an uncertainty in the HU constancy, especially between regions inside the conventional and extended FOVs. To overcome this problem, a density override technique (22) might be needed. Then, the daily dose distribution can be calculated for the fast MVCT images.

The parameter w in Eq. (1) and the number of iterations for the IR algorithm were empirically set to 0.01, and 200, respectively. Though there is a potential to increase registration accuracy with optimal parameter values, it might have a low impact because the mean registration error was less than 3 mm in the current cadaver results. In addition, as

shown in Eq. (3), the 2-D TV penalty term was used in the IR algorithm. Although the effect of the 3-D TV term was reported by Persson et al. (23), the registration accuracy with the 2-D TV term was better than the 3-D one in our analysis. In particular, mean $\pm$ standard deviation of registration errors at 4 mm/sec couch speed was 2.66 ± 2.24 for the 2-D TV, and 3.49 ± 2.58 for the 3-D TV term. This may be due to the fast couch shift. The usage of far voxel information in the TV term might reduce the registration accuracy.

This report, to the best of our knowledge, is the first attempt to use a cadaveric model to develop and implement MVCT imaging techniques in a clinical setting. The novelty of this study is as follows: First, the cadaveric model provides real human tissue equivalent image visualization that is closest to live human patients. Second, cadaver imaging offers more information on how increased couch motion could affect the visualization of human anatomy. Third, cadavers offer the inter individual differences not represented by phantoms. Fourth, the cadaver model offers a unique opportunity for rapid translation from bench to bedside.

Obviously, the effect of body motion, especially breathing, cannot be evaluated in cadavers. Our group has started a phase I clinical trial of TMI (6) with new patient positioning methodology (16). Further imaging assessment in patients undergoing TMI will allow the procedure to be validated. We will test the feasibility of this imaging in multiple centers through an international consortium of total marrow irradiation (ICTMI). Additionally, fast MVCT is expected to be useful shortening imaging time (and potentially increase patient comfort) for other treatments with long target extensions such as total body irradiation, Cranio-spinal irradiation (CSI), and head & neck cancer.

One of the limitations of the iterative reconstruction algorithm is the computational cost. It takes approximately 20 s/slice for FBP and 10 min/slice for IR with our workstation (20 CPUs of 3.1 GB Intel Xeon® and 62.8 GB memory). On-the-fly reconstruction during the scanning will reduce the wait time. By using on-the-fly reconstruction, the calculation for the reconstruction can be started immediately after obtaining one data slice. Also, there are several reports of graphics processing units (GPUs), which could reduce computational cost of the IR algorithm (24,25). Jia et al. (24) in 2010 that the reconstruction time of cone-beam CT volume data with an iterative reconstruction algorithm could be shortened to 77–130 s (100 times faster than conventional approaches) by using the NVIDIA Tesla C1060 (NVIDIA, Santa Clara, CA) GPU card. In our case, we are estimating the latest CPU/GPU will reduce the reconstruction time to 30 s/slice or faster, and all slices can be reconstructed concurrently by parallelization. XXXXXX et al. (16) reported a patient setup method with 2-D orthogonal images from HT detector data. Although the scan and registration time for 2-D imaging is shorter, 2-D imaging lacks the ability to visualize 3-D anatomical locations, which can be obtained using our fast MVCT imaging. The use of a human body (instead of Rando phantom) provided a new opportunity to gain a greater understanding of the physiological system in physical space using MVCT. For example, supplemental Figure S2 shows how various optimization parameters can enhance the distinguishability of soft tissue, bone, air, connective tissue, and the framework of the lungs. The lung and bone interface is perhaps the most sensitive region for dose escalation strategies because of the potential for lung toxicity. 3-D imaging is essential, not only for detailed patient localization, but also for

the calculation of daily dose distribution and organ motion analysis. In future work, we should investigate a parallelized algorithm with GPUs to achieve real time reconstruction of fast MVCT.

Our study has several other limitations. First, because of the total-variation regularization, low contrast structures tended to be smoothed in the IR algorithm. In future work, the other regularization terms, such as prior image constrained compressed sensing (26), should be incorporated into the IR algorithm to increase image quality. Second, the small sample size makes the statistics less reliable. We will test the feasibility of the fast MVCT in larger clinical trials in future work.

CONCLUSIONS

In conclusion, with this combination of cadaveric and patient studies, we have demonstrated the clinical feasibility of fast MVCT to significantly reduce overall time for treatment procedures. The IR-based reconstruction algorithm with fast couch speeds improved registration accuracy over that of the FBP algorithm. The proposed method could be useful for fast patient 3D localization with a long target. Automated integration of this imaging technique is a must to further assess its clinical benefits.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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SUMMARY

We report the feasibility of a new “Fast MVCT” imaging modality to improve total marrow irradiation (TMI) treatment management. Using human cadavers, we acquired multiple whole-body megavoltage CT images with iterative reconstruction (IR) algorithm at increasing couch speeds in helical tomotherapy. The scanning time and the imaging radiation dose could both be reduced by employing the IR algorithm with minimal registration error. We also confirmed these findings in three TMI patients.

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Figure 1.

(a) Kilo-voltage computed tomography image (kVCT), which was used for validating registration error, and (b) megavoltage computed tomography image (MVCT) in conventional coarse scan mode, of a cadaver.

Figure 2.

MVCT images, which were reconstructed with (a) the conventional filtered back projection (FBP) algorithm, (b) iterative reconstruction algorithm with various couch speeds (1–4 mm/s).

Figure 3.

Relationship between iteration number and sum of squared difference between current iteration and one iteration before the current iteration images reconstructed by iterative reconstruction algorithm.

Figure 4. Relationship between registration accuracy and couch speed; (a) Registration error of kVCT and MVCT using FBP algorithm, (b) Registration error of kVCT and MVCT with iterative reconstruction (IR) algorithm.

Figure 5.
Comparison of total marrow irradiation patient images: (a) kVCT image, (b) conventional MVCT in coarse mode, and (c) fast MVCT reconstructed with IR algorithm.

Table 1

Scan time and dose for megavoltage computed tomography (MVCT) at various couch speeds. Time ratio is the ratio of the actual time to the coarse mode scan time.

Couch speed	Coarse mode (1.2 mm/s)	1 mm/s	2 mm/s	3 mm/s	4 mm/s
Total scan time (s)	833	1000	500	333	250
Time ratio (%)	100	120	60	40	30
Imaging dose (cGy)	0.721	0.899	0.449	0.286	0.216