MEGAVOLTAGE CONE-BEAM CT: SYSTEM DESCRIPTION AND CLINICAL APPLICATIONS

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Abstract—In this article, we describe a clinical mega-voltage cone-beam computed tomography (MV CBCT) system, present the image acquisition and patient setup procedure, discuss the positioning accuracy and image quality, and illustrate its potential use for image-guided radiation therapy (IGRT) through selected clinical examples. The MV CBCT system consists of a standard linear accelerator equipped with an amorphous-silicon flat panel electronic portal-imaging device adapted for mega-electron volt (MeV) photons. An integrated computer workspace provides automated acquisition of projection images, image reconstruction, CT to CBCT image registration, and couch shift calculation. The system demonstrates submillimeter localization precision and sufficient soft-tissue resolution to visualize structures such as the prostate. In our clinic, we have used the MV CBCT system to detect nonrigid spinal cord distortions, monitor tumor growth and shrinkage, and locate and position stationary tumors in the lung. MV CBCT has also greatly improved the delineation of structures in CT images that suffer from metal artifacts. MV CBCT has undergone significant development in the last few years. Current image quality has already proven sufficient for many IGRT applications. Moreover, we expect the range of clinical applications for MV CBCT to grow as imaging technology continues to improve. © 2006 American Association of Medical Dosimetrists.

Key Words: External beam, Image-guided radiation therapy, Radiotherapy imaging, MV cone-beam CT.

INTRODUCTION

Image-guided radiation therapy (IGRT) refers to the use of patient imaging in the treatment room to increase the conformality of the radiation dose to the tumor, improving tumor control, and reducing normal tissue complications.

The development of image-guidance tools and techniques in radiotherapy has been greatly motivated by the continual advances in external beam radiation delivery. With 3-dimensional (3D) conformal radiotherapy and intensity-modulated radiotherapy (IMRT), it is now possible to deliver radiation doses that conform tightly to the tumor volume. Many clinical studies and simulations indicate that these more conformal, higher dose treatments can decrease both the spread of disease and normal tissue complications.1-5 However, as the planned dose distributions conform more closely to the pretreatment planning computed tomography (CT), the precision of dose delivery becomes limited by the validity of using the planning CT to represent the patient on the treatment table throughout an extended course of treatment. Organs may change in size, shape, and position from day to day and week to week due to normal anatomical variability, as well as due to the patient’s reaction to radiation therapy, such as tumor shrinkage or weight loss.6-10 Therefore, patient anatomical and positional information that can be obtained immediately before treatment is extremely valuable.

Imaging has long played a key role in assuring the accuracy of radiation therapy treatment. Recent implementation of highly sensitive and automated on-board electronic portal imaging devices (EPIDs) now enables daily low-dose portal imaging to visualize and adjust the patient position before each treatment. However, the utility of portal imaging to adjust the patient position is limited by reduced soft-tissue and 3D geometrical visualization caused by projection onto a 2-dimensional (2D) plane. This has motivated the development of 3D imaging of the patient while lying on the treatment table. Because CT is the current standard for localization of soft-tissue organs and target in treatment planning, there is a growing interest in CT imaging in the treatment room. Several systems have been developed including (1) a “CT on rails” system11,12 requiring an additional diagnostic (CT) machine in the treatment room; (2) a kilovoltage cone-beam CT (kV CBCT) system13,14 consisting of an additional kV x-ray source and detector attached to the treatment gantry; (3) a mobile C-arm
kilovoltage imager\textsuperscript{15}; (4) a megavoltage cone-beam CT (MV CBCT) system\textsuperscript{16,17} using the pre-existing treatment machine and EPID for imaging; (5) an MV CT system\textsuperscript{18,19} using the pre-existing treatment machine with an attached change arc of detectors; and (6) a tomotherapy system\textsuperscript{20} replacing the traditional treatment machine (beam) with a CT ring and an MV beam source. The potential clinical applications of these IGRT technologies will depend on imaging performance, which continues to improve for many of the systems. As we learn more about patient anatomical variability using in-room 3D imaging, more clinical applications will also become apparent. In general, the goal is to provide more accurate and reproducible patient setup. The possibility of delivered dose verification combined with in-room imaging is also being explored and should provide an extra level of verification in the radiotherapy processes.

We present the recent developments in MV CBCT, describe an MV CBCT system, including the time required for acquisition and setup, the positioning accuracy, and the image quality. Then, a few chosen clinical examples are presented to illustrate how MV CBCT can be used for patient setup based on bony anatomy and/or soft tissue, to identify non-rigid deformation of the patient anatomy on the treatment couch and to monitor anatomical changes due to weight loss or tumor response. The superiority of MV volumetric imaging in presence of metallic objects is also demonstrated. Finally, ongoing research to improve image quality is discussed, as well as research to combine image guidance with dose verification.

**BASICS OF MEGAVOLTAGE CONE-BEAM CT**

A cone-beam CT image is reconstructed from a set of open-field projection images acquired at different positions around the patient. The process is similar to conventional CT, which uses the signal from a single row of detectors to reconstruct a slice. For conventional CT, the 3D image is formed by translating the patient and imaging several slices. For CBCT, a 2D detector array is used and the reconstructed data set is a direct 3D image without multiple gantry rotations, table movement, or slice artifact. For MV CBCT, projection images are acquired using a radiotherapy linear accelerator (linac) with photons primarily in the mega-electron volt (MeV) energy range.

**Historical perspective of 3D MV imaging**

Approximately 20 years ago, researchers in radiation oncology first used a linac beam for 3D imaging. These early systems reconstructed 2D slices using a fan-beam geometry.\textsuperscript{21,22} Recently, MV fan-beam CT has been integrated into the helical tomotherapy system (Tomotherapy Inc., Madison, WI).\textsuperscript{20,23} As the technology of 2D x-ray detectors has advanced,\textsuperscript{24} cone-beam reconstruction systems have become increasingly feasible. Several researchers have acquired MV CBCT images using standard linacs with liquid-filled ionization chamber detectors,\textsuperscript{25} video-based EPIDs,\textsuperscript{25,26} and amorphous silicon (a-Si) flat panel detectors.\textsuperscript{27,28} In much of the early work, signal was maximized by applying high doses (50–200 cGy). Strategies such as the development of more sensitive detectors\textsuperscript{29,30} and the restriction of the imaging volume to the treatment volume\textsuperscript{31,32} have reduced these doses to clinically acceptable values and will continue to decrease imaging doses. Other developments include the adaptation of MV CBCT for lung tumor visualization by synchronizing image acquisition with respiration.\textsuperscript{16}

The University of California San Francisco (UCSF), in collaboration with Siemens Oncology Care Systems, has been working on the clinical implementation of MV CBCT for the last 5 years. Our first MV CBCT imaging system has been previously described.\textsuperscript{17} During this times, we have reduced exposure and improved image quality using a special triggered acquisition,\textsuperscript{33} reduced the acquisition time, demonstrated soft-tissue contrast\textsuperscript{34} and, recently, initiated a clinical patient setup study comparing portal imaging to MV CBCT.

**Soft-tissue visualization using kV and MV imaging**

The shared use of the linac beam for treatment and imaging is inexpensive and convenient. However, the use of MeV photons for imaging is a departure from the general preference for kilo-electron volt (keV) beams in diagnostic imaging. The basic physics of x-ray interaction with matter can be used to explain the tradeoffs between using keV or MeV beams for imaging in radiotherapy. The visibility of large low-contrast objects in tomographic images, for example the prostate, depends on the contrast-to-noise ratio. Contrast is determined by the differential attenuation of the beam through different bodily tissues. In the MeV range, Compton scattering provides the majority of the beam attenuation. Due to the small energy dependence of Compton interaction, the contrast in MeV imaging is thus relatively constant over a large energy range. However, the greater dose per photon deposited by MeV photons reduces the imaging beam intensity that may be applied given patient dose constraints, thus reducing the signal. Moreover, the attenuation coefficient differences between bodily tissues are smaller for MeV energies, diminishing image contrast. The other important parameter, noise, includes the statistical fluctuation of photon detection as well as any source of unwanted radiation (i.e., radiation containing no imaging information). In transmission imaging, the x-rays reaching the detector consist of unscattered (primary) and scattered (secondary) components. The primary fluence produces the signal in the resulting image, while the secondary fluence introduces noise and image artifacts and produces quantitative inaccuracies in the reconstructed CT numbers. The magnitude of scatter reaching the detector depends on the photon energy, the
field size, the object (size and composition), and the object-to-detector distance. The fan beam geometry rejects a considerable amount of scattered radiation, while the cone-beam geometry exposes the detector to scatter radiation. For a typical kV CBCT pelvic image (cone angle $\sim 10^\circ$) acquired with the optimal air gap, the scatter-to-primary ratio (SPR) is greater than 170%, leading to CT number inaccuracies on the order of 40%. Methods of reducing the effects of scatter include changing the acquisition parameters (dose, field-of-view, voxel size, etc.), using an antiscatter grid, performing preprocessing of the 2D projection raw images, and applying post-processing on the 3D reconstruction. Antiscatter grids have been studied for kV images but, so far, have not greatly improved the contrast-to-noise ratio for high-scatter acquisitions. For an MV projection image of a pelvis (cone angle $\sim 14^\circ$), the SPR is much smaller, on the order of 20–40%. The small energy dependence of MeV photon interaction also makes the scatter fluence less dependent on the patient internal anatomy. The reduced effect of scatter for MeV images greatly narrows the difference in kV and MV cone-beam imaging quality. The lower dependence of the scatter on the exact patient anatomy may also make it easier to correct MV CBCT for scatter and allows for the accurate calibration of the voxel intensities into electron or physical density. Simple MV CBCTs of 2 water cylinders (pelvis and head-size cylinders) have been used with good results to develop geometric models of correction factors that reverse the spatially-induced cupping artifact. This correction of the nonuniformity caused by scatter allows dose calculation to be performed directly on the MV CBCT image.

**Imaging system**

Our clinic has 2 in-room MV imaging systems capable of portal imaging and cone-beam CT. Both systems consist of a standard treatment unit, one Primus™ and one ONCOR™ linear accelerator (Siemens Medical Solutions, Concord, CA) equipped with an amorphous silicon (a-Si) flat-panel adapted for MV photons. The $41 \times 41$ cm$^2$ flat-panel x-ray detector (AG9-ES, PerkinElmer, Optoelectronics) consists of a 1-mm copper plate and a Kodak Lanex Fast scintillator plate (Gd$_2$O$_2$S:Tb) overlaid on top of light-sensing and charge-integrating thin-film transistor (TFT) array. The flat panel has 1024 $\times$ 1024 TFT detector elements with a pitch of 0.4 mm. The detector is mounted on a retractable support, which deploys in less than 10 seconds with a positional reproducibility of 1 mm in any direction. The entire imaging system, presented in Fig. 1, operates under a prototype SYNGO™-based COHERENCE™ therapist workspace, which communicates to the control console, the linac, and a local patient database. The workspace contains applications allowing for the automatic acquisition of projection images, image reconstruction, CT-to-CBCT image registration, and couch position adjustment. Each projection of the CBCT acquisition is corrected for defective pixels, as well as for pixel-to-pixel offset and gain variations before 3D reconstruction.

**Imaging geometry**

In conventional CT, the relative source and detector positions are constant during rotation, and analytical equations can be used to describe the geometry of the reconstruction. The linac x-ray source and an EPID positioner, however, often lose their ideal isocentric positions as the gantry rotates, due to sagging of the mechanical supports. A geometric calibration is performed to correct for this effect and conserve image quality. The position of the EPID must then only be reproducible for the calibration to remain geometrically accurate. The absolute position of the reconstruction volume isocenter is determined by the placement of the calibration phantom during geometric calibration. The room lasers are used to accurately place the phantom at the isocenter. The validity of the calibration method was verified by reconstructing a gold seed placed at isocenter with the room lasers. The center of the seed was located at the central voxel of the reconstruction, as expected. Simulations indicate that lateral deviations from the calibration geometry as small as 1 mm cause streaking artifact around high-contrast regions, while longitudinal deviations create shifts in the reconstruction volume, potentially introducing setup errors. Our system was found to be reproducible to better than 1 mm in both directions over several months.
tions are conducted to assure image quality and will be used to track the system long-term geometrical stability.

Imaging procedure

An MV CBCT acquisition is similar to an arc treatment. The user first creates imaging template protocols by specifying the total dose for a CBCT acquisition (2–60 monitor units [MU]), the reconstruction size (128, 256, or 512), and the slice interval (1, 2, or 3 mm). A CBCT acquisition field is added to the existing patient treatment field list using one of the pre-defined CBCT protocols, which contain all the information needed by the system to perform the acquisition (field size, start and end angle, total dose, flat panel distance, etc.). The field parameters are directly transferred to the control console of the linac and the user can rapidly place the system in position for imaging. The linac gantry then rotates in a continuous 200° arc (270° to 110°, clockwise), acquiring one portal image for each angle. This acquisition procedure lasts 45 seconds. The image reconstruction starts immediately after the acquisition of the first portal image, and a typical $256 \times 256 \times 274$ reconstruction volume ($1.1 \times 1.1 \times 1.0$ mm$^3$ voxel size) is completed in 110 seconds. The reconstructed MV CBCT and the raw projection images are saved in the patient database as DICOM images.

3D setup method

The MV CBCT imaging procedure is well integrated in the clinical workflow for patient alignment. Upon start of the MV CBCT acquisition, the reference planning CT of the patient is automatically loaded into the COHERENCE™ Adaptive Targeting registration software, with the anatomical contours and the points of interest (Fig. 2a) defined in the planning system. Immediately after reconstruction, the software automatically registers the MV CBCT with the reference CT using a maximization of mutual information algorithm. Further manual adjustment of the registration in any of the typical planes (axial, coronal, and sagittal) is possible. In the current software version, rotations have been disabled from the registration. The system can display each CT with different color scheme, and the transparency levels can be adjusted to visualize either CT or the MV CBCT image sets. The table shift correction is constantly updated as the user fine-tunes the registration. The shift represents the distance between the planned treatment isocenter as specified on the CT image during planning and the true treatment isocenter, which correlates intrinsically to the center voxel of the MV CBCT reconstruction. The table shift needed to align the treatment image with the diagnostic CT is typically available 3 minutes after the start of the MV CBCT acquisition.

System validation

To validate the new setup method, MV CBCT images (1 mm$^3$ voxel size) and orthogonal portal images of a phantom with 3 embedded gold seeds were obtained with the phantom positioned at 30 different known locations in the treatment field. The initial alignment of the seeds served as the reference position. The Syngo-based COHERENCE™ therapist workspace was used to measure the applied translations using the Portal Imaging (2D-2D) and the Adaptive Targeting (3D-3D) registration applications. The mean and standard deviation of the differences between the applied shift and the measured shift were 0.0 mm and 0.25 mm, respectively, for both data sets. This indicates that MV CBCT used with the Adaptive Targeting tool has the potential to verify patient shifts with submillimeter precision. Portal imaging was also demonstrated to be highly accurate in identifying translations of gold seeds.

Similar measurements were performed using an anthropomorphic head phantom (Rando) to compare a 2D setup technique using digitally-reconstructed radiographs (DRR) and portal images with a 3D setup technique using a diagnostic CT and MV CBCT images. Two CT scans were acquired on Rando using (A) a typical spiral 3-mm slice thickness, and (B) a fine sequential 1-mm slice thickness. The CT room laser alignment was marked on Rando using 3 small fiducials. The images
were imported into the planning system and a simple 2-field plan was created using the fiducials to define the treatment isocenter. Two pairs of orthogonal DRRs were created using CT scans (A) and (B). Finally, the plan, the CT scans, the treatment isocenter points, and the DRRs were transferred to the treatment unit. The Rando head was then aligned on the treatment table and translated to 30 different locations in the treatment field. For each position, a pair of orthogonal portal images was acquired to compare with the coarse (A) and fine (B) DRR references. MV CBCT images were also acquired at each position to compare with CT scans (A) and (B) in the Adaptive Targeting application. Only the automatic registration was used to align the MV CBCT acquisitions with the CT scans. The standard deviation of the differences between the applied shift and the measured shift was 0.4 mm and 0.9 mm for the 3D registration using the fine and the typical CT scans, respectively. This suggests that finer CT scans are more accurate for patient positioning using 3D alignment. Because the registration was almost entirely based on bony anatomy, there was no difference in the setup accuracy using the 2D or 3D method. However, the possibility of verifying setup in every plane in 3D greatly facilitated the process of obtaining the shift. Three-dimensional alignment should also provide an added benefit in the case of object rotation, which was excluded in the 2 described studies. Future work will include small rotations to study how they affect the shift assessments made using the 2D and 3D methods.

CLINICAL APPLICATIONS

The MV CBCT system described above offers several image-guided techniques outlined in Fig. 3. One possibility is the monitoring of intrafraction motion of high-contrast features or fiducial markers using the flat panel in ciné mode. This could be used to gate treatments for anatomical sites where in-treatment motion may be problematic. With the same system, portal imaging can be used to ensure setup based on bony anatomy or gold seeds. Finally, with the introduction of an MV CBCT acquisition mode, it is possible to perform 3D setup based on bony anatomy and soft tissues to determine patient specific anatomical variation using images. This new information can be used to tailor the treatment plan for future fractions to account for the individual’s variation. The application of this technique to different anatomical sites will depend on the ability to visualize the relevant organs.

The following sections describe the work that has been done to introduce MV CBCT in the clinic. Our IGRT objectives are to improve target positioning and to monitor anatomical changes as the treatment progresses. The patient acquisitions performed so far have demonstrated that MV CBCT provides information about the patients that was not available with portal imaging. Several studies are underway to determine the best usage of these new images.

Patient acquisitions

To date, 90 acquisitions have been performed on a total of 45 patients. The anatomical sites imaged include head and neck, lung, and pelvis. All patients imaged with MV CBCT are required to give informed consent, and the image acquisitions are performed in accordance with the institutional review board’s ethical standards. The patients enrolled in our setup study are positioned on the table using traditional immobilization devices and markings and are aligned with the room lasers. Both an MV CBCT and an orthogonal pair of 2D portal images are acquired in this initial position. The patients are then aligned using the orthogonal portal images compared with the reference DRRs. The applied shift is recorded and compared offline with the shift that would have been applied using MV CBCT. The dose used for MV CBCT

![Image of Fig. 3](image-url)
images ranges from 2 to 15 MUs depending on the frequency of the acquisition and on the anatomical site.

Figure 4 provides a comparison of a diagnostic CT (left) with the MV CBCT (right) performed on the first day of treatment for a typical head-and-neck patient. The window level of both sets of images was adjusted to provide the best soft-tissue contrast.

Patient dose in MV CBCT

The dose delivered to the patient during the MV CBCT was estimated using a commercial treatment planning software (Philips Pinnacle, Bothell, WA). An arc treatment was simulated on typical prostate and head-and-neck patients. With our current acquisition settings (projection angles and field size), the dose at the centers of the head and prostate were 0.9 and 0.75 cGy per MU, respectively. The maximum dose reached 1.24 cGy/MU in a small anterior portion of the field of view. Although the dose delivered during MV CBCT imaging is generally negligible compared to the therapy dose, this extra dose could easily be taken into account in the patient’s treatment plan.

MV CBCT for prostate patient setup

The prostate can shift daily up to 1 cm relative to pelvic bones due to gas and variations in rectal/bladder filling. The variability in rectal distension can decrease the probability of biochemical control, local control, and rectal toxicity in patients who are treated without daily image-guided prostate localization. At UCSF, most prostate patients treated by external beam radiotherapy have 3 gold markers implanted in the prostate, which are visualized daily on orthogonal portal images for alignment. Gold seeds are implanted via a minor invasive procedure, usually well tolerated; however, this may not be feasible or appropriate in all circumstances. Patients are asked to have their bladder full and an empty rectum at the time of treatment to place the gland at the most inferior and posterior position in the body. In the example we present below, a typical prostate patient was aligned using the 3 markers on portal images. After setup but prior to treatment, the patient was imaged with MV CBCT. A total dose of 10.8 cGy (in the center of the prostate) was used to obtain the MV CBCT image. A large portion of the nonuniformity effect caused by scattered radiation was removed from the MV CBCT reconstruction using a gain calibration performed with solid water in the field of view. This had the effect of compensating for the additional signal in the center of the panel caused by scattered radiation on a given projection.

The axial and coronal views of the patient diagnostic CT with anatomical contours are presented on Figs. 2a. Figure 2b shows that MV CBCT is capable of volumetric imaging with a good amount of soft-tissue information. Structures such as the prostate, the rectum, muscles, fat, air cavities, and gold seeds can be seen. It is clear by comparing the gold seeds on Fig. 2a and 2b that MV imaging performs better in the presence of metal objects. Figure 2c represents the patient anatomy prior to treatment fused with the reference anatomy and the anatomical contours of the planning. Despite some minor change in the rectum filling, the prostate shape and position at the time of treatment matches well with the anatomy on the diagnostic CT. In the presence of gold seeds, we have found that MV CBCT acquisitions of less than 2 MU can be used for direct 3D alignment. Figure 2c, however, shows the potential of using MV CBCT to align the patient based on soft tissue without the need of gold seeds. MV CBCT acquisitions of approximately 9 MU are currently required on typical pelvic patients for consistent prostate visualization without the need of gold seeds. By superimposing the anatomical contours on the CBCT image, the user may verify the impact of daily changes in rectum filling on the definition of the gross
tumor volume (GTV). More accurate treatment schemes using MV CBCT images could be studied by displaying anatomical contours and isodose lines from the treatment plan on the MV CBCT. Therapists could ensure, for example, that the rectal wall would not receive more than a limit dose on a given day of treatment.

**MV CBCT for evaluating complex spinal cord displacement during setup**

In this example, a patient with a T2N2b squamous cell carcinoma of the hypopharynx was imaged during radiation treatment using MV CBCT. The patient was positioned using an aquaplast head-and-shoulder mask indexed to the treatment couch. Originally, a TIMO-C head holder was used, which provided a more pronounced angle of neck flexion during treatment. A standard CT was used to obtain images for IMRT treatment planning. MV CBCT images were acquired at various times during treatment. Orthogonal pairs of 2D portal images were also obtained at the time of MV CBCT acquisition to compare the 2 modalities.

Figure 5a displays a DRR of the patient as initially simulated and planned. Easily visible structures such as the posterior vertebral bodies, base of skull, anterior maxilla, and aquaplast mask are outlined. Several weeks into the treatment, an MV CBCT and a corresponding set of portal images were acquired for this patient. Figure 5b shows the outlines from Fig. 5a superimposed on this portal image. Although the base of skull and mask line up well, the line of the anterior maxilla is not aligned with the current position of the anterior maxilla. Additionally, the line of the posterior vertebral bodies is difficult to compare with the spinal anatomy. Figure 5c displays a sagittal image from the MV CBCT (gray scale) overlaid on the planning CT (color). The 2 sets of images have been registered to obtain an overall alignment based on the anatomy of the skull and face, as was similarly done using the 2D technique.

As seen in Fig. 5c, the patient alignment using the MV CBCT and planning CT allows for further assessment of not only global position, but also the relative positions of structures. Although the base of the skull is well aligned, a 6-mm difference in the position of the anterior vertebral bodies between the planning CT and the MV CBCT is clearly visible. The patient was subsequently resimulated using a head holder with less flexion (TIMO-B) to place the patient in a robust and more comfortable position. Once this plan was complete, an additional MV CBCT was obtained, as seen overlaying the new planning CT in Fig. 5d. Comparison of the new MV CBCT and planning CT indicates that overall alignment, from the base of skull and along the vertebral bodies, was significantly improved using the new setup.

In this case, MV CBCT provided clear, informative images that allowed a more complete evaluation of patient setup. The 2D portal images did show some variation in patient positioning, but did not reveal the origin and the full magnitude of the misalignment. Using MV CBCT images, we were able to measure the magnitude of the misalignment, identify its source (a distortion of the neck), and confirm the correction of the problem. MV CBCT was a critical tool that led to replanning for more accurate treatments.

**MV CBCT to monitor anatomical changes**

In this next example, a patient with a T4bN1 squamous cell carcinoma of the nasal cavity was imaged using MV CBCT at various times while under treatment with external radiation therapy. The tumor involved the right nasal cavity and extended anterolaterally into the maxillary sinus and posteriorly to the nasopharynx. Prior to treatment, the extent of tumor was only evaluable on CT or magnetic resonance imaging examination. The tumor was unresectable, and the patient was treated definitively with concurrent chemoradiation. A conventional noncontrast CT was used to obtain base images for treatment planning. Four MV CBCTs were obtained during the course of radiation treatment in an effort to assess tumor anatomy variation that could not otherwise be easily visualized.

Representative images of the planning CT and 2 subsequent MV CBCTs are shown in Fig. 6. T0 represents the start of radiation treatment. Examination of the
MV CBCTs revealed an obvious soft-tissue density within the right maxillary sinus. The air interface present anteriorly provided excellent contrast with the soft-tissue density. In comparison, the left maxillary sinus was completely air filled, as seen on the planning CT and subsequent MV CBCTs. These images show that there is more soft-tissue density within the right maxillary sinus on the first MV CBCT (T₀ + 6 days) as compared to the original planning CT (T₀ − 14 days). This may indicate that there was tumor growth between planning and start of treatment. A comparison of the first (T₀ + 6 days) and second (T₀ + 14 days) MV CBCT shows some decrease in the amount of soft tissue in the cavity.

The amount of air filling for each side of the maxillary sinus at the given timepoints was calculated. This is plotted for the right (tumor affected sinus) and the left maxillary sinus (uninvolved sinus) in the figure. If we were to assume that the soft-tissue density within the affected sinus were exclusively tumor, rather than a combination of tumor and secretions, this quantitative assessment of air volume within the sinuses may serve as a surrogate for tumor response. This example demonstrates the potential of this imaging modality to monitor changes in target volume that are not otherwise evaluable.

The variation in target volume over a course of treatment may have important dosimetric consequences that require replanning. At what point during treatment a patient needs to be replanned is currently difficult to define. Because the MV CBCT images are obtained in the treatment position, it is possible to project the radiation treatment plan onto these images to assess the exact daily delivered dose.

**Dose calculation using MV CBCT**

A recent validation study of dose calculation using MV CBCT in a commercial planning system was performed to assess the dose calculation accuracy. An IMRT plan for a nasopharyngeal carcinoma was first defined using a conventional CT. On the first day of treatment, an MV CBCT acquisition was acquired. The patient anatomy and position on the MV CBCT was in good agreement with the initial CT. The same plan (isocenter, contours, and beams) was applied to the MV CBCT image, which had been corrected for nonuniformity and calibrated for electron density. The isodoses and the dose-volume histograms from the regular CT and the MV CBCT were in very good agreement. A gamma function was computed to compare quantitatively the 2 dose distributions. The dose calculation accuracy using MV CBCT was better than 3% or 3 mm everywhere. This result opens the possibility of using MV CBCT to monitor the dosimetrical impact of setup errors, local deformations, weight loss, and soft-tissue shrinkage/swelling.

**MV CBCT to perform setup for lung tumor**

An MV CBCT was used to position a patient with a T2N0M0 squamous cell carcinoma of the lung. The patient had refused surgery and, therefore, was treated with definitive radiation therapy. At the time of fluoroscopic simulation, the tumor was noted to be immobile. This is obviously not the case for most lung tumors. The isocenter was placed within the tumor volume and a nongated planning CT was obtained.

A hypofractionated course of radiation was prescribed, and it was therefore exceedingly important to ensure accurate set up of the tumor within the field. For this reason, and because of the reduced number of fractions, MV CBCT was used for daily setup.

On the first day of treatment, a pair of orthogonal portal images and an MV CBCT was acquired. The MV CBCT images were aligned with the planning CT using the soft-tissue mass itself to ensure adequate tumor dose. On the first treatment day, 2 additional MV CBCTs were
obtained to verify this positioning method; the first following the applied shift, and the second after treatment delivery to evaluate any intrafraction motion during the 20 minutes of IMRT treatment. The post-shift MV CBCT showed excellent alignment with the planning CT, and the post-treatment MV CBCT remained well aligned. On subsequent days, a single MV CBCT was performed for positioning.

As an academic exercise, the measured shift that could have been made using only 2D portal images for positioning was applied to the MV CBCT and reference CT images. As can be seen in Fig. 7, if the sternum is aligned (Fig. 7c), the tumor in the right lung is not (Figs. 7a and 7b), and would be underdosed. A similar misalignment of tumor happens when the MV CBCT and the planning CT are aligned based on vertebral body position, a common way to verify the position of thoracic patients.

MV CBCT to complement planning for patient with dense metal objects

Metal artifacts on diagnostic CT images cause a significant problem for identifying structures. Several post-processing algorithms have been developed to reduce the image degradation. However, the level of artifact reduction is still only adequate on images affected by small metal objects, such as gold seeds. In comparison to the keV energy range, the presence of high atomic number (Z) material has relatively little impact on the image quality of MV CBCT. Therefore, MV CBCT images can be used to complement missing information during planning or patient position verification. Figure 8 demonstrates the superiority of MV CBCT in the presence of metal objects. An MV CBCT was performed on a patient who underwent major reconstruction of the left portion of the pelvis. Figures 8a and 8b compare the same sagittal and axial slices on the diagnostic CT (left) and the MV CBCT (right). Figure 8c shows that only the MV cone-beam image, which was window leveled to show the metal pieces, can render the 3D object correctly.

The presence of metal artifacts in CT makes it impossible to use the CT numbers quantitatively for dose calculations. For these cases the treated volume is usually assumed to be water-equivalent in the treatment plan calculations. Treating the volume as water and ignoring the presence of metal may cause severe deviations between the planned dose distribution and the real dose delivered. Ongoing research is being performed to calibrate the MV CBCT for direct use in dose calculations, thus allowing for more accurate dose calculations using inhomogeneity corrections. Currently at UCSF, most prostate patients with hip prosthesis undergo an MV CBCT acquisition to complement the CT during the contouring process in the planning system. Other cases where MV CBCT could be used include patients with dental amalgam or implants, orthopedic implants or prostheses, and high-dose-rate brachytherapy catheters.

**FUTURE DIRECTIONS**

We have described the performance of a clinical MV CBCT system and discussed some of its possible
uses in IGRT. Despite the simplicity of the system, which consists of a conventional linac with an attached EPID, we have been able to locate objects with millimeter accuracy and visualize a variety of organs, including the prostate. Clinically, MV CBCT has already proven useful to evaluate the alignment of the spinal cord, locate and position immobile lung tumors, track the evolution of tumors in the sinus, and improve the delineation of structures in CT images that suffer from metal artifacts. These examples demonstrate the potential for MV CBCT to increase our understanding of the patient position on the treatment table and improve tumor targeting.

Soft-tissue resolution is key for in-room 3D imaging to complement the offering of portal imaging. Using our current MV CBCT system, we are able to visualize the prostate using approximately 9 MU. Ongoing research to improve image quality will further increase soft-tissue resolution. Monte Carlo simulations and experiments have demonstrated that using a lower-Z target generates more low-energy photons and enhances the contrast of portal images significantly. In fact, simply removing the flattening filter causes contrast improvement in the order of 200%. Combinations of target and flattener have been studied to optimize the combined applications of therapy and high-contrast megavoltage imaging. Recent acquisitions of MV CBCT on a sheep head and on a CT contrast phantom using a carbon target and no flattening filter showed contrast resolution on the order of 0.5% for a dose of 3.5 cGy. The difference in density between the prostate and the surrounding tissues is in the order of 1–4%. With the improved beam line, one could project the resolution of the prostate and optic nerve with 1–2 cGy. Clinical images will soon be acquired with the new beam line to determine the extent of soft-tissue resolution.

New adaptive filtering schemes for MV imaging have also been developed and showed important noise reduction on projection images. Finally, the biggest improvement in image quality might come from the detector itself, using denser and new scintillation materials, which would push the detection efficiency peak toward the photon energies of the treatment beam. The net result of all these efforts is that the contrast-to-noise ratio can still be significantly improved, which will allow MV CBCT to become a routine option for a wider range of clinical applications.

While the use of 3D imaging to account for the patient anatomy at treatment time is a great advance in assuring radiotherapy accuracy, the true determining factor for treatment outcomes is the dose delivered to the patient. MV CBCT may also play a key role in tracking the dose distributions delivered to the patient. As previously mentioned, we are currently researching the correction of MV CBCT image artifacts and the calibration of MV CBCT for electron or physical density. The calibrated MV CBCT images could be used to recalculate the dose delivered by the treatment plan to obtain a more accurate estimate of the true delivered dose. Another possibility under investigation is the additional use of the EPID during treatment to measure the energy fluence delivered by the linac. The measured fluence and the MV CBCT of the patient would be used together to estimate the delivered dose. In this case, the effect of both patient anatomical changes as well as linac delivery errors could be assessed. These dosimetric verifications may provide additional information, which can be used to further optimize and improve radiation therapy treatments.

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