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The Role of In-Room kV X-Ray Imaging for Patient Setup and Target Localization

Report of AAPM Task Group 104

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The Role of In-Room kV X-Ray Imaging for Patient Setup and Target Localization

Report of Task Group 104 of the Therapy Imaging Committee American Association of Physicists in Medicine

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

In-room kilovoltage (kV) x-ray imaging has become a widely accepted practice for radiotherapy patient setup and target localization. In-room kV imaging refers to radiographic imaging using kV x-ray sources in the radiation treatment room. Task Group 104 (TG-104) reports on the various in-room systems that are commercially available using one or more kV imaging modalities. In-room kV imaging systems are divided into three categories: *rail-track–mounted systems, ceiling/floor-mounted systems,* and *gantry-mounted systems.* Several distinct systems have been made commercially available, each with unique capabilities, limitations, and levels of operational complexity. A hybrid system is also introduced, which combines two different mounting systems. TG-104 reports on the configurations, specifications, and operational principles of each of these in-room kV x-ray imaging systems. Methods by which these systems can be used to improve treatment accuracy and their limitations are discussed. The report also provides an overview of the issues related to effective implementation of these systems for routine clinical procedures. General guidance is made for appropriate acceptance testing and quality assurance of these systems for safety, image quality, and data management. The report includes a review of image-guided processes in the clinical setting, and strategies for effective modification of these processes based on clinical data. Several noteworthy works in progress towards the development of kV- based image guidance are briefly discussed in this report. It is the desire of this Task Group to provide useful information to the radiation therapy community to facilitate the implementation and operation of high- quality kV x-ray image guidance for radiation therapy.

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I. INTRODUCTION

In radiation therapy, it is imperative that the clinical target volume (CTV) be accurately positioned during treatment in order to avoid the detrimental effects of a geographic miss. Historically, a patient is positioned based on skin marks, and the treatment setup is verified with megavoltage (MV) portal imaging. The obvious limitations of this approach are (1) low subject contrast at MV energies and (2) the use of two-dimensional (2D) projections of bony landmarks to infer the accuracy of three-dimensional (3D) setup and target localization. As such, a substantial planning target volume (PTV) margin is added to the CTV to compensate for the uncertainty in patient setup and organ motion. International Commission on Radiation Units and Measurements (ICRU) reports 50 and 62 formally define planning volumes and margins (ICRU 1993,1999). Portal imaging is traditionally done only on a weekly basis. The philosophy of portal imaging in the past has been focused on quality assurance (QA) of major errors in treatment ports or setup errors, with less emphasis on daily image guidance for more accurate treatment delivery. With the advent of conformal radiation therapy (CRT) and intensity-modulated radiation therapy (IMRT), the margin dictated by conventional simulation and portal imaging limits the new potential for exquisite, conformal dose delivery and normal tissue sparing. A wide variety of in-room imaging methods have been developed over the last decade to ensure more accurate patient setup and target localization and to facilitate margin reduction.

The major challenge of treatment verification with conventional portal imaging technology is the low subject contrast at MV energies. Improvements in the quality of these images have been achieved through the development of low-noise digital imaging devices. These developments have culminated in the commercial availability of large-area amorphous silicon (a-Si) detectors that offer portal image quality limited only by the inherent physics of image formation at MV energies (Munro and Bouius 1998; El-Mohri, Jee et al. 2001). Ideally, one would want to achieve similar levels of contrast-detail detection in the treatment verification images as those used for treatment simulation and planning. For this reason investigators began pursuing in-room kilovoltage (kV) imaging.

While the focus of this task group report is on the use of in-room kV x-ray imaging, it is worth mentioning that the use of MV imaging for image guidance has also evolved over the past decade. Advances in detector technologies have greatly enhanced the visualization of implanted opaque markers in MV projection images as a means of assisting target localization. MV helical (Mackie, Holmes et al. 1993) and cone beam (Pouliot, Bani-Hashemi et al. 2005) computed tomography (CT) technologies have also been developed utilizing the treatment x-rays. These systems have been shown to be largely effective in clinical applications. There is a perception that the contrast-detail quality of these MVCT images is less than that acquired at the kV energies, although a rigorous quantitative study has yet to be performed. On the other hand, it is clear that MVCT images of subjects with high density contain fewer artifacts than kVCT images. A full description of the physics and applications of MV projection and CT imaging for image guidance is a rich topic, which is beyond the scope of this report.

This Task Group was formed to address the on-line and off-line application of in-room kV x-ray imaging. The on-line approach adjusts the treatment parameters or patient position based on data acquired during the current treatment session. This may be as simple as adjusting

the couch position or as complex as full re-optimization of the treatment parameters based on changes in the shape and relative position of target and normal structures. The off-line approach is one in which the intervention is determined from an accumulation of information that may be drawn from previous treatment sessions or other times of measurement. Here, in-room kV imaging refers to radiographic imaging using one or more kV x-ray modalities in the treatment room. At present, several kV imaging developments have evolved into commercial products offered by major manufacturers. There is a clear eagerness in the radiation therapy community to embrace kV x-ray imaging technologies for localization. The various in-room kV x-ray imaging systems offer important and unique capabilities but also have distinct limitations. Effective implementation of these new technologies requires a clear understanding of the capabilities and limitations and how they relate to specific clinical goals. There are also issues regarding the possible reduction of margins, and the associated demand on personnel and infrastructure resources.

The purposes of the Task Group are to (a) review the current existing kV x-ray systems used in the radiation treatment room, including system configurations, specifications, operation principles, and functionality, (b) discuss the current clinical applications and methods that could be used to improve treatment accuracy as well as their limitations, (c) discuss issues related to routine clinical procedures for effective implementation, and (d) discuss issues related to acceptance testing and quality assurance. The goal of TG-104 is to produce a comprehensive report on the effective selections and clinical applications of these emergent technologies. The guidance provided in this report is not intended for regulatory use.

I.A. Imaging Techniques

It is useful to review the in-room kV imaging techniques that are currently used in the community. There are three major classes:

(1) **Radiographic Imaging:** The most basic imaging technique is the acquisition of 2D projection or planar images. This capability is available on all systems described in this report, except the rail-track–mounted systems that could produce digitally reconstructed radiographs (DRRs). The size of the object imaged is dependent on the size of the detector and the distance between the detector and imaging object.

(2) **Fluoroscopic Imaging:** Fluoroscopic imaging is a continuous stream of planar x-ray images acquired in real time during patient setup or treatment. It allows real-time monitoring and verification of treatment structures, based on visible anatomical landmarks or implanted fiducial markers. The information can be used for the management of intrafractional patient motion and organ motion and the adjustment of treatment in some cases.

(3) **Tomographic Imaging:** The acquisition of many projections at different gantry angles allows the generation of volumetric CT images through various reconstruction methods. Helical CT and cone beam CT (CBCT) methods are both available with certain in-room kV imaging systems.

I.B. Historical Perspective on In-Room kV Imaging in Radiation Therapy

The use of kV x-ray imaging for setup verification is not new. By the late 1950s the use of kV x-ray sources in the treatment room had been implemented in a variety of ways. These included a separate kV x-ray system and cobalt-60 treatment unit linked through the use of a mobile couch (Karolinska University Hospital [Sweden]); a kV x-ray source attached to the beam stopper of a cobalt-60 unit (Holloway 1958); the development of a customized cobalt-60 unit (Johns and Cunningham 1959) and linear accelerator (Weissbluth, Karzmark et al. 1959) which employed in-line x-ray tubes; a cobalt-60 unit and a kV x-ray tube mounted at 90 degrees from each other on a circular ring (Netherlands Cancer Institute [NKI], Amsterdam); and a cobalt-60 unit with an x-ray tube mounted to the collimator at a well-defined angle with a graticule for optical and radiographic projections (Shorvon, Robson et al. 1996).

For example, the Ontario Cancer Institute's X-otron cobalt-60 unit, shown in Figure I-B-1, was put into operation in 1958 with a kV x-ray source mounted in the head slightly above the position assumed by the cobalt-60 treatment source during irradiation (Johns and Cunningham 1959). Portal images acquired with this system result in a slightly smaller beam's eye view (BEV) of the patient than the geometric edge of the treatment field. In a different design, the Stanford University medical accelerator used an industrial (anode grounded) x-ray tube that could be inserted into an opening below the x-ray target of the accelerator. This generated a slightly larger BEV of the patient than the geometric edge of the treatment field since the kV source was approximately 10 cm closer to the patient than the MV treatment source. Note that in the Stanford design, the x-ray tube had to be withdrawn before treatment.

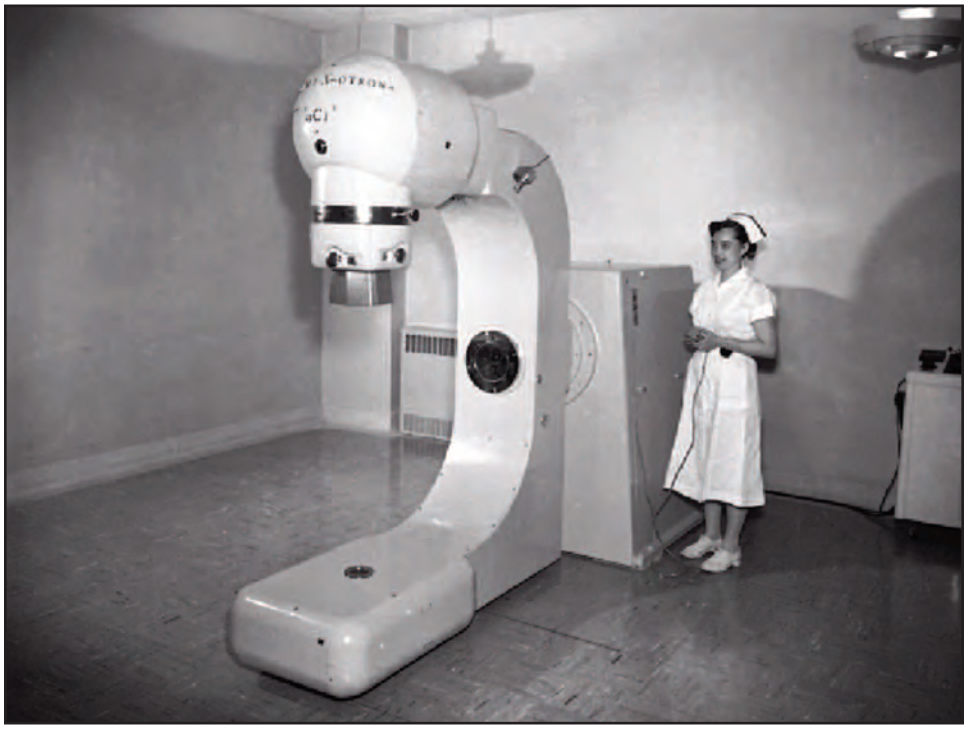

Figure I-B-1. Ontario Cancer Institute's X-otron cobalt-60 unit. (Reprinted from Fig. 7.1, p. 261, *The Modern Technology of Radiation Oncology, Volume 2*, J. Van Dyk (Ed.), with permission from Medical Physics Publishing.)

Very little progress was made with these early innovations until the mid 1980s when Biggs et al. (Biggs, Goitein et al. 1985) mounted an offset kV x-ray source to a 10 MV medical accelerator at Massachusetts General Hospital. In 1987, Shiu et al. described a setup verification technique by exposing a cobalt-60 treatment beam and an offset gantry-mounted kV beam on the same screen/film system, thereby yielding diagnostic quality verification images (Shiu, Hogstrom et al. 1987). In these early gantry-mounted methods, the gantry would be rotated to move the kV source in place for generating the necessary double-exposed image on a single imaging system (film). These efforts evolved into the RADII product by HRL Inc, which was used primarily for performing simulation on a medical accelerator.

Besides the use of an add-on kV source, Galbraith experimented with low-*Z* accelerator targets for generating kV or near-kV x-rays for imaging (Galbraith 1989; Ostapiak, O'Brien et al. 1998). This was followed by Cho and Munro in 2002 (Cho and Munro 2002), who presented the design of a new x-ray target for producing both kV and MV beams. This latter concept awaits further development, perhaps due in part to the necessary modification of the accelerator manufacturing process. Faddegon et al. also experimented with a low-*Z* target to improve MV cone beam CT images (Faddegon, Wu et al. 2008).

The group in Japan must be acknowledged with the foresight to integrate the function of a CT scanner with the medical accelerator in the treatment room via the use of a communal couch and software utilities (Akanuma, Aoki et al. 1984; Uematsu, Fukui et al. 1996). That achievement marked the beginning of the modern era of image-guided radiation therapy (IGRT) emphasizing soft-tissue localization.

During the 1990s, development of in-room kV imaging systems took on more fervent activities, spurred by the improvement of electronic portal imaging devices (EPIDs) and the anticipation of flat-panel detector (FPD) technologies. In 1993, Mackie et al. proposed a concept to integrate a kVCT/linac system and described the in-room image-guided process (Mackie, Holmes et al. 1993). In 1994, Stanford University began treating radiosurgery patients with a robotic linear accelerator guided by the dual orthogonal kV imaging systems, the first version of the CyberKnife® system (Murphy and Cox 1996). In 1998, the group at the University of Michigan (Schewe, Lam et al. 1998) described a diagnostic x-ray imaging system consisting of a pair of wall-mounted x-ray tubes and a novel portable charge-coupled device (CCD)-based imager to acquire orthogonal kV images. In 2000, Shirato et al. (Shirato, Shimizu et al. 2000) introduced a system using four ceiling-mounted fluoroscopic imagers and four opposing floor-mounted kV sources to track implanted radiopaque markers in real time. During this period, these efforts were paralleled by the independent development of commercial ceiling/floor-mounted kV image guidance methods for radiosurgery by Accuray Inc. (Sunnyvale, CA) in the mid 1990s and BrainLAB Inc. (Feldkirchen, Germany) in 2001 (Adler, Murphy et al. 1999; Yin, Ryu et al. 2002).

The configuration of mounting a kV system to the treatment machine gantry is the modernized extension of the systems of Biggs et al., and Shiu et al. Unlike the portable image intensifier system as developed by Sephton et al. (Sephton and Hagekyriakou 1995) to produce digital image capabilities from a gantry-mounted kV source, Jaffray et al. (Jaffray, Chawla et al. 1995) described a dual-beam imaging system consisting of both kV and MV imaging systems. This system featured a kV source mounted at 45 degrees from the MV source and a shared CCD imag-

ing device. With radiographic and fluoroscopic imaging capabilities, the system rapidly evolved into a device that was also capable of tomographic imaging using CBCT methods. This device featured MV and kV sources mounted 90 degrees apart and dedicated CCD imaging devices for each source (Jaffray, Drake et al. 1999). That effort eventually led to the development of the Synergy® accelerator, first marketed by Elekta Inc. (Stockholm, Sweden) for IGRT. Also available commercially are the similar On-Board Imager® (OBI) kV imaging system marketed by Varian Medical Systems (Palo Alto, CA) starting in 2003 and the ARTISTE™ solution proposed by Siemens (Concord, CA) in 2007. A hybrid imaging system combining the Varian OBI system and the BrainLAB floor/ceiling-mounted system became available for clinical application in 2008.

In addition to the kV imaging in the photon treatment room, kV imaging in the other types of radiation treatment rooms underwent somewhat parallel developments. In the United States, fast neutron beam treatment heads circa 1980 had integral kV systems to provide better contrast than neutronography (Almond, Marbach et al. 1981; Marbach 1981; Myers, Miller et al. 1987; Risler and Jacky 1991; Maughan and Yudelev 1999). Proton and other light ion treatments have used in-room kilovoltage x-ray systems for daily pre-treatment patient alignment since the first treatments in 1954 (Tobias, Anger et al. 1952; Lawrence 1957; Larsson, Leksell et al. 1958; Lawrence, Tobias et al. 1958; Kjellberg, Sweet et al. 1962; Chen, Singh et al. 1979; Lyman and Chen 1979; Verhey, Goitein et al. 1982; Saunders, Chen et al. 1985; Miller 1995; Blair, Lesyna et al. 1998; Murakami, Kagawa et al. 2002; Hishikawa, Oda et al. 2004; Smith 2006). These systems were required because the treatment beams did not exit the patient to make an image. More than 50,000 patients at some 20 institutions around the world have been aligned with these systems over the years. For example, in the early days, institutes such as Lawrence Berkeley Laboratory, Gustav Werner Institute (Sweden), Harvard Cyclotron Laboratory, and ITEP (Institute of Theoretical and Experimental Physics—Russia) installed orthogonal kV x-ray tubes in room with film (Chuvilo, Goldin et al. 1984) and contemporarily, institutes like M.D. Anderson Cancer Center (MDACC, Houston, TX) and University of Florida Proton Therapy Institute (UFPTI) installed orthogonal kV x-ray tubes in room with flat-panel detectors. Recently, a CBCT imaging system controlled by a robotic arm was installed at Heidelberg University for its heavy particle facility treatment room (Haberer, Debus et al. 2004). These systems were required for particle treatment because the treatment beams did not exit the patient to make an image. It should be noted that some of the pioneering use of in-room imaging systems for particle therapy probably stimulated some of the later works in in-room imaging for photon therapy.

I.C. Process of Care

The general clinical workflow (or process) of image-guidance in the treatment room using radiographic imaging includes steps shown in Figure I-C-1. The workflow could vary among institutions, users, imaging systems, and applications such as correction strategy, etc. As will be discussed in section IV.C., there are two main strategies: on-line correction (Figure I-C-1a) and off-line correction (Figure I-C-1b). With any strategy selected, radiographic imaging could be achieved using any type of imaging systems and any type of imaging methods (2D radiographs, fluoroscopy, and 3D tomographic images). This image-guidance workflow includes three stages of imaging: (1) imaging after initial setup (In-room imaging I); (2) imaging after correction

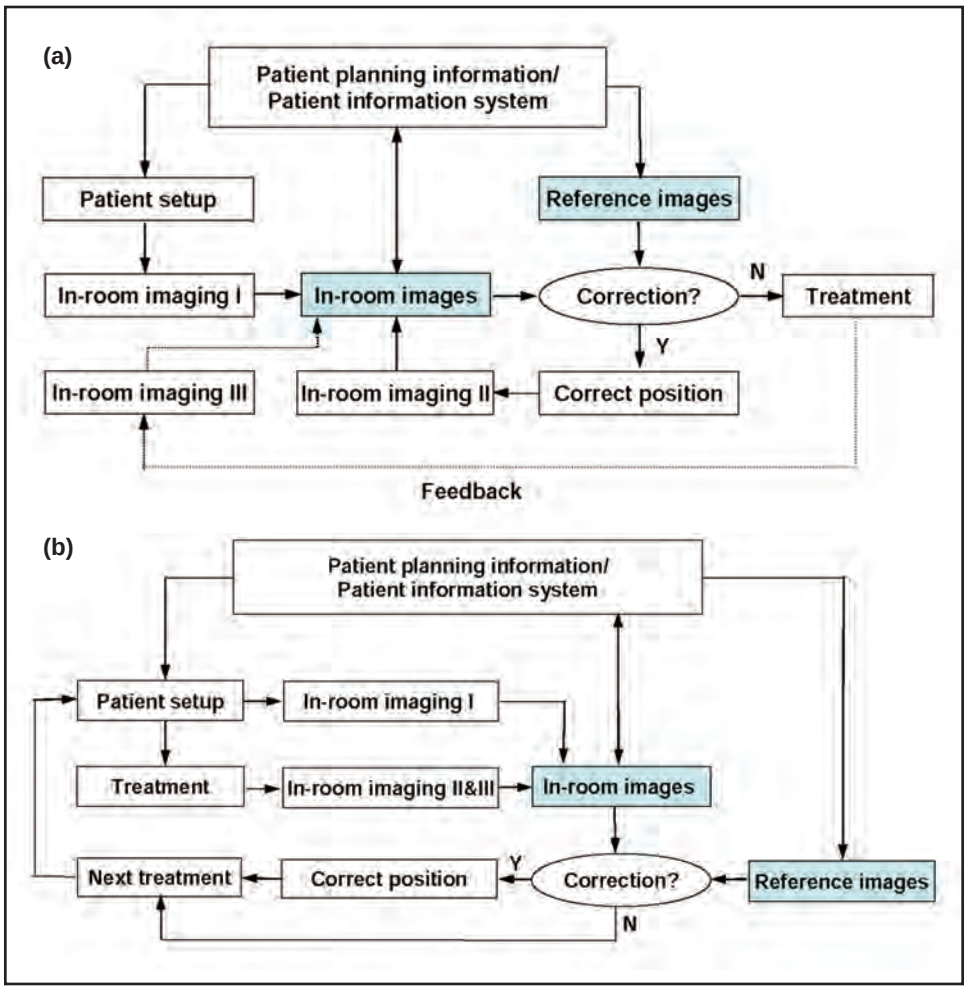

Figure I-C-1. General scheme for in-room image-guidance with (a) on-line and (b) off-line corrections. (a) On-line corrections based on In-room Images I are followed In-room Images II as confirming the shifts made for Images I; and In-room Images III, which are made after treatment, can be used to confirm patient in the same position during treatment, and to assist off-line corrections if it is discovered that the patient moves around a lot during treatment. (b) In-room images can be taken immediately before or after the treatment to capture the patient's treatment position, and to assist off-line corrections if it is discovered that the patient moves around a lot during treatment.

(In-room imaging II); and (3) imaging during and/or after treatment (In-room imaging III). Depending on individual application, imaging at stage II and stage III may not be applied. The off-line correction shown in Figure I-C-1b indicates that the positioning deviation between in-room and reference images can be analyzed either before or after treatment, and the correction, if there is any, will be applied to the next treatment. In addition to imaging, the process of the described correction scheme involves both comparison and judgment. Comparison between reference and in-room images can be done either manually or automatically. Ideally, it should be done automatically first and then checked manually by a qualified expert. Judgment refers to action decisions about how to correct for identified deviations.

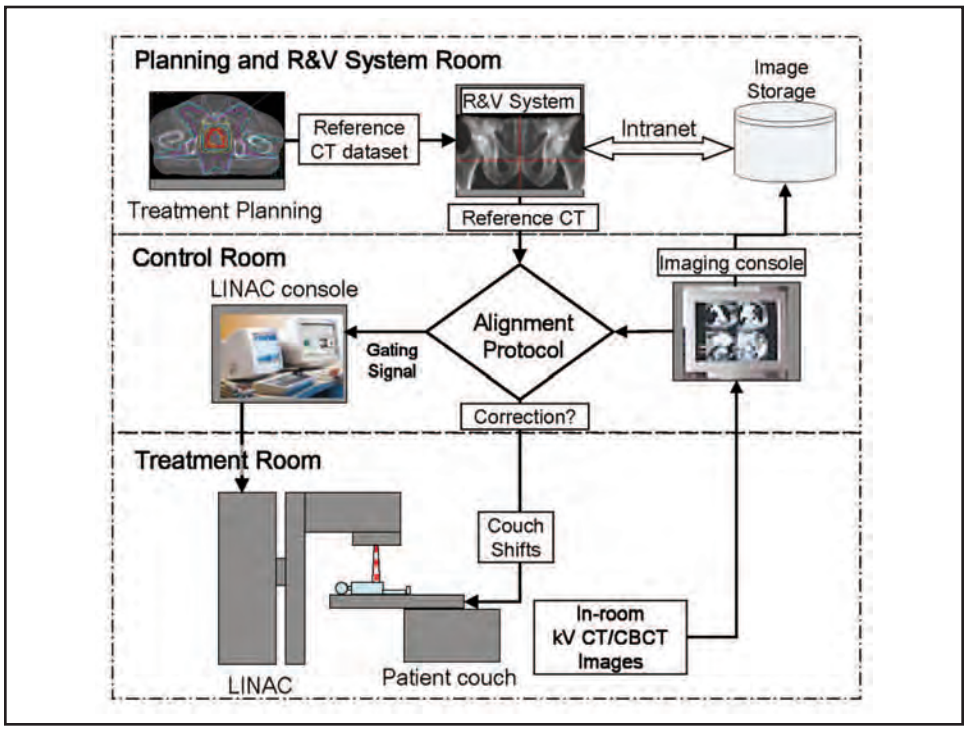

Figure I-C-2. Schematic illustration of a typical treatment process using in-room radiographic imaging.

An example of clinical workflow (or process) using x-ray imaging, particularly CBCT, for on-line localization is illustrated in Figure I-C-2. Steps involved in image guidance could include but are not limited to:

- CT-based image-guided treatment consists of first acquiring a treatment planning scan of the patient in the treatment position under the direction of the physician. The physician will guide the therapists in regard to the volume to be scanned for the patient's treatment. The combination of the resulting CT images and associated contours defines a reference CT dataset.
- The reference CT and planning data are imported to the workstation in the treatment area.
- The patient is positioned on the treatment couch in the treatment room and aligned to the laser positions.
- Respiratory signal acquisition may be set up if a motion management method is used for treatment.
- Localization imaging (i.e., CBCT) is then performed. After scanning, the localization CBCT is registered to the reference CT to determine patient and target position.
- This registration/alignment/fusion of the two datasets may be performed by a physician, planning personnel, or treatment unit staff under a physician's supervision. Multiple options for registration of the reference and localization CT images may

exist. The registration may be performed using algorithms such as mutual information (Kessler 2006; Brock 2007) or manually. Automated registration approaches will perform better for unambiguous elements, such as bone or implanted metallic fiducial markers. Automated soft-tissue registration is more challenging. Regardless of the registration surrogate, it is imperative that these images be inspected, and, if necessary, manually adjusted prior to changing the patient's position.

- Once the required adjustments are determined, the necessary translations/rotations are automatically sent to the treatment unit, and the couch moves automatically.
- The physician, or delegate, reviews the images daily if they are taken daily. This review includes comparison with previous shifts and should note systematic changes in target volumes or organs at risk. Feedback is given to the therapists about the adequacy of registrations and, if necessary, about the steps required to improve future registrations.
- The registration information and the fusion graphic can be stored in a database or printed out for record keeping and/or final physician approval.

The above excerpt provides the potential practitioners a glimpse of the process of IGRT and an appreciation of the necessary infrastructure and personnel organization that is required. Qualified Medical Physicists should play critical roles in developing clinical flow and secure the quality and accuracy of each process.

I.D. Nomenclatures

In-room kV systems can be classified into different categories based on the way they are installed. In general, they can be divided into three categories: rail-track–mounted, ceiling/floor-mounted, and gantry-mounted systems. Differentiations among categories can be made based on the imaging capabilities.

Rail-track–mounted system: This type of system is commonly called *CT-on-rails*. The rail-track–mounted kV tomographic imaging systems consist of a conventional CT scanner installed in the treatment room such that it can be moved into a position for acquiring helical CT scans of the patient on the treatment couch. The scanner is mounted on rails, along which it can move. In all systems both treatment couch and the CT scanner are mobile. There is a fixed geometrical relationship between the rails and treatment isocenter.

Ceiling/floor-mounted system: This type of system is commonly referred to as a stereoscopic imaging system. In these systems, the kV x-ray tubes are mounted permanently either to the ceiling or to the floor such that the tube and detector locations are fixed relative to the coordinates of the treatment room or a rigid patient. Both radiographic and fluoroscopic imaging modalities are offered. The stereoscopic images are also used to provide 3D information of the patient geometry.

Gantry-mounted system: Examples of this type of system are On-Board Imager® (OBI) also called On-Board Imager® (Varian), X-ray Volume Imaging (Elekta), and kVision (Siemens). The imaging system is mounted on the treatment gantry, usually orthogonal to the central axis of the treatment beam. One or two imaging systems may be mounted. The kV imaging system moves as the gantry rotates and shares the same isocenter as the MV treatment beam. This type

of system can be used to generate radiographs, fluoroscopic images as well as tomographic images such as CBCT.

Helical CT scanners make use of a fan beam. Transmitted projections are taken in either helical or spiral form. The data are then interpolated or re-binned before reconstructing a set of slices that make up a volume. CBCT uses a cone-beam x-ray source that encompasses a large volume with a single rotation about the patient. Images are then reconstructed into 3D images.

A hybrid imaging system has also been introduced in a single treatment room, which combines both ceiling/floor-mounted and gantry-mounted systems.

II. CURRENT SYSTEMS

Table 1 lists the commercially available systems (except Siemens kVision system which is pending certification of conformity or *U.S. FDA clearance*) according to the three categories described earlier. The current configuration and specifications of these systems will be discussed in detail in the following sections.

II.A. Rail-Track–Mounted Tomographic Systems

The placement of a conventional CT scanner in the treatment room with a known geometric relationship to the treatment isocenter (or coordinate system) offers a feasible and robust approach to CT-guided radiation therapy. After the pioneering work by investigators in Japan, Uematsu et al. have spearheaded this approach over the past years (Uematsu, Fukui et al. 1996; Uematsu, Shioda et al. 1998, 2001; Uematsu, Sonderegger et al. 1999; Uematsu 2002; Kuriyama, Onishi et al. 2003; Onishi, Kuriyama et al. 2003). Currently, multiple manufacturers provide products of this type, e.g., the PRIMATOM™ system (Siemens Medical Solutions, Concord, CA) consists of a Siemens PRIMUS™ linear accelerator and a modified SOMATOM diagnostic CT scanner that travels on two parallel rails in the treatment room (Wong, Cheng et al. 2001; Cheng, Wong et al. 2003; Fung, Grimm et al. 2003; Paskalev, Ma et al. 2004; Paskalev, Feigenberg et al. 2005a,b; Wong, Grimm et al. 2005; Stutzel, Oelfke et al. 2008). Two other systems are the EXaCT Targeting™ system with a Varian linac and a GE CT scanner (Court, Rosen et al. 2003a); and the Mitsubishi's accelerator in combination with a GE CT scanner (Kuriyama, Onishi et al. 2003; Onishi, Kuriyama et al. 2003).

Examples of these systems are shown in Figure II-A-1 (Varian-GE system) and in Figure II-A-2 (Siemens system). All systems are based on a CT scanner placed in close proximity to the medical linear accelerator, allowing a single couch to be moved from an "imaging" position to the treatment position. These systems vary in the amount of motion and degrees of freedom required to move the patient from one position to the other. The commercially available systems minimize the amount of couch movement by translating the CT scanner gantry during acquisition, thus receiving the name "CT-on-rails". This has the merit of minimizing differences in couch deflection at different couch extensions (Kuriyama, Onishi et al. 2003).

Typically, the CT gantry travels on either two rails (Siemens system) or three rails (Varian-GE system). The rails provide both motion stability and motion guidance. For example, there are three rails in the Varian-GE system. The two outside rails provide stability in leveling

Table 1. Commercially Available Systems for In-Room kV Imaging

System Configuration		Rail-Track-Mounted Systems		Ceiling/Floor-Mounted Systems		Gantry-Mounted Systems			Hybrid Systems
Manufacturers		Varian/General Electric EXaCT	Siemens PRIMATOM	BrainLAB Novalis Body	Accuray CyberKnife	Elekta Synergy	Varian On-Board Imager	Siemens ARTISTE (Pending FDA)	Varian/ BrainLAB Novalis Tx
Imaging Capabilities	Radiography	No	No	Stereoscopic	Stereoscopic	Yes	Yes	Yes	Yes
	Fluoroscopy	No	No	No	No	Yes	Yes	Yes	Yes
	Tomography	Yes	Yes	No	No	Yes	Yes	Yes	Yes
Reference Images		Planning CT	Planning CT	Digitally reconstructed radiograph	Digitally reconstructed radiograph	Digitally reconstructed radiograph/ Planning CT	Digitally reconstructed radiograph/ Planning CT	Digitally reconstructed radiograph/ Planning CT	Digitally reconstructed radiograph/ Planning CT
Correction Methods	Translation	Couch motion	Couch motion	Couch motion	Source moves on robotic arm/ couch motion	Couch motion	Couch motion	Couch motion	Couch motion
	Rotation	No	No	Couch motion	Source moves on robotic arm/ couch motion	No	No	No	Couch motion
Projection Imaging	Flat-Panel X-ray Detectors	0	0	2	2	1	1	1	3
Tomographic Imaging	Image Quality	Diagnostic	Diagnostic	N/A	N/A	Sufficient for localization	Sufficient for localization	Sufficient for localization	Sufficient for localization
	Field of View (H×W×L cm)	50 cm	50 cm	N/A	N/A	50 × 50 × 25.6	45 × 45 × 17	48 × 48 × 27?	45 × 45 × 17
Verification Imaging		No	No	Stereoscopic	Fluoroscopic monitoring of treatment	Possible	Possible	Possible	Possible
Target Surrogates		Bone/Fiducial markers/ Soft tissue	Bone/Fiducial markers/ Soft tissue	Bone/Fiducial markers	Bone/Fiducial markers	Bone/Fiducial markers/ Soft tissue	Bone/Fiducial markers/ Soft tissue	Bone/Fiducial markers/ Soft tissue	Bone/Fiducial markers/ Soft tissue
Potential Uncertainty Reduction		Interfraction positioning/ adaptive planning	Interfraction positioning/ adaptive planning	Interfraction/ intrafraction positioning	Interfraction/ intrafraction positioning	Interfraction positioning/ adaptive planning	Interfraction positioning/ adaptive planning	Interfraction positioning/ adaptive planning	Interfraction/ intrafraction positioning/ adaptive planning
Installation in Conventional Treatment Room		Possibly	Possibly	Yes	No	Yes	Yes	Yes	Yes
Works in Progress	Works in Progress	Siemens CBCT with C-arm				IRIS, Digital Tomosynthesis, Combined kV/MV CBCT			

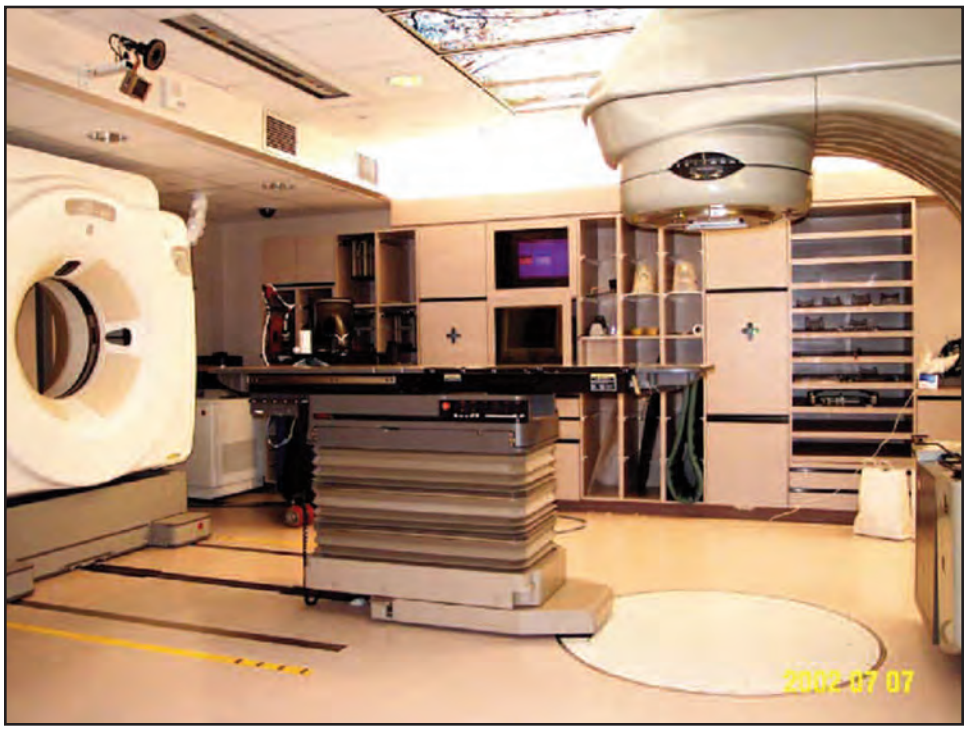

Figure II-A-1. Illustration of a rail-track–mounted system: Varian-GE EXaCT™ system. (Courtesy of Lei Dong, Ph.D., M.D. Anderson Cancer Center, Houston, TX)

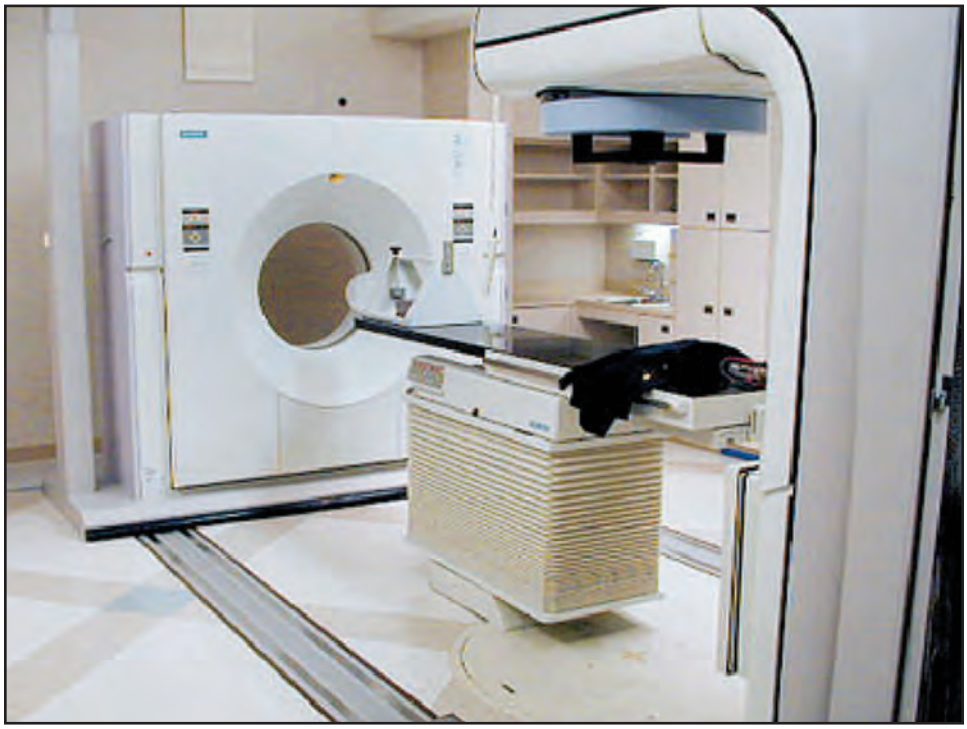

Figure II-A-2. Illustration of a rail-track–mounted system: Siemens PRIMATOM™ system. (Courtesy of Lisa Grimm, Ph.D., Morristown Memorial Hospital, NJ)

the system horizontally during scanning. The middle rail guides the gantry to move forward and backward linearly in the direction of scanning. A magnetic strip containing linear scale is also placed in the sidebars of the middle rail, along with a number of reference markers (Figure II-A-3). The reference markers are spaced at fixed intervals, providing precise positional calibration along the rail. The gantry moves while reading the magnetic data, and the reference markers ensure accurate scanning.

A CT gantry, such as the EXaCT Targeting system, has an aperture diameter of 70 cm, and the maximum gantry rotation speed is 1 second per rotation. At the time of writing, conventional single- or two-slice CT scanners are used by the EXaCT Targeting system. A new version with a 16-slice CT scanner is available and has been installed at M.D. Anderson Cancer Center. The maximum scanning speed is 3.0 cm/s during helical scanning mode and 7.5 cm/s in scout scanning mode. The CT images are calibrated such that after a 180-degree couch rotation, a point at the isocenter position of the linac is mapped to the center of the acquired CT image at slice "0.0" location. In another words, this point in the CT image is a mirrored isocenter position.

In the Varian-GE system, the EXaCT couch top is slightly modified to reduce width. This allows a lower vertical limit for the treatment couch when scanning a bigger patient. To prevent collision of the moving CT gantry with the treatment couch, the couch must be in the left-right center position during CT scanning. In addition, there is a limit of 20 cm on the CT gantry movement past the mirrored isocenter position on the CT side. This is usually not a problem because the treatment couch top (which carries the patient) can also move towards the CT gantry independently, increasing the CT imaging range in the superior-inferior direction.

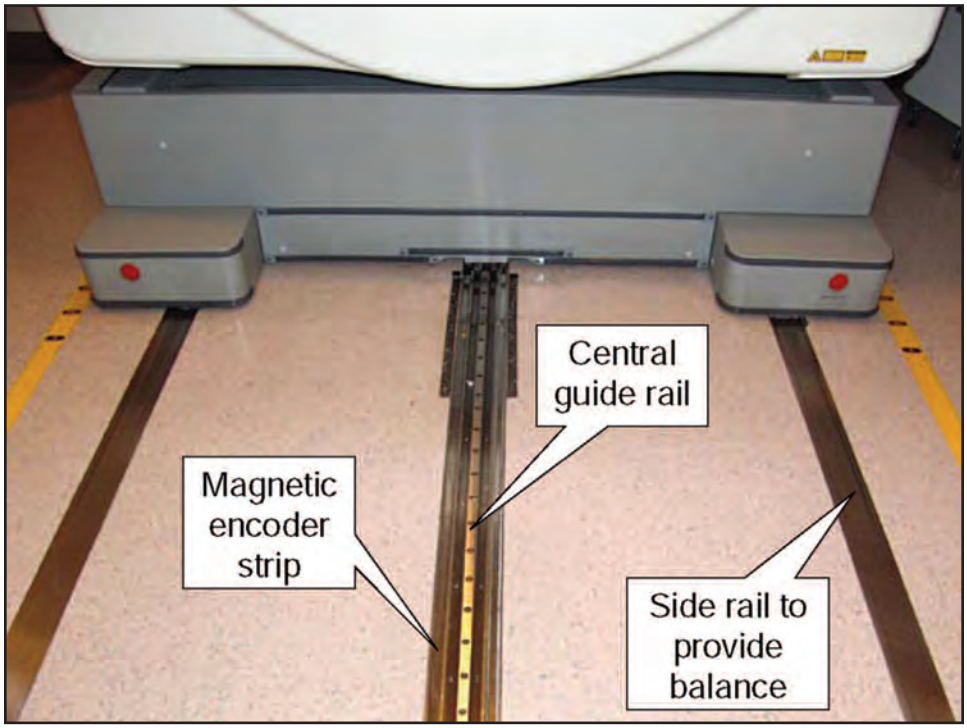

Figure II-A-3. Three rails for the rail-track–mounted CT scanner. The central rail contains positional sensor and drive mechanisms; and the two side rails provide stability during movement. (Courtesy of Lei Dong, Ph.D., M.D. Anderson Cancer Center, Houston, TX)

The Siemens PRIMATOM system travels on two parallel rails in the treatment room. The gantry is installed on a motor-driven carriage that runs on rails installed on the floor. The gantry is driven by a belt motor, located behind the gantry park position. Control signals and the power outlet are connected to a ceiling-mounted tract to avoid a collision during operation. The linac gantry and the CT gantry can be positioned on opposite ends of the treatment couch. By rotating the couch 180 degrees, the system allows a 3D CT localization of the treatment target while the patient remains in an immobilized treatment position. The tabletop of the treatment couch is made of carbon fiber in order to eliminate any scanning artifacts. The PRIMATOM system has evolved since its first installation in 2000 at Morristown Memorial Hospital, Morristown, NJ. Initially the system was equipped with a BALANCE SOMATOM scanner, which is a single-slice scanner with minimum slice thickness of 1 mm and scan time of 1 second per rotation. The diameter of the CT gantry is 70 cm, and the diameter of the field of view (FOV) is 50 cm. More advanced 16-slice CT scanners of the same family (SOMATOM) are used in later versions of PRIMATOM. The speed of the gantry along the rails can vary between 1 mm and 100 mm/s, and the gantry position accuracy is 0.5 mm.

Because CT imaging is not performed on the same side as the linac, identification of the isocenter in the acquired CT image set is important for image-guided treatment. Typically, a CT-on-rails scanner is calibrated so that the isocenter, after a 180-degree couch rotation, is mirrored to the image center of the CT slice marked with the table position "0" in the CT coordinate system. Unfortunately, due to couch sag and tilt, this image center does not accurately represent the isocenter in the patient setup. Alternatively, radiopaque fiducial markers can be used to transfer the isocenter information between the linac and the CT scanner. The radiopaque markers can be aligned to the lasers at the linac side first and attached to the patient's skin surface or the immobilization device as a temporary reference for the imaging session and treatment setup. If the couch sags or moves differently at the CT side, the attached radiopaque markers will move with the patient and therefore will not be affected by the uncertainties with the couch support device. This later method showed improved accuracy (<1 mm) for repositioning (Court, Rosen et al. 2003b). Further improvement in CT slice resolution can be achieved through the use of non-invasive head frames and body frames specially designed for stereotaxy localization (Paskalev, Feigenberg et al. 2005b; Wang, Feigenberg et al. 2006).

Several designs of the carbon fiber tabletop have been tested in order to lower its position in the CT gantry. The useable size of the FOV in the anterior-superior direction is 40 cm in the current version. This is enough for most applications including scans of extracranial stereotactic radiosurgery (SRS) frames. The table column rotation is a standard feature for PRIMUS treatment tables, so no further modifications are needed as far as the linac couch is concerned. The PRIMUS couch also has a digital readout, which is very useful when scanning large patients. The readout allows the user to "zero" the position of the tabletop right after the 180-degree rotation of the column. Then the user can move the tabletop in all three dimensions in order to maximize the clearance in the CT gantry and to avoid potential collisions. After the scan is completed, the tabletop can be brought back to the "zero" position. The sliding CT gantry has one collision safety bar on each side. If any of these bars is activated while the gantry is moving, the gantry stops immediately, and the procedure can only resume after the user manually clears the interlock.

Although respiratory-gated imaging is possible using rail-track–mounted tomographic imaging systems, monitoring gated treatment would not be possible because imaging is not performed at the treatment position.

The rail-track–mounted tomographic imaging systems fully employed all of the development that has been invested in conventional CT technology over the past 20 years—leading to unquestioned image quality and clinical robustness (Ma and Paskalev 2006). In a recent article, Kuriyama et al. (Kuriyama, Onishi et al. 2003) reported a positional accuracy for the Mitsubishi-based system of under 0.5 mm, while Court et al. (Court, Rosen et al. 2003a) reported an accuracy of 0.7 mm that can be further reduced to 0.4 mm when using radiopaque fiducial markers with a solid phantom. The results of a patient study (Paskalev, Feigenberg et al. 2005b) showed that a combination of 3D coordinate transformation and image fusion could be used for recalculation of the isocenter coordinates for brain patients with uncertainties on the order of 1 mm. This uncertainty could be reduced by using a smaller CT slice thickness. Such accuracy, in combination with excellent image quality, promises excellent management of interfraction setup errors and organ-motion. However, the issues of intrafractional motion between imaging and delivery systems still remain and will have to be accommodated through the appropriate selection of PTV margins and may potentially be minimized by the use of a non-invasive (stereotactic) localization frame.

Workflow

The general workflow as described in Figure I-C-1 is suitable for this imaging system with the exception that stages II and III of in-room imaging will not be feasible due to patient relocation for imaging. The CT images are reconstructed at the CT console and sent directly to the alignment workstation via Digital Imaging and Communications in Medicine III (DICOM-III) image transfer protocol. Once the image reconstruction starts, the radiation therapists can enter the treatment room, park the CT scanner, rotate the couch back to the linac side, reposition the couch, and wait for couch shift instruction as a result of image registration of the daily CT image with a reference CT image. The CT scanning and image reconstruction usually take less than 4 minutes.

The following example shows the image guidance workflow at MDACC using a Varian-GE EXaCT CT scanner. When the treatment CT images are received at the alignment workstation, software tools are available to streamline image registration and to derive the necessary corrections as shown in Figure II-A-4. These include automated fiducial marker localization, overlay of the target and organ contours, and automatic image registration of the treatment and planning CTs using grayscale pixel intensity information in a region of interest (ROI) (Court and Dong 2003). Optionally, the therapist or physician can make manual corrections to the alignment interactively (Court, Dong et al. 2004). Because of the excellent quality of these CT images, the review process usually takes 1 to 3 minutes depending on the experience of the operator and complexity of the review. The overall time needed for localization is usually less than 10 minutes.

Siemens has developed an image fusion package that can be used for daily image alignment. The algorithm was described by Fung et al. (Fung, Wong et al. 2005). For image registration, the system provides two alternative techniques, both based on the axial CT slices and

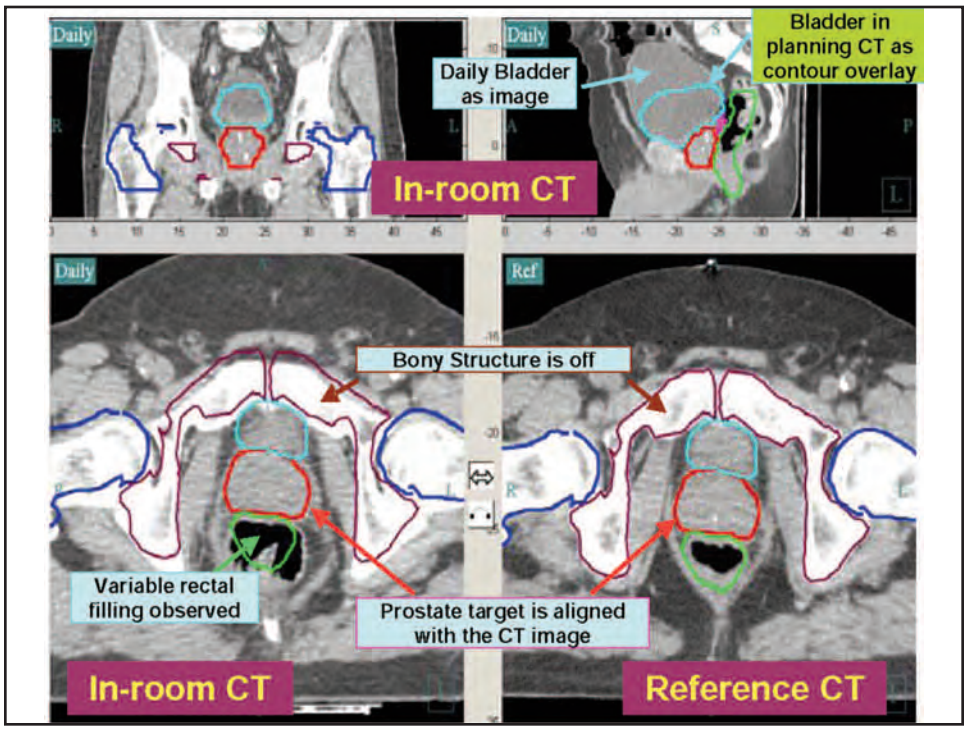

Figure II-A-4. Image analysis and patient position tool from Varian EXaCT System. In this example, the prostate target is aligned with the treatment beam, but the bony structure is off due to internal target motion. (Courtesy of Lei Dong, Ph.D., M.D. Anderson Cancer Center, Houston, TX)

supplemented by reconstructed sagittal and coronal cross sections. In both situations, skin marks are used to align the patient at both the CT scanner side and the linac side. For the landmark-based registration, landmarks are selected by identifying common points for both the daily CT and the treatment planning CT, which are displayed side by side. Then the software uses an optimization routine to align these landmarks using a 3D rigid transformation. The isocenter shift deduced from the difference between the planning and treatment CT image sets is then used to translate the couch. As an alternative, visual alignment software can be used to superimpose the two CT datasets. The system first aligns the isocenter by aligning the cross-hairs. One of the images can then be moved with respect to the other to perform a visual anatomical alignment. The alignment gives the shift needed to reposition the patient. Other researchers also developed an automatic grayscale image-based alignment technique for Siemens systems (Paskalev, Feigenberg et al. 2005a).

II.B. Ceiling/Floor-Mounted Planar kV Imaging Systems

Ceiling/floor-mounted systems have kV source-detector assemblies mounted onto the walls, ceiling, or floor of the treatment room. These systems are designed for stereoscopic radiographic or fluoroscopic projection imaging. Target localization is based on bony landmarks or implanted radiopaque markers as surrogates. In general, ceiling/floor-mounted systems are efficient and low dose in terms of clinical applications, on the order of 0.5 mGy as reported by AAPM TG-75

(Murphy et al. 2007). The common limitation for the ceiling/floor-mounted systems is their lack of tomographic imaging capabilities. In the absence of 3D volume-based target verification, quantitative monitoring of tumor/organ deformation and volumetric changes is not possible.

Currently, two commercial vendors offer products with imaging subsystems which are integrated with the treatment machines. They are the Novalis ExacTrac® 6-D X-ray system (previously called Novalis Body system) from BrainLAB and the CyberKnife system from Accuray. The term, "6-D" indicates the capability of couch movement in 6 degrees of freedom, 3 for translations (vertical, longitudinal, and lateral) and 3 for rotations (yaw, roll, and pitch).

II.B.1 The Novalis ExacTrac® 6-D X-ray System

The Novalis ExacTrac 6-D X-ray system, as shown in Figure II-B-1, is a well integrated image-guided treatment system for target localization, setup correction, and delivery of high-precision stereotactic radiosurgery and stereotactic radiotherapy. Image guidance utilizes two distinct imaging subsystems; a real-time infrared (IR) tracking subsystem and a kV imaging subsystem.

The IR tracking subsystem in the Novalis ExacTrac 6-D X-ray system consists of two IR cameras and one video camera. The kV subsystem consists of two x-ray tubes and two 20×20 cm flat-panel detectors. The x-ray tubes are recessed in the floor and project on opposing imagers, which are mounted on the ceiling. The distance from the x-ray tube to the opposite detector panel is approximately 360 cm. The imaging axes are coincident with the isocenter at oblique angles relative to that defined by the gantry rotation plane. The distance from each x-ray tube to the linac isocenter is 234 cm.

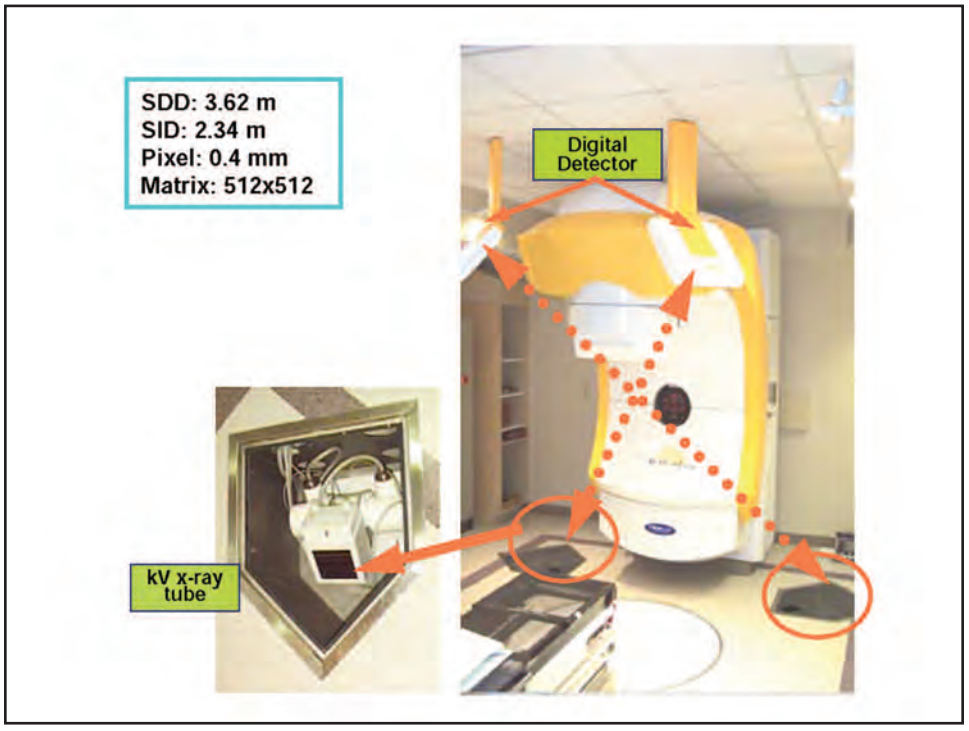

Figure II-B-1. Illustration of Novalis image-guidance system. (Courtesy of Fang-Fang Yin, Ph.D., Duke University Medical Center, Durham, NC)

In the earlier version of the Novalis kV subsystem, dual stereoscopic kV x-ray tubes were mounted on the ceiling within the treatment room at an angle of approximately 40 degrees from the mid-sagittal plane of the accelerator. X-ray quality from 40 to 150 kVp was available for exposure. Images were acquired with a single 20.5×20.5 cm (512×512 pixels) flat-panel imager, positioned in the appropriate lateral and longitudinal directions for each kV source by a swing-arm mounted onto the pedestal of the treatment couch. In this manner, the vertical position of the imager varied with the height of the couch.

Proper target localization with the Novalis ExacTrac 6-D X-ray system requires calibration of the spatial relationship of the x-ray tubes, the detectors, and the isocenter of the treatment machine. The position of the detector with respect to the tube is based on edge detection of the radiation field borders. The spatial relationship with respect to the treatment isocenter is established using a calibration phantom with internal radiopaque markers for x-ray imaging and external IR-reflective markers for IR tracking. The specific kV x-ray configuration geometry is then stored in the planning system. Geometric accuracy of the Novalis ExacTrac 6-D X-ray system was determined to be less than 1.5 mm in a phantom study by Yan et al. (Yan, Yin et al. 2003). As described before, a 6-D couch movement (called ExacTrac® Robotics) is also available in the Novalis system, which allows either automatic or manual adjustment of patient positioning with three translational and three rotational directions. The IR optical system is used to guide the couch movement automatically.

Workflow

The general workflow as described in Figure I-C-1 could be selectively applied for this imaging system (i.e., Applications of Imaging I, II, and III). However, the couch movement for position correction is guided by an optical guidance system. Patient localization and setup correction using the IR camera and x-ray imaging subsystems are integrated with the treatment planning software of the Novalis ExacTrac 6-D X-ray system. The integration serves two purposes: to register imaging coordinates with the treatment machine coordinates and to communicate the correction information to the treatment machine.

The major function of the two infrared cameras is to detect in real-time IR reflecting markers placed on the patient's skin, or alternately, on a reference frame mounted on the treatment couch. The marker configuration is automatically compared to the stored reference information. The treatment machine is then instructed to move the patient to the pre-planned position by moving the treatment couch. A dedicated video camera system is coupled to the IR camera system to provide visual confirmation of patient positioning. Subsequently, the x-ray projection images are acquired and the final localization is determined by registering bony landmarks or implanted markers with those from DRRs provided by the Novalis planning system (Yin, Ryu et al. 2002). The Novalis ExacTrac 6-D X-ray system provides an automatic 2D/3D rigid body fusion method. Two projection kV x-ray images are acquired and automatically fused to DRRs projected from a 3D CT dataset to determine relative shifts and rotations in all three orthogonal axes. Three-dimensional anatomic information can then be inferred from the fused simulation images (Kim, Yin et al. 2005).

When accessible and tolerable, implanted radiopaque markers can be used as surrogates for soft tissue and are readily visible; albeit given the caveats of the invasive procedure and

potential marker migration. Generally, more than three seeds/markers are needed to correlate 3D locations between them in the stereo images and to identify potential translations and rotations, assuming a rigid-body model. In the Novalis ExacTrac 6-D X-ray system, the markers can be identified both for static and moving objects. For the static markers, the markers on both the reference images (DRRs) and acquired kV x-ray images are manually identified, and an automatic image fusion technique is used to define the relative shift and rotation.

For moving markers, real-time patient tracking can be performed using the real-time IR images of the reflective markers. Gating software is used to define at which respiratory phase the images are acquired. For verification, procedures for the static markers are again employed to find the relative shift and rotation. Because of the angulations of the x-ray imaging systems, interpretations of fluoroscopic images may be difficult. Therefore, fluoroscopy is not currently available with the Novalis ExacTrac 6-D X-ray system. Instead, "snap-shot" stereoscopic images can be acquired during treatment for direct verification of gated delivery relative to the reflective marker surrogates for intrafraction motion (Jin and Yin 2005).

II.B.2 The CyberKnife® System

The CyberKnife® Robotic Radiosurgery system, as shown in Figure II-B-2a, delivers radiation using a small X-band driven linear accelerator mounted on a robotic arm. There is no mechanical isocenter as there is on conventional linear accelerators. Similar to the ExacTrac 6-D X-ray system, the CyberKnife system is well integrated with its treatment planning and kV imaging subsystems for IGRT. The imaging subsystem consists of two kV sources and detectors. The x-ray sources are permanently mounted on the ceiling, and the imaging detectors are mounted to the floor on either side of the treatment couch. The central lines of sight of the two imaging subsystems are orthogonal to one another and intersect the patient symmetrically at a 45-degree angle with respect to the mid-sagittal plane. These lines intersect approximately at a "virtual isocenter" of the treatment system (the reference coordinate system between treatment and imaging systems), which is the approximate position of the treatment site. The imaging detectors use amorphous silicon flat panels of 41×41 cm area with 1024×1024 pixels (earlier systems have 20×20 cm detectors with 512×512 pixels). Depending on the room configuration, the sources are approximately 225 cm from the "virtual isocenter" and 345 to 365 cm from the detector panels. The sources typically operate in pulsed mode at 100 to 125 kV and up to 90 mAs depending on the anatomical position of the treatment site. Respiratory-tracked treatment and monitoring options are available as part of the integrated system. Unlike other systems currently available, CyberKnife moves the beam to compensate target motion as opposed to gating the beam when the target is in the beam path.

The CyberKnife Robotic Radiosurgery system is specifically designed for intrafraction motion adaptation, especially for those treatments requiring a radiosurgical level of precision or where significant patient motion may occur. The imaging system is fixed in the treatment room, so it is not necessary to monitor and correct for moving camera viewpoints during the delivery of radiation. The positions of the robotic accelerator are chosen to avoid interference with the imaging lines of sight to facilitate continuous monitoring of patient position throughout the treatment. Furthermore, the newly designed configuration (as shown in Figure II-B-2b) has x-ray detectors recessed under the floor to allow the gantry a greater range of motion.

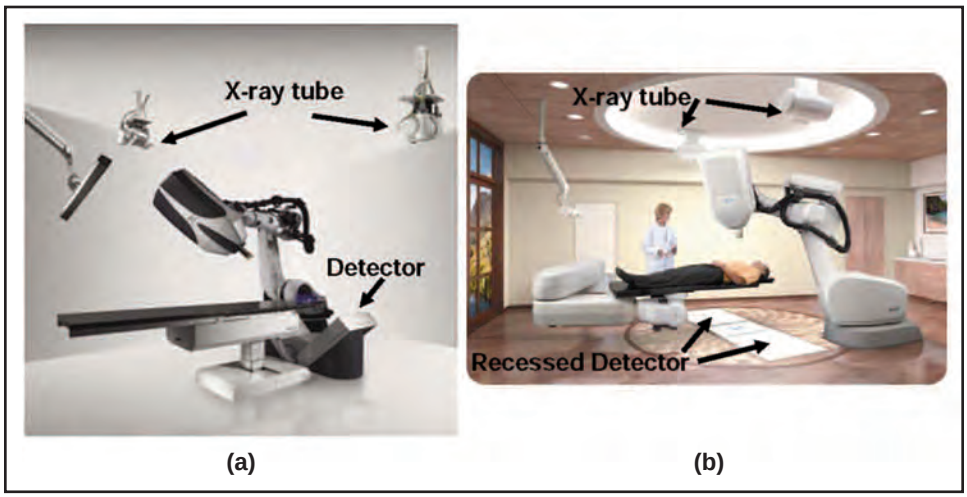

Figure II-B-2. Illustration of current CyberKnife image-guidance system with two detectors mounted (a) above the floor and (b) under the floor. (Courtesy of Accuray, Inc.)

Workflow

The general workflow as described in Figure I-C-1 could be selectively applied for this imaging system (Applications of Imaging I, II, and III). However, the operating principle of the CyberKnife Robotic Radiosurgery System is to dynamically adjust the beam to correct for the difference between the treatment and planning poses of the patient at the time of treatment (Murphy 1997, 2002). The treatment planning CT study is used to provide the reference geometry for defining the patient's pose (position and orientation) during treatment. The imaging subsystem in the treatment room forms a 3D coordinate frame that is taken to be congruent to the CT study's coordinate frame. The patient's relative pose during planning and treatment is represented by a rigid body transformation matrix that translates and rotates the anatomy within the common coordinate frame.

The integration of the imaging system with the planning system is maintained by computing DRRs from the CT study for registration with the orthogonal setup images acquired in the treatment room. The process begins with the acquisition of two orthogonal images of the treatment site. These images are automatically registered to projection images calculated from the treatment planning CT study to determine the treatment pose of the patient relative to the planning pose. The pose difference, expressed as a rotation and translation matrix, is automatically communicated to the controller for the robotic arm. The CyberKnife corrects for translational changes in patient position by translating the treatment beam by the observed amount using the robotic arm. Rotational changes in position are corrected partly be rotation of the linear accelerator (±1.3 degrees) and partly by repositioning the patient (±5 degrees in roll and pitch). This process is initially used for patient setup and is then repeated at specified intervals throughout the treatment fraction to monitor and adapt to changes in the patient's position.

When the CyberKnife Robotic Radiosurgery system is used to treat sites within the cranium, it is assumed (according to standard radiosurgical practice) that the treatment site is fixed with respect to the skull. The imaging system acquires images that highlight the bony contour of

the skull. The complete skull silhouette is then registered to the DRRs derived from the treatment planning CT to determine the 6 degrees of freedom needed to describe translation and rotation of the skull relative to the CT study.

Sites along the thoracic and lumbar spine are either located by bony landmarks or marked with either small stainless steel pins implanted in the spinous process nearest to the treatment site or gold fiducials. During treatment, the CyberKnife system acquires two orthogonal images of the spine. Automatic image-processing software locates the landmarks or implanted fiducials in the images and determines their coordinates in the imaging coordinate system using a non-rigid mesh and rigid-body transformation matrix, respectively. The transformation matrix that connects these coordinates to the CT study is then computed and used to align the treatment beam.

Both CyberKnife and Novalis systems in general are not presently capable of locating and registering soft-tissue tumor volumes via their 2D imaging systems. CyberKnife does offer the option of tracking soft-tissue tumors in the lung under certain conditions. Consequently, soft-tissue tumor sites are normally marked with several fiducials in the same manner as for the spine. It is assumed that the fiducials maintain fixed positions within the tissue from the time that the treatment planning CT study is acquired until treatment is completed. This assumption is verified by measuring the relative spacing of the fiducials in the alignment images during treatment. If the relative fiducial spacing is unchanged from the CT study, it is assumed that the fiducials have not migrated. Both systems can potentially generate images more efficiently than other types of x-ray imaging systems mainly due to their fixed configurations relative to the beam delivery unit and hence can acquire images without mechanical movement.

II.C. Gantry-Mounted kV Imaging Systems

Gantry-mounted kV imaging is the key feature of new medical accelerators specifically marketed for IGRT, mainly due to its in-room tomographic imaging capability at the patient treatment position. The two available commercial products, Elekta's Synergy X-Ray Volume Imaging (XVI) and Varian's On-Board Imager (OBI), are quite similar in mechanical arrangements and operations. The kV imaging subsystems are mounted on the gantry orthogonal to the MV treatment and portal imaging subsystems, nominally sharing the same isocenter of the treatment radiation sources.

The orthogonal configuration originated from the earlier work of Jaffray et al. (Jaffray, Drake et al. 1999). A secondary advantage with orthogonal mounting is that the kV imaging system's FOV is never blocked by the head of the treatment unit. This guarantees the capability to image the patient regardless of gantry angle. The limitations with this configuration are mainly in the potential for collision at various couch and gantry angle combinations and the inexact coincidence of the kV and MV beam isocenters. In addition to the obvious applications for kV projection and fluoroscopic imaging, it was recognized early on that kV tomographic imaging would also be feasible using cone beam reconstruction methods (Jaffray, Drake et al. 1999).

Configurations of the Synergy and Varian gantry-mounted systems are quite different. However, they offer very similar imaging capabilities for image guidance and comparable image qualities under similar acquisition conditions. The continuous challenge for both systems are

CBCT image quality, especially soft-tissue contrast for target localization and CT number consistency for direct dose calculation. Numerous studies on the performance of flat-panel detectors applied to the generation of CBCT images have been published to address the issues of detector efficiency, signal lag, x-ray scatter, and overall performance (Siewerdsen and Jaffray 1999, 2000, 2001; Jaffray and Siewerdsen 2000; Jaffray, Siewerdsen et al. 2002; Yin, Guan et al. 2005). The potential for high resolution, soft-tissue imaging of the patient is demonstrated despite the presence of several technical and physical challenges. Currently, the most significant factors affecting CBCT performance are (1) the limited dynamic range of the x-ray detector, (2) the presence of elevated x-ray scatter at large cone-angles and object diameters, and (3) patient motion during the scan. Despite these challenges, the image quality being generated in the clinical environment is sufficient to consider the use of CBCT images for image guidance of many anatomic sites (Yin, Wang et al. 2008). More user-friendly image analysis tools and better imaging options for respiratory motion have also been active directions for both academic research and clinical application developments.

The FOV of on-board CBCT is typically limited due to the detector size if the detector is centered at the beam axis (called full-fan CBCT reconstruction). In order to increase the FOV of CBCT, the detector center can be shifted from the beam axis so that one side of the anatomy can be fully sampled by the projections with the initial 180-degree gantry rotation and the other side of the anatomy can be completely sampled by the projections with the second 180-degree gantry rotation. CBCT reconstruction using two clipped sets of data is commonly referred to as half-fan CBCT.

II.C.1. The Synergy® System

In the Elekta Synergy® system, as shown in Figure II-C-1, the kV x-ray source is supported by two straight cylindrical rails that can be retracted manually into the face of the machine's drum gantry, out of the way for initial patient setup. A second retractable arm, mounted on the face of the drum, supports a 41×41 cm (1024×1024 pixels) flat-panel detector at a source-to-detector distance of 155 cm. This arm is constructed to permit lateral displacement of the imager by up to 19 cm with respect to the central axis of the kV beam. Lateral displacement, typically less than 19 cm, is used to increase the size of the reconstructed volume in the lateral dimension. The imager has three positions: retracted into a folded position; semi-extended; and fully extended. The imager assembly is kept at a fixed vertical position to minimize the imager motion during rotation. Software is used to correct for flexes and torques encountered during gantry rotation using a calibration "flexmap" (Sharpe, Moseley et al. 2006) that directly shifts projections according to the expected arm flexes prior to reconstruction. Long-term reproducibility and stability of these flexmaps have been reported (Bissonnette 2007). One advantage of this approach is that the volumetric image dataset is directly linked to the radiation isocenter of the accelerator.

Accurate characterization of the imaging geometry is imperative for the generation of accurate volumetric reconstructions. The stability of the imaging system's geometry has been well characterized and demonstrates its capacity for accurate back-projection and sub-mm precision in guidance of patient positioning (Sharpe, Moseley et al. 2006). CBCT operates on the same principles as conventional CT with the advantage of a large longitudinal FOV for image

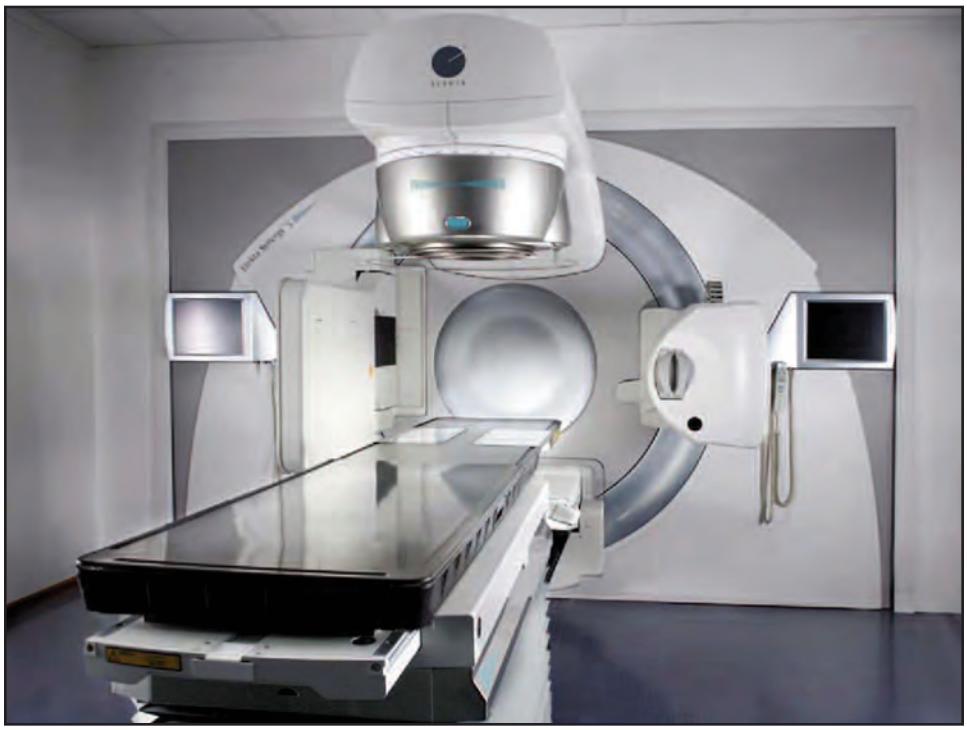

Figure II-C-1. Illustration of Synergy image-guidance system. (Courtesy of Jean-Pierre Bissonnette, Ph.D., Princess Margaret Hospital, Toronto, ON, Canada)

acquisition using a single rotation. Methods to reduce the contribution of scattered photons in the projection images include the use of a 10:1 scatter rejection grid (Letourneau, Wong et al. 2005; Siewerdsen, Moseley et al. 2005) and software correction using a semi-empirical scatter distribution (Wiegert, Bertram et al. 2005), with the former, more direct approach imparting more imaging dose to the patient.

The Synergy system is marketed kV radiographic, fluoroscopic, and tomographic imaging as planar, motion, and volume view, respectively. Software tools for automatic and manual 2D and 3D image registration are available on the Synergy system, as incorporated from the image processing tool-kit from the Netherlands Cancer Institute (NKI), a collaborating institution, in the developing of the Synergy product. The commercial system can be used for interrupted image acquisition, which allows the assessment of thoracic motion under active breathing control (Hawkins, Brock et al. 2006; Dawson and Jaffray 2007). A novel research development with the Synergy system includes the generation of 4D CT data with breathing motion using internal landmark as surrogate of the breathing phases (Sonke, Zijp et al. 2005; Li, Xing et al. 2006).

For the Synergy systems, the resolution of the reconstruction matrix is user configurable. Presets are supplied for 0.5 mm, 1 mm, and 2 mm voxels. Acquisition parameters are user configurable within the software through the implementation of preset parameters. These parameters include x-ray generator settings (i.e., tube current and voltage, current-time product), start and stop rotation angles, appropriate FOV settings and collimated x-ray field. The offset capability of the panel allows for nominal FOV settings of 27 cm, 41 cm, and 50 cm. The reconstructed CBCT image set in the superior-inferior direction is typically 25 cm in length. Optionally, a kV

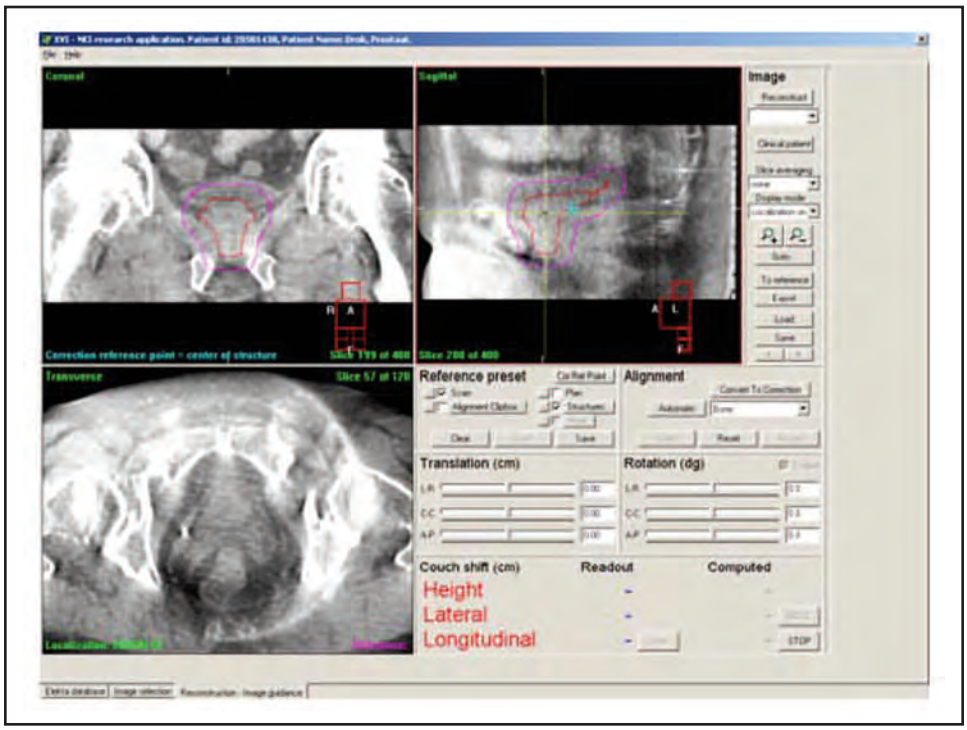

Figure II-C-2. Image analysis tools in the Synergy image-guidance system. Automatic registration based on bony landmarks or soft-tissue defined within a 3D region of interest, as well as manual registration methods, are available. Contours of the CTV, PTV, or organs at risk can be overlaid onto the daily CBCT images. Translation only or translation and rotation adjustments are calculated. (Courtesy of Jean-Pierre Bissonnette, Ph.D., Princess Margaret Hospital, Toronto, ON, Canada)

x-ray blade collimator can be set to reduce the field length to 12 cm or even 3 cm, thereby reducing scatter contributions for smaller imaging volumes.

Scan times on the commercial system, with concurrent reconstruction in the background, range from 35 s for head and neck with small FOV and partial gantry rotation, to 120 s for prostate with a large FOV. The "live" cone beam reconstruction is displayed on a Synergy monitor. Image quality of the commercial system is of sufficiently high quality to facilitate image guidance; i.e., prostate localization is possible with about 3 cGy CT dose index (CTDI) imaging dose (see Figure II-C-2). For other anatomical locations, lower doses may be sufficient; about 1 cGy for head and neck and 2 cGy for the lungs.

Workflow

The general workflow as described in Figure I-C-1 could be selectively applied with the Synergy image-guidance system (Applications of Imaging I, II, and III). It means that the three phases of in-room imaging may not be applied for all applications. For example, if the patient immobilization is stable and organ motion is minimal, in-room imaging III (i.e., imaging post treatment) may not be necessary. This product includes 3D image viewing, analysis, and registration software tools for use at the treatment machine. A single workstation is used to support all operations. Figure II-C-2 also shows a page of the Synergy guidance software. From this screen, the

user can access tools for automatic registration based on bony landmarks or soft-tissue defined within a 3D ROI, as well as manual registration methods. A "clipbox" can be defined that limits the automatic registration to voxels within a desired ROI, and ignores anatomy outside this volume. Treatment planning CT, contours, and isocenter location are exported from the treatment planning system via DICOM-RT, and imported into the Synergy software for viewing and comparison with the treatment CBCT at the treatment machine. One can therefore overlay the position of the CTV, PTV, or organs at risk onto the daily volumetric dataset and provide complementary information for therapists to act upon. While the software does not import the dose distribution, an interesting strategy is to create and export, on the treatment planning system, a contour conforming to an isodose volume of interest. This contour can be used to assess, on the daily volumetric dataset, whether a target is covered or an organ at risk is far enough from a dose gradient. Following registration and interpretation of volumetric datasets, the necessary translation only, or translation and rotation adjustments are calculated. The former is facilitated by automatic couch motion; the latter is only possible with products such as the robotic HexaPOD™ (Medical Intelligence, Schwabmünchen, Germany) couch that allows for positioning with 6 degrees of freedom. Finally, the volumetric and radiographic imaging data from the Synergy system can be exported for off-line analysis using a DICOM transfer protocol.

For patient setup, orthogonal kV radiographs have been used to localize surgical clips in breast patient (Sharpe, Moseley et al. 2003), and CBCT has been used for soft tissue based positioning (Letourneau, Wong et al. 2005; Oldham, Letourneau et al. 2005). An off-line adaptive radiotherapy strategy based on repeated daily CBCT imaging and plan re-optimization has also been studied (Nijkamp, Pos et al. 2008; Wu, Thongphiew et al. 2008; Thongphiew, Wu et al. 2009). Fluoroscopic imaging, currently at 7 frames per second, has also been used to evaluate respiration-induced tumor motion in lung patients (Hugo, Agazaryan et al. 2002; Sonke, Zijp et al. 2005; Li, Schreibmann et al. 2006).

II.C.2. The Varian On-Board Imager® (OBI) System

The On-Board Imager® (OBI), as shown in Figure II-C-3 is a kV imaging system that can be added as an option to new or currently installed (Varian 21EX or above series) Varian high-energy medical accelerators. The system consists of two, electronically stabilized, robotic arms (EXaCT arms) that hold x-ray tubes (G242) and high-performance 40×30 cm flat-panel imagers (PaxScan 4030CB). A third identical robotic arm holds the MV imager. The PaxScan 4030CB imager has been customized for CBCT imaging where a dual gain readout method is used to increase its dynamic range to 18,500:1 (Roos, Colbeth et al. 2004). X-ray scatter is reduced using a custom designed 10:1 scatter rejection grid.

One enabling technology of OBI is the use of the electronic servo arms to maintain the stability of the imaging equipment. Measurements show that the wander of a projected metal ball bearing (BB)—located at isocenter—onto the PaxScan 4030CB imager while the gantry is rotating is 0.3 mm in the left-right direction and 0.8 mm in the gun-target direction (Jeung, Sloutsky et al. 2005). The residual flex or motion of the arms is reproducible and can be corrected using software.

Figure II-C-3. Illustration of On-Board Imager (OBI) image-guidance system. (Courtesy of Fang-Fang Yin, Ph.D., Duke University Medical Center, Durham, NC)

The deployed position of the imager on the OBI system is typically set at 50 cm below isocenter but can be moved along the kV beam direction from +0.5 cm above the isocenter (toward the source) to –80 cm from the isocenter (away from the source). It can also be moved laterally by ±16 cm, and extended 19.5 to 23 cm past the isocenter longitudinally, depending upon the source to imager distance. The x-ray tube can also be positioned at either 80 or 100 cm from the isocenter. The EXaCT arms have parked, partially extended, and extended positions; there are five preset operating positions that can be programmed into the arm controllers, and the arm positions can be extended and retracted remotely. The three EXaCT arms can be controlled individually, as a pair (OBI source and OBI imager) or as a triple (OBI plus MV imager). The OBI and MV imaging systems share the same hand pendant.

The OBI system has three modes of operation: radiographic, fluoroscopic, and CBCT. Fluoroscopic and projection imaging for CBCT are acquired at 15 frames/s. The OBI system can be used along with the Real-Time Position Management™ RPM respiratory gating system to check if the gating system is turning the treatment beam on and off at the correct phase of the breathing cycle. Likewise, gated radiographs can be acquired to allow the analysis of patient position separate from motion due to respiration.

CBCT with an OBI uses pre-generated modes to standardize acquisition parameters. These modes identify the acquisition technique (kVp, mAs) and reconstruction parameters (matrix size, slice thickness, convolution filter). These modes are similar to scanning protocols in conventional CT scanners. They must be generated and calibrated before the image guidance

sessions. There are two FOV selections: head and body. The head acquisition has a reconstruction field of view of 25 cm diameter and ~17 cm longitudinal coverage, while the body scan has a 45 cm diameter and a 15 cm axial coverage. The latest version (OBI 1.4) increased the longitudinal coverage by about 1.5 cm. Acquisition—typically between 360 to 650 projections—takes 40 seconds to one minute—the times that it takes to rotate the gantry at maximum velocity around the patient from 200 to 360 degrees, respectively. The data are automatically transferred to a separate computer for reconstruction, so reconstruction can occur simultaneously with acquisition. Currently, the time from the start of the acquisition to the end of the reconstruction ranges between 62 to 90 seconds depending upon factors such as number of projections, the reconstruction matrix size (256×256 or 512×512), and the number of slices in the reconstruction. The exact times change constantly, since the calculations use standard PCs, and the calculation speed of these computers is constantly changing. At the time of writing, reconstructions typically finish ~10 seconds after acquisition ends, yielding a 512×512×70 slice (2.5 mm slice thickness) volume. The spatial resolution is ~6 line pairs per centimeter (lp/cm) in all directions (axial, sagittal, and coronal slices). The contrast resolution is better than 1.0% when imaging the low-contrast insert—CTP515—of a Catphan 504 phantom using a dose (CTDI body phantom) of 38 mGy.

The OBI system allows all image guidance activities—image acquisition, image registration/interpretation and patient correction—to occur remotely. Remote couch motion allows all axes of the couch (*x,y,z* translations and couch rotation) to be adjusted remotely using the results generated by the OBI system. The magnitude of remote couch motions can be restricted. The default installation limits remote couch motions to 2 cm and 2 degrees or smaller; however, these can be increased to 5 cm and 5 degrees. Thus, once the therapist walks out of the treatment room after positioning the patient, all image guidance activities can be completed without walking back into the treatment room.

The OBI system uses the concept of a "setup" field to allow the image-guidance session to be prepared before the patient comes to the treatment machine. The setup field contains all data needed for the image acquisition (e.g., gantry angle, reference images, imager positions, type of image to acquire—radiograph or CBCT, etc.) and is part of the patient plan. All data are transferred to and from the oncology information system using DICOM RT (RT Plan, RT Structure Set, and RT Image objects are all required for transfer of complete data).

Workflow

The general workflow as described in Figure I-C-1 could be selectively applied with the OBI image-guidance system (Applications of Imaging I, II, and III). The OBI system has been designed to work as an integral part of the existing oncology information systems. The information required for patient positioning (e.g., isocenter location, reference CTs, DRRs) is transferred from the planning system to the oncology information system and from the information system to the 4D Console (the workstation the controls the Varian medical linear accelerator) and to the OBI workstation. Thus—especially in the case of non-Varian planning systems or non-Varian information systems—there is a preparation step required to make sure that the plan has been transferred properly from the treatment planning system to the oncology information system. The benefit of this extra effort is that there is no possibility of selecting one patient (or plan) for treatment and a different patient for imaging/repositioning,

because the dataflow is controlled by the information system. Furthermore, once the patient has been repositioned and treated, the radiographic and/or CBCT images, as well as the patient position shifts are saved back to the information system for review by physicians and for re-planning. This allows physicians to review what happened during treatment without being present at the treatment machine.

Most clinical users of the OBI system have adopted the radiographic mode for guided treatment. Figure II-C-4 shows a pair of orthogonal kV images on the OBI workstation. Automated image registration for analyzing radiographic images is part of the OBI system, with algorithms for anatomy matching (mutual information) and radiopaque markers available. Other viewing and evaluation tools, such as superposition with DRRs, alpha blending (the process of combining a translucent foreground color with a background color, thereby producing a new blended color), contour overlays, a moving spy-glass window, and split windows are also available to evaluate pre- and post-correction setup. Localization with radiopaque markers can be performed either manually or using automated software. Studies have shown that there is a learning curve to use the OBI software and that the OBI radiographic repositioning process takes ~4 minutes when therapists are familiar with the software (Fox, Elder et al. 2006). Most of the time is spent analyzing and reviewing the images to make sure that the "automatch" algorithm has given the correct result, with acquisition taking a relatively small fraction of the time.

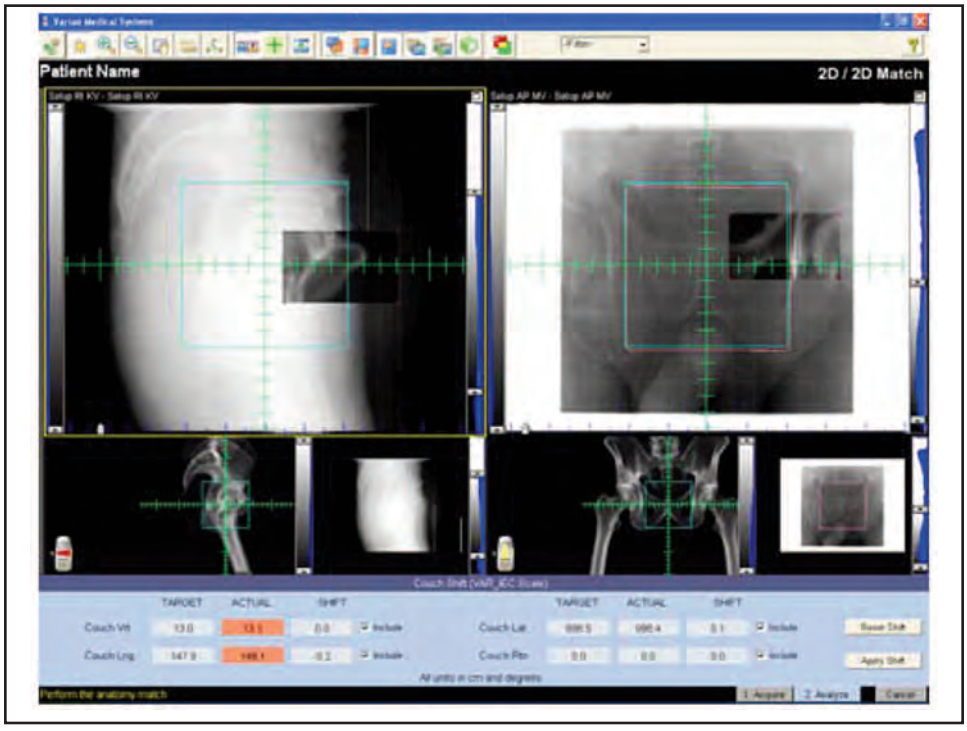

Figure II-C-4. Image analysis tools in the On-Board Imager image-guidance system. Automatic and manual registration methods are available. DRR images, as well as contour projections of the CTV, PTV, or organs at risk, can be overlaid onto the daily images. Translation only or translation and rotation adjustments are calculated. (Courtesy of Fang-Fang Yin, Ph.D., Duke University Medical Center, Durham, NC)

Studies have examined the accuracy of CBCT for patient repositioning (Kriminski, Lovelock et al. 2006; Yin, Wang et al. 2006b; Yin, Das et al. 2006; Chang, Wang et al. 2008; Li, Zhu et al. 2008; Nelson, Yoo et al. 2009; Wang, Nelson et al. 2009). Phantom results (Zhang and Yan 2007) show that the errors are within 1 mm and 1 degree of the expected values when tested using known phantom shifts. The early users of OBI CBCT have examined a variety of clinical applications. These include daily patient repositioning of prostate patients undergoing standard fractionation (Sorcini and Tilikidis 2006), the positioning of prostate patients undergoing hypofractionation (Pawlicki, Kim et al. 2007), the positioning of patients undergoing stereotactic body radiation therapy (SBRT) treatments (Elder, Schreibmann et al. 2006; Kim, Chung et al. 2006; Yin, Wang et al. 2006b; Yin, Das et al. 2006; Ali, Lovelock et al. 2007), the verification of both free breathing and breath-hold treatments (Yin, Das et al. 2006; Wang, Wu et al. 2007), and cautions of replanning using the CBCT images (Yoo and Yin 2006; Yang, Schreibmann et al. 2007).

One of the biggest challenges for CBCT is patient motion during the scan. The OBI CBCT acquisition can be interrupted part way through the scan without forcing the operator to start the acquisition at the beginning (Yin, Das et al. 2006). This capability has enabled breath-hold CBCT acquisition, which greatly reduces the motion artifacts in the CBCT images. The acquisition is divided into multiple sub-arcs, sufficiently small for patients to hold their breath during each sub-arc. The acquisition process is repeated until all projections are acquired.

In addition, the OBI system has a fluoroscopic (15 frames/s) capability that can be used along with the RPM respiratory gating system to check that the gating system is turning the treatment beam on and off at the correct phase of the breathing cycle. The gantry is rotated so that the kV x-ray beam is oriented to provide fluoroscopic images of the patient in the direction (BEV) of a treatment beam. The RPM system can also be used in combination with the OBI to acquire radiographs at the same phase in the respiratory cycle. This allows analysis of patient position to be separated from motion due to respiration (Li, Schreibmann et al. 2006; Li, Xing et al. 2006; Lu, Guerrero et al. 2007).

II.D. Hybrid kV Systems

Radiographic, fluoroscopic, and tomographic imaging provide different and complementary capabilities for patient setup and position monitoring. Tomography, for example, can provide high-contrast resolution for 3D soft-tissue localization during initial patient setup but is impractical for monitoring intrafraction movement. Orthogonal planar kV imaging generally cannot resolve soft-tissue structures and thus is limited to localization of radiopaque landmarks. It can, however, be used repeatedly to monitor intrafraction movement. Fluoroscopy is valuable for short-term tracking of continuous motion due to respiration, while radiography offers a lower-dose modality for longer-term tracking. These diverse capabilities can be combined into hybrid kV imaging configurations consisting of different imaging systems, e.g., gantry-mounted kV CBCT and ceiling/floor-mounted dual planar imaging systems. This can provide the clinician with maximum flexibility in target localization and beam alignment.

An example of such a hybrid kV imaging system is commercially available in a new delivery unit, NovalisTx™ as shown in Figure II-D-1, which is jointly marketed by Varian Medical Systems and BrainLAB. The hybrid imaging system in this treatment unit combines the

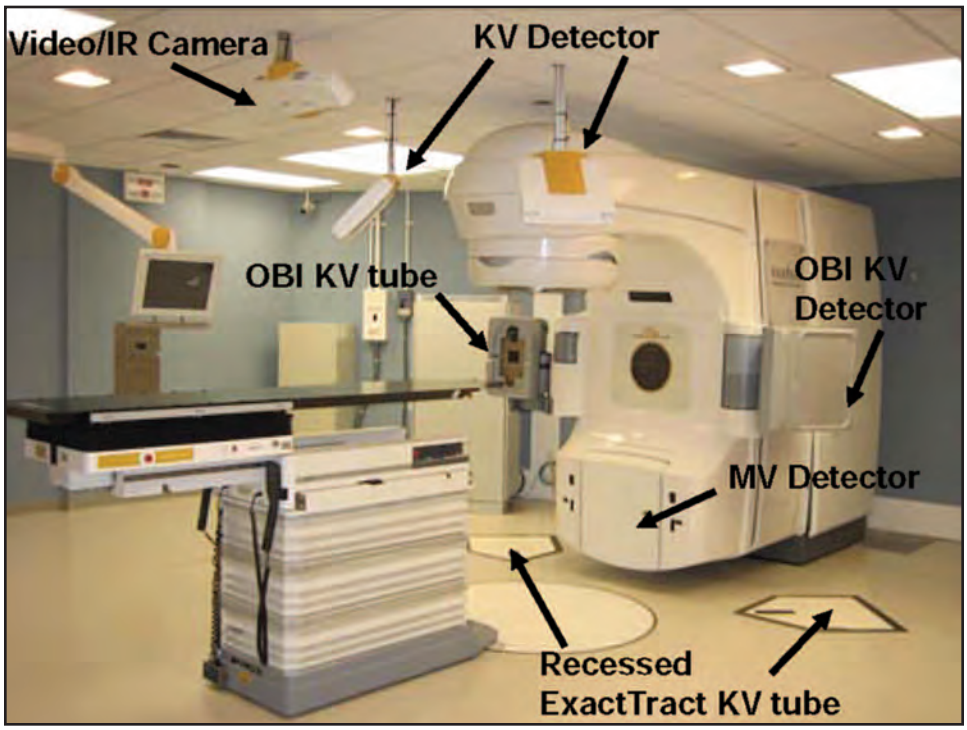

Figure II-D-1. Illustration of NovalisTx Hybrid image-guidance system. (Courtesy of Fang-Fang Yin, Ph.D., Duke University Medical Center, Durham, NC)

Varian OBI system with the BrainLAB ExacTrac 6-D (Novalis Body) x-ray system to provide both 3D tomographic imaging and dual planar imaging for patient positioning (Chang, Wang et al. 2008; Yin, Wang et al. 2008; Nelson, Yoo et al. 2009; Wang, Nelson et al. 2009).

Workflow

The general workflow as described in Figure I-C-1 could be selectively applied for this imaging system (Applications of Imaging I, II, and III). The methodology described in the gantry-mounted kV CBCT and ceiling/floor-mounted dual planar imaging systems could also be selectively applied. However, this specific hybrid imaging system has its unique applications. The fundamental feature difference from the non-hybrid system is that the hybrid system takes the advantages of two different non-hybrid systems. It is capable of tomographic imaging for soft-tissue target localization. Moreover, it could also use the ceiling/floor-mounted system to quickly generate images within a minute (including both imaging and analysis) at any time throughout the patient treatment while the gantry-mounted system either requires several minutes for image acquisition of orthogonal views or is only available for a single view at a certain treatment position.

One user application case for the image-guided stereotactic radiosurgery (SRS) is described below. For a patient receiving SRS and immobilized with a mask system, the ceiling/floor-mounted system could be applied to check the positioning after the patient setup using lasers. The 6-D couch (Jin, Yin et al. 2008) could be used to perform correction if needed. This 6-D couch is linked to the ExacTrac system and allows automatic adjustment of 3D translations

and 3D rotations. After the stereoscopic verification images are taken, the gantry-mounted system can then be used to take CBCT images to verify the target location based on soft-tissue matching. Couch positioning verification during the treatment can be continuously monitored using the ExacTrac system. This process is independent of the treatment and is an efficient image-guidance technique for high-quality patient care. With the fixed system, it takes just few seconds to obtain one set of orthogonal kV planar images. However, it takes about 30 seconds to a minute using an OBI as it involves gantry rotations, and very often, more than one set of images is needed. For regular fractionation, CBCT imaging may be only used for the first fraction or once a week. The limitation of this application procedure is that, sometimes, the imaging view may be blocked by the gantry.

III. ACCEPTANCE TESTING, COMMISSIONING, AND GENERAL QA

III.A. General Considerations

Acceptance testing, commissioning, and quality assurance (QA) programs are three critical routine steps to be performed by the clinical site after an IGRT system installation is completed but prior to clinical applications. These procedures and processes should be performed and exclusively supervised by Qualified Medical Physicists with support from clinicians and other technical staff such as dosimetrists and therapists. The kV imaging systems described in the previous section essentially consist of a combination of established technologies, such as radiographic and fluoroscopic units, CT scanners, flat-panel detectors (kV/MV), and linear accelerators. Several performance criteria for these established technologies have been covered extensively in the literature. However, performance criteria will vary depending on the clinical objective. Since many technical features of the imaging devices are very similar to those used in the imaging department, collaborative efforts by physicists in the therapy, imaging, and health physics departments are strongly encouraged.

Generally speaking, both hardware and software affecting image quality, localization accuracy, imaging dose, and system operation should be carefully checked during these processes. Although the operation procedures or measurement methods are very similar for acceptance testing, commissioning, and QA, the extension and depth, as well as frequency and criteria, will be quite different. Acceptance testing and commissioning are only performed once for each installation, major upgrade, and/or repair. The resulting parameters could be used as the baseline for QA criteria and also for establishing the criteria for clinical applications.

If acceptance testing and commissioning documents are not provided by the vendors, or not sufficient for a particular clinical site, users should develop their own documents and procedures. User-specific specifications for acceptance should be determined and documented with the purchase agreement. If the acceptance testing does not meet the specifications set for a clinical application, the user should not consider the installation complete and should work with vendors to resolve related issues. Additionally, if the imaging system is modified, upgraded, or repaired, etc., the physicist should judge whether or not re-acceptance testing and re-commissioning are necessary. QA content, frequency, and criterion may need to be updated accordingly.

III.B. Acceptance Testing

The primary goal for acceptance testing is to verify the components, configurations, functionality, safety, and performance of the system relative to the specifications described in the purchasing agreement and/or installation documentation from the vendors.

III.B.1 Verification of Imaging System Installation

The users should use the purchase specifications to validate that all purchased equipment is installed and functional. Acceptance testing will involve verifications including but not limited to: (1) proper installation of all software and hardware; (2) function of each component; (3) consistency of imaging parameters with measurements, such as kVp, mAs, etc.; (4) positioning parameters such as field (aperture) size, x-ray tube and detector positions, etc; (5) calibration methods; (6) operational and mechanical safety features; (7) imaging options and functionality; (8) software features, integration and accuracy; (9) system integration with information system, accelerators, motion management devices, and other devices; and (10) the identification of potential limitations and problems with the system. The following sections provide more specific details about some major elements of acceptance testing. This process requires a close working relationship between the staff in the clinic and the installation engineers of the vendors.

III.B.2 Shielding and Room Design Considerations

This safety feature should have been evaluated prior to the purchase of a specific imaging device. The shielding requirements of kV imaging technologies are far less demanding than those of the medical linear accelerator; the radiation shielding present in existing bunkers (treatment room) far exceeds the requirements for kV imaging. However, kV image-guided systems impact room design and functionality, the most spectacular to date being the introduction of conventional CT scanners inside a radiotherapy bunker.

Besides the railing and floor design, considerations for the mobile CT gantry, the cost involved with the larger room sizes and the associated larger secondary barriers due to increased room size complicate the introduction of such systems into existing radiotherapy bunkers (Cheng, Wong et al. 2003). Installation of ceiling/floor-mounted systems requires modification of floor and conduits, because detectors and/or x-ray tubes are recessed into the floor. On the other hand, while integrated CBCT devices are more compact, one must consider the clearance of the imaging components as they move with respect to the patient as well as the treatment couch. Such constraints may limit the isocentric rotation of the couch and therefore constrain the selection of non-coplanar beams that are common in high-precision therapies such as stereotactic brain or body radiation therapy. If the kV imaging systems in the treatment room are to be used for simulation or verification simulation, it may be useful for a well-designed image-guidance suite to include a shielded section inside the treatment room where the kV imaging components can be controlled; such a strategy minimizes separation between the operator and the patient during kV image acquisition, and alleviates patient throughput issues in busy radiotherapy clinics.

III.B.3 Safety and Mechanical Configurations

Safety and collision detection devices are designed mainly to prevent injuries to personnel and patients and to complement simple visual inspection. Particular attention should be paid to those systems using motorized or detachable mechanical components. Such components are usually equipped with collision detectors or manual interlocks that disable gantry, couch, and imager movement when triggered. For instance, the Synergy XVI system from Elekta and the OBI system from Varian have latches and locking levers that disable accelerator motion and image acquisition when the retractable components are not securely fastened. The CyberKnife has a sophisticated collision-avoidance system to protect the patient, couch, and imaging devices from the moving robotic arm. The rail-track–mounted CT scanners are also equipped with both touch sensors and couch position interlocks to prevent the CT scanner from colliding into the treatment couch. Users should always ensure that all collision detectors, switches, interlocks, and bypass systems are operational.

III.B.4 Geometric Calibration

As the goal of in-room kV imaging systems is to verify and eventually correct patient positioning for radiation therapy, the acceptance procedures for these systems should verify that the movable components are spatially reproducible, and, more importantly, that the image space obtained with these systems is accurately related to the radiation beam geometry. Most, if not all of the geometric calibration test procedures described in the literature are variations of the Winston-Lutz test developed in 1988 to perform a quick evaluation of overall isocenter accuracy for stereotactic radiosurgery (SRS) (Lutz, Winston et al. 1988). The Winston-Lutz test is a typical stereotactic radiotherapy QA measurement used to examine the coincidence of mechanical isocenter, light field, and radiation field. The test is typically done by placing a small radiopaque ball at the mechanical isocenter and irradiating the ball with the treatment beam. The relative position between the ball and the center of the circular or square radiation beam is used to judge the degree of agreement between the positioning and irradiating systems. The original implementation of the Winston-Lutz test involves only the treatment beam. For kV IGRT application, the test also involves the imaging beam, which needs to be accurately centered relative to both the mechanical isocenter and the treatment beam.

Rail-Track–Mounted Systems: Acceptance testing for rail-track–mounted systems (Uematsu, Shioda et al. 1998; Uematsu, Sonderegger et al. 1999; Court, Rosen et al. 2003a; Kuriyama, Onishi et al. 2003) includes verification of the accuracy of motions from the following components: the CT scanner gantry, the remote-controlled accelerator couch, and the coincidence of the CT and linac isocenters. The accuracy of the CT scanner is assessed by imaging a crosswire phantom with regularly spaced crosswires at known positions, which are confirmed by the relative separation of the crosswires measured on the acquired images (Cheng, Wong et al. 2003; Kuriyama, Onishi et al. 2003). The table position (lateral, longitudinal, vertical, and isocentric rotation) accuracy can be assessed by readouts, imaging, and actual measurements (Court, Rosen et al. 2003a). The coincidence of the CT and linac isocenters is verified by placing an acrylic ball bearing at the accelerator isocenter and rotating the couch by 180 degrees; the

ball bearing should then be at the CT image center. This is similar to the Winston-Lutz test for radiosurgery QA. However, this coincidence of CT and Linac isocenter may not be necessary as long as the isocenter position can be established by other methods, such as the use of radiopaque markers attached to patient's external reference points (Lutz, Winston et al. 1988). The fact that the treatment couch must be moved between imaging and treatment is a unique feature of these systems that requires particular attention. The accuracy of the entire image-guidance procedure must also be tested using phantoms (Court, Rosen et al. 2003a).

Ceiling/Floor-Mounted Systems: In ceiling/floor-mounted imaging systems (e.g., Accuray CyberKnife and BrainLAB ExacTrac 6-D X-ray), the precise alignment of the imaging and beam delivery coordinate systems is extremely important, because any misalignment would translate to a fixed systematic shift in delivered dose distribution relative to the intended target. Accuray uses a 3D film dosimetry and an imaging phantom to determine the precise placement of the dose volume when guided by the kV imaging system. Novalis ExacTrac 6-D X-ray system uses a phantom and the optical tracking device to align the treatment and imaging geometric coordinates (Chen, Ryu et al. 2008). Calibration procedures which align the imaging isocenter to the treatment isocenter enable the delivered dose to be placed within 0.5 mm of the imaging isocenter (Chang, Main et al. 2003). This procedure should also be repeated during periodic QA. The process similar to the Winston-Lutz test used for radiosurgery QA may be used to verify the coincidence between the imaging and delivery coordinate geometries.

Gantry-Mounted Systems: The acceptance procedure for these systems should verify that the motorized or manual deployment of movable components is spatially reproducible. One method to perform the geometric calibration of gantry-mounted systems is to ensure that the source to detector distance at preprogrammed positions is stable and reproducible and the projection of the beam central axis at each gantry position corresponds to the same pixel over all gantry angles. Gantry-mounted systems involve retractable components mounted on the accelerator gantry or drum. Mechanical sag resulting from motion of the center of the x-ray detector with respect to the accelerator central axis as the accelerator gantry is rotated should be minimized if not eliminated by hardware and be reproducible, so it may be corrected using software. The mechanical stability and reproducibility should be part of acceptance testing procedures and routine QA procedures (Zhang and Yan 2007). A rigid imager, or one that flexes in a reproducible manner, ensures that the scale of the images and location of the isocenter with respect to the image grid are accurately known at all times, thus facilitating the application of on-line patient positioning correction protocols.

Another approach is to measure the accelerator flex and sag and properly correct it. The periodic determination of the accelerator flex map, which establishes the motion of the beam central axis with respect to the image matrix as a function of gantry angle, ensures accurate CT reconstructions. Flex maps are determined by taking radiographic images of a ball bearing previously located at the radiation isocenter of the accelerator over a 360-degree gantry rotation, This is similar to Winston-Lutz test, as shown in Figure III-A-1. A plot of the apparent motion of the ball bearing on the projections, as a function of gantry angle, yields a flexmap that directly relates the kV beam geometry to that of the MV treatment beam. A much simpler and quicker daily QA procedure has been proposed recently. The accuracy of this procedure is

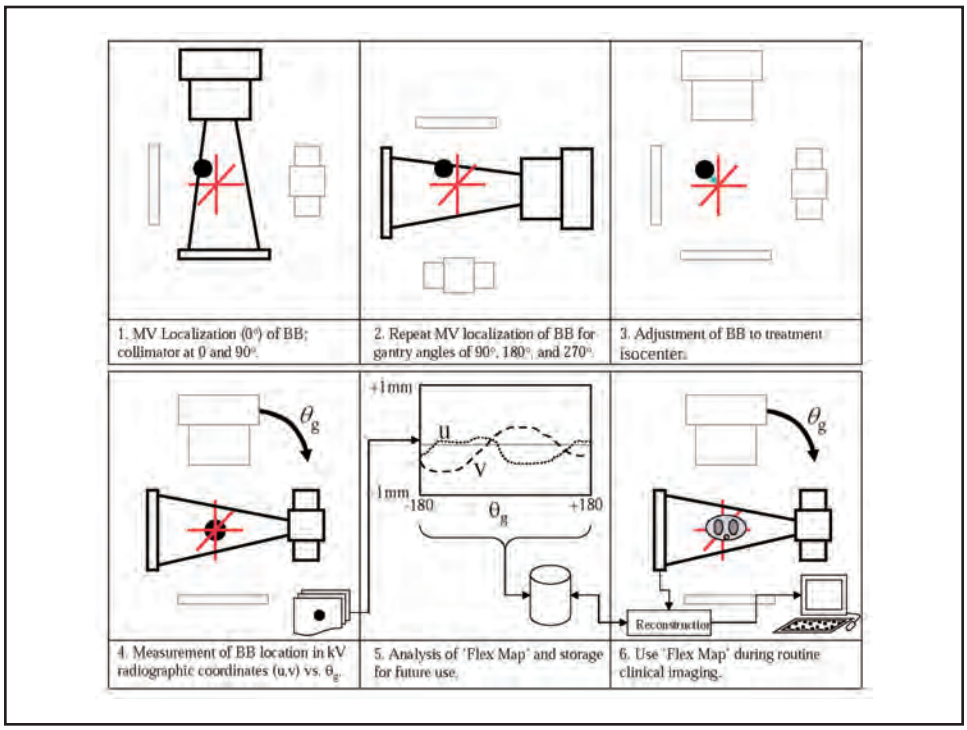

Figure III-A-1. Illustration of QA method for a gantry-mounted imaging system. (Courtesy of Jean-Pierre Bissonnette, Ph.D., Princess Margaret Hospital, Toronto, ON, Canada)

related to the accuracy of the room lasers (Bissonnette 2007). Specialized phantoms and calibration method for gantry-mounted systems have been reported (Cho, Moseley et al. 2005).

III.B.5 Localization Accuracy

The localization accuracy is determined by the positioning and repositioning of the phantom, based on imaging information. This accuracy could be affected by the quality of the imaging hardware and software. The software related to image registration and comparison, as well as reviewing, may not provide consistent information. A systematic error may be introduced when the software is misconfigured and not properly tested. An example of this would be when software predicts a right lateral shift and the couch moves in the opposite direction. Therefore, careful examination of software accuracy and performance consistency is critical for the acceptance testing, commissioning, and QA programs. This could be done by performing a set of phantom imaging studies with different known shifts and rotations. In routine patient treatment, acquiring verification images following a couch correction would confirm localization accuracy prior to the administration of any therapeutic dose and build up staff confidence in the image-guidance system.

The accuracy and precision of couch motions should also be tested. It can be verified using an acrylic ball bearing located at a known position within a visually opaque phantom (Kuriyama, Onishi et al. 2003; Sharpe, Moseley et al. 2006; Yoo, Kim et al. 2006; Moseley, Li et al. 2007; Zhang and Yan 2007). Prior to the test, virtual simulation and planning are performed to generate a reference image with the ball bearing at isocenter coordinates (i.e., 0, 0, 0).

In the treatment room, the ball bearing phantom is intentionally placed in an off-isocenter position with known displacement, and image acquisition is made with the in-room kV imaging device. The in-room kV images can then be registered with respect to the reference CT scan to determine required table displacements to reposition the ball bearing at the accelerator isocenter using a remotely controlled treatment couch. Subsequent in-room kV imaging will confirm that the automated couch displacements are accurately performed. This tests the accuracy of positioning and re-positioning of the imaging system.

III.B.6 Image Quality

The image quality requirements for IGRT are often complicated by patient throughput requirements and imaging dose in addition to some general consideration for radiographic imaging. The metrics that describe image quality for conventional CT scanners in AAPM reports 39 and 74 are also appropriate for CBCT (AAPM 1993, 2002; Bissonnette, Moseley et al. 2008b) with spatial resolution, low-contrast detectability, and uniformity being among the most useful. Prior to the establishment of image-guidance procedures as the standard-of-care in a radiation therapy practice, clinics must ensure adequate image quality. Users must understand that, while localization accuracy may not require the same image quality as diagnostic imaging, localization accuracy could be compromised by the presence of noise and image artifacts. Noise can be alleviated by increasing the mAs of the imaging technique, but artifacts due to scatter and beam hardening are topics of current research.

The image quality requirements for IGRT are application-specific, considering on-board CBCT images have, at present, poor image quality compared to diagnostic CT images. The image technique parameters must be carefully chosen and established to accomplish the desired task, such as detection of implanted markers, soft-tissue delineation, or bony anatomy visualization, and should be considered together with the frequency of the imaging. Once commissioned, the imaging technique remains fixed for a given site or task, and the QA program for image-guided systems must emphasize the consistency of image quality over time. This should be part of commissioning procedures for any imaging system.

In addition to the training recommendations in section IV, it is constructive to communicate effectively with therapists to have a good understanding about the imaging technique settings. A technical chart or equivalent for different imaging techniques would ensure optimal image quality and minimal imaging dose.

Radiographic and Fluoroscopic Imaging: Radiographic and fluoroscopic kV imaging with flat-panel detectors require calibrations similar to MV imaging. Most flat-panel systems must be calibrated to compensate for signal offsets and defective pixels. Periodic recalibration of the flat panel is necessary. Bissonnette recommends recalibration every 6 months or following servicing of the equipment (Bissonnette, Moseley et al. 2008b). The users may also determine recalibration frequency based on the vendor's recommendation or their own experiences (Bissonnette, Moseley et al. 2008b). For example, failure of routine image quality QA tests may also suggest the need to recalibrate the flat panel. These tests are identical to those encountered in diagnostic radiology and CT imaging. Readers are referred to the recommendations made in several reports (AAPM 1993, 2002) (http://www.aapm.org/pubs/reports/rpt_39.pdf, http://www.aapm.org/pubs/reports/rpt_74.PDF).

Tomographic Imaging: The image-quality criteria of systems incorporating conventional CT scanners shall not be addressed in this report, as they have been covered extensively elsewhere (AAPM 1993, 2002). Examples of applications of these criteria have been presented elsewhere (Bissonnette, White et al. 2004; Dong and O'Daniel 2006; Moseley, White et al. 2006; Yoo, Kim et al. 2006). The scale, geometric accuracy, uniformity, and linearity of CT numbers have been demonstrated, under test conditions, for commercial systems.

Image quality for CBCT has been under constant improvement. When amorphous silicon panels are used for CT imaging, image artifacts may arise due to (1) the spectrum of x-rays used for imaging, (2) the object being imaged, as well as (3) faults in the detector, (4) the imaging geometry, and (5) the reconstruction process. In the cone beam geometry, changing beam hardening and scatter conditions affects image uniformity and introduces capping or cupping artifacts. Examples are shown in Figures III-B-1A and B. Departures from test conditions (i.e., larger object, changes in the x-ray field size, changing the scatter environment, and beam hardening) will result in different imaging performance, and may be quantifiably different in image uniformity, high-contrast spatial resolution, low-contrast delectability, CT number accuracy, etc.

In the cone beam geometry, scattered x-rays and beam hardening conditions change according to field and object size, as well as object contents. For example, the CT numbers for given materials have been demonstrated to change according to the size of the object being imaged as well as imaging conditions (Moseley, White et al. 2006; Yoo and Yin 2006; Letourneau, Wong et al. 2007); increasing the amount of scattered radiation introduces a shift in the CT calibration curve. Similarly, eliminating scatter from test conditions improves the spatial resolution of these systems (Bissonnette 2007). Therefore, careful consideration of these issues is required when using CBCT datasets for quantitative imaging and treatment planning.

Besides cupping and capping artifacts, the object being imaged influences image quality when the size of the object, projected onto the flat panel, is larger than the flat panel; the resulting image is clipped, resulting in an incomplete external contour; an example is shown in Figure III-B-1F. Flat panels used for CBCT can be offset to reduce or eliminate this FOV artifact. Additionally, patient motion and breathing are likely to introduce blur and motion artifacts as the time required to acquire a CBCT dataset may range from 30 to 120 seconds. Figure III-B-1C, shows an example of a motion artifact.

Artifacts may also arise from the imaging geometry. While not requiring absolute mechanical rigidity, accurate CBCT reconstruction requires that the acquisition geometry be well known, reproducible, and consistent over time so that software corrections are accurate. As the imaging geometry may change over time, the tube and the imager sag information as a function of gantry position should be updated periodically. In addition, the image acquisition geometry must ensure that an adequate range of projection angles, usually 180 degrees plus the opening angle of the fan, be acquired in order to collect a complete dataset. The fan angle is usually determined by the angle subtended by the flat-panel detector.

The defects found in current flat panels may cause artifacts. For instance, an intermittent pixel may be barely noticeable on a single projection but may produce significant ring artifacts in reconstructed images (Figure III-B-1D). Lag in a-Si flat panels results in information acquired in a given projection angle to be carried over to the following, resulting in streaks and comet-like artifacts (Figure III-B-1E). Non-equiangular projections may also cause artifacts.

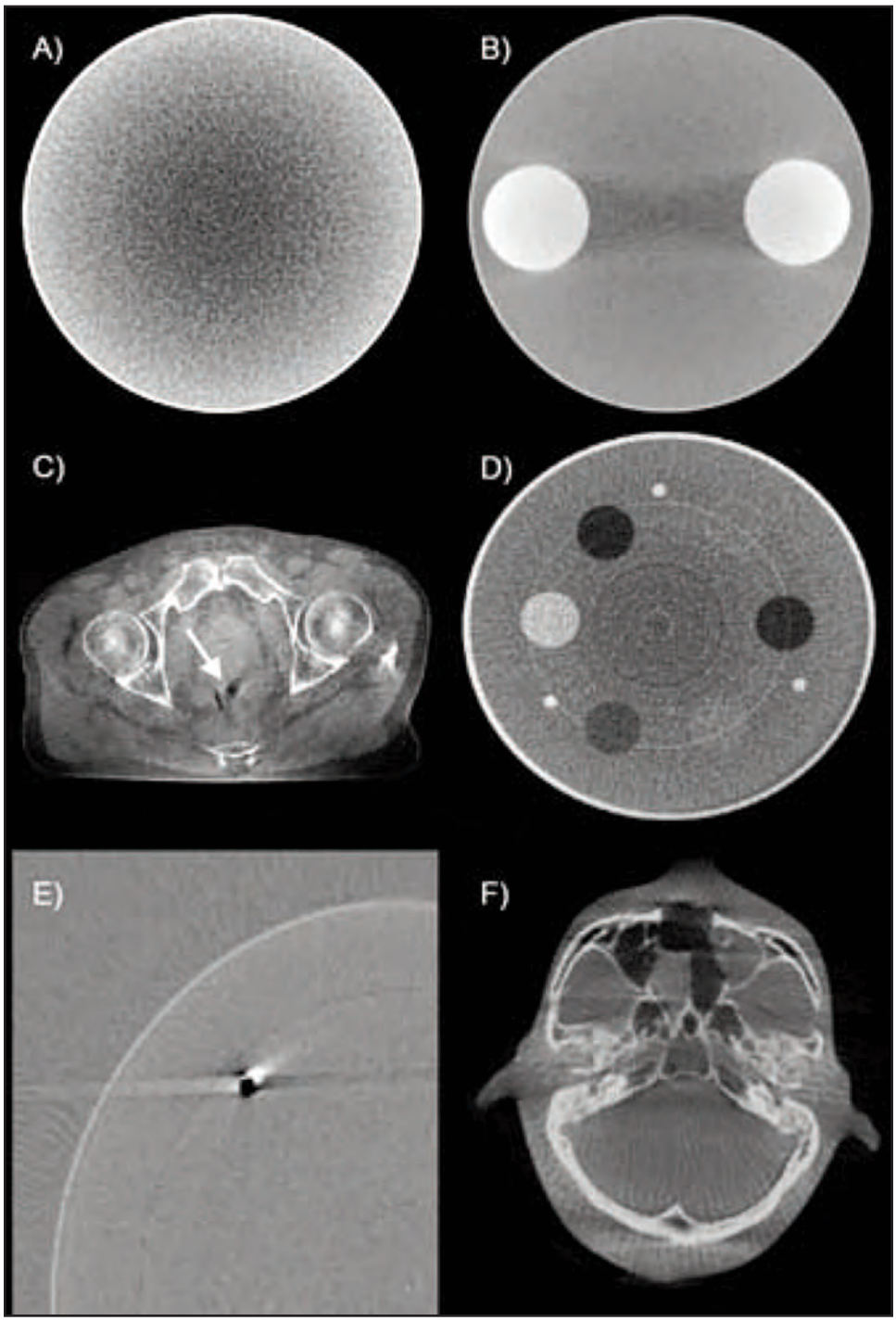

Figure III-B-1. Artifacts arising in kV cone beam CT: (A and B) cupping and streaks due to hardening and scatter; (C) gas motion streak; (D) rings in reconstructed images due to dead or intermittent pixels; (E) streak and comets due to lag in the flat-panel detector; and (F) distortions (clip external contours and streaks) due to fewer than 180 degrees + fan angle projection angles. (Reprinted from Fig. 7.8, p. 274, *The Modern Technology of Radiation Oncology, Volume 2*, J. Van Dyk (Ed.), with permission from Medical Physics Publishing.)

Management of image artifacts requires an appreciation that some are symptoms of machine issues, while others are inherent to CBCT imaging. The latter can be broadly classified as patient factors and imaging physics limitations. Patient motion causes image blur for internal anatomical structures, and implanted metal markers often introduce streaks on the reconstructed images. Imaging physics limitations may also introduce artifacts. Scattered photons cause cupping, while beam hardening causes streaking artifacts, and an inadequate FOV will truncate the information in the reconstructed images. The artifacts described above often occur in properly functioning devices. Commercial vendors are actively pursuing solutions to some of these issues.

Artifacts such as rings and structured inhomogeneity that appear in homogeneous phantoms may represent improper function of the device. Blurring that degrades spatial resolution or "double-images" may also be indicative of mechanical or reconstruction problems. These artifacts may be due to issues with calibration of the flat-panel imager or the geometric calibration of the device. These may be remedied by appropriate recalibration by the medical physicist. However, when simple remedies such as recalibration do not successfully restore image quality, equipment or software faults may be responsible, generally requiring the attention of a service engineer.

III.C. Commissioning

The principal aims for commissioning are to experimentally determine imaging parameters for optimal image quality and localization accuracy for different anatomical sites and to identify potential limitations of the imaging system. These parameters are then used to setup operational procedures for different localization purposes. It is also important that users perform an evaluation of imaging dose prior to clinical application, since the imaging volume is much larger than the target volume. Dose may also have an impact on image quality and x-ray tube lifetime.

III.C.1 Imaging Protocol Development

Clinical application of IGRT needs to be tailored to the anatomical site and treatment requirements. Different anatomical sites may need different imaging methods such as 2D orthogonal imaging, 3D CBCT, 2D fluoroscopic imaging, and 4D CBCT. This choice can be influenced by factors such as the imaging surrogate (fiducial markers, bone, and soft tissue), the need to manage respiratory motion, and geometric clearance of the immobilization device. Different imaging procedures may require different imaging techniques. In order to determine imaging parameters for optimal image quality and localization accuracy for different anatomical sites, prior to clinical use, the clinic should define imaging goals, the procedure needed to achieve those goals, and potential adverse effects of performing the procedure.

The commissioning procedure is primarily aimed at determining whether different procedures are needed for different treatments and anatomical sites and optimal development of procedures to achieve specific goals. The next steps are to determine the accuracy each imaging procedure can achieve, how each procedure should be done, the roles of each member of the multidisciplinary team, what training may be needed for staff performing the procedure, and any potential adverse consequences (both staff and patient may be informed). The end point is to develop a step-by-step operational protocol for each imaging procedure.

The parameters and operational procedures used for imaging should be thoroughly documented for different localization purposes. Most systems allow the creation of preset techniques that are stored in software and easily selected from a list. Those parameters should be periodically reviewed based on changes of the imaging system.

Additionally, it is critical to consider which imaging processes are necessary for each specific application. Unnecessary use of any technology should be avoided.

III.C.2 Imaging Limitations and Dose

It is important to understand the limitations for each imaging procedure and to identify potential limitations of the imaging system. Following the general guidelines of radiation safety and protection, an evaluation of imaging dose prior to clinical application should also be performed and documented. Specific details related to this issue were discussed in the AAPM TG-75 report (Murphy, Balter, et al. 2007). An additional estimation methodology for kV-CBCT imaging dose was also discussed by Ding et al. (Ding, Duggan et al. 2008). They have also found that the dose to the bone due to the photoelectric effect can be as much as 25 cGy, about three times the dose to the soft tissue. For some experimental trials, clinical protocols should be developed and Institutional Review Board (IRB) approval should be acquired.

III.D. General Quality Assurance

Quality assurance procedures are designed to ensure that the imaging systems, including both hardware and software, function safely and reproducibly and perform as accepted and commissioned.

III.D.1 QA Contents

QA procedures involve periodic measurements of specified parameters using dedicated tools and phantoms that are validated with specific acceptability criteria and tolerance levels. The report of TG-142 [Quality Assurance of Medical Accelerators (Klein, Hanley et al. 2009)] includes recommendations for QA parameters of imaging systems as well as their measurement frequency and acceptable criteria. Some examples are available in publications (Yoo, Kim et al. 2006; Bissonnette 2007). Sometimes, vendors may provide the clinical site instructions and tools to be used for the measurements as well as instructions about how to perform the measurements. The users should analyze these materials and decide how to proceed or set up their own measurement protocols. If the QA process identifies parameters that are out of specified tolerances, investigations and fixes should be performed with engineer assistance if necessary.

In general, each clinic should define daily, monthly, and annual QA procedures. The daily QA should include safety feature checks, positioning and repositioning accuracy tests, and basic tests to verify the coincidence of imaging and treatment coordinates. The monthly QA should consider thorough tests of the coincidence of imaging and treatment coordinates, image quality including noise, resolution, and contrast, Hounsfield unit (HU) consistency, and the scaling factor. The annual QA should include a full range of mechanical traveling accuracy, imaging dose, kV beam energies, tube current, etc.

QA phantoms and measurement methods may differ with different imaging systems and with different institutions. Typically, the tools and methods used to perform acceptance testing could be also used for QA purposes. It would be ideal that similar methods were used for the same system for all users. The AAPM Therapy Physics Committee is establishing a task group to define QA methodologies for in-room imaging systems. In the following sections, we will only highlight some important materials related to QA programs. Materials related to hands-on descriptions about how to perform each specific QA item are beyond the scope of this report, and readers are encouraged to refer to other related reports.

III.D.2 QA Frequencies and Criteria

A successful QA program should start by determining the necessary parameters to be checked. Information generated during the acceptance testing procedure and commissioning could be used as the baseline criteria. Alternatively, the clinical sites could define their own criteria or measurement frequencies for their own QA program. Any deviation of imaging parameters could affect and compromise the imaging quality for positioning evaluation. Therefore, the performance parameters should include geometric reproducibility and accuracy, repositioning accuracy, image quality and reliability of image analysis tools, and the integration of the IGRT system. Examples of these parameters can be found in the previous publication (Klein, Hanley et al. 2009) for the QA worksheets for the Varian OBI system, as developed in a collaborative effort by Duke, Emory, and Stanford universities and Henry Ford Hospital (Yoo, Kim et al. 2006).

QA baseline values and frequencies are very critical in the QA process. The criteria used in the acceptance testing could be used as the baseline criteria of measurement parameters. The frequency of these tests should be based upon an analysis of system stability during the initial operation of the device. The previous published report (Klein, Hanley et al. 2009) also included recommended QA frequencies for the Varian OBI/CBCT by those institutions (Yoo, Kim et al. 2006). Table 2 is another example of the quality assurance elements adopted for the Elekta Synergy system at Princess Margaret Hospital (Toronto, ON, Canada). The frequency of the tests have been set from an understanding of the device elements and from recommendations offered in TG-40 (Kutcher, Coia et al. 1994) for devices like the radiotherapy simulator and portal imaging systems and from TG-142 for other in-room imaging systems. While the initial test tolerance and values can be established from vendor literature and accepted QA guidelines, appropriate test frequencies and accepted variability from baseline values can only be ascertained after analysis of QA data acquired over extended periods of time Bissonnette, Moseley et al. 2008a,b).

It should be noted that QA test procedures, baseline values and acceptable deviations, and frequencies for in-room IGRT are still in developmental phases due to the limited data available for references and clinical comparisons. Mainly, in-room kV imaging systems have only been used in the clinic environment for a relatively short period of time. There exist a variety of imaging systems commercially available, and these systems are continuously being improved. Therefore, some variations of QA methods may exist both between institutions and between imaging systems. However, it would be ideal to adopt uniform and consistent sets of measurement techniques, phantoms and criteria. The AAPM Therapy Physics Committee has produced the TG-142 report (Klein, Hanley et al. 2009) and is developing a task group report (TG-179,

Table 2. Summary of QA Recommendations for CBCT on a Linac from Princess Margaret Hospital. Tolerances may change according to expectations, experience and performance.

Frequency	Procedure	Tolerance
Daily or each use	Detector stability and system performance	
	Dark image calibration acquisition before each scan	
	Geometry	
	Localizing lasers	<1 mm
	MV/kV/laser alignment	
	Accuracy of shift	±2 mm
	Safety	
	Collision detectors: interrupts or prevents irradiation	Functional
	Warning lights	Functional
	Warm-up	
	Generator operation	Functional
	Detector operation	Functional
	Detector signal	Within expected range
	Collimator operational	Functional
	Clinical process issues	
	Database integrity	
	Storage space availability	
Weekly	Safety	
	X-ray arm and door interlocks: interrupts or prevents irradiation	Functional
Monthly or after service	Imaging system performance	
	Gain stability	Replace/refresh
	Defect maps	Replace/refresh
	Image quality	
	Scale and distances	±0.5 mm
	Uniformity	Baseline
	High contrast spatial resolution	>7 lp/mm
	CT Number Accuracy	Baseline
	Artifacts	Absence
	Geometry	
	Geometric calibration (flexmap)	Replace/refresh
	Couch shifts: accuracy of detection and correction motions	±1 mm
	Review of daily test results	Complete
Annual or after service	X-ray generator system performance	
	kVp accuracy and waveform	Baseline
	mAs linearity	Baseline
	Radiation quality (HVL)	Baseline
	Accuracy of mA and mAs	Baseline
	Geometry	
	Detector tilt	Baseline
	Detector skew	Baseline
	Couch scale and motion accuracy	± 1 mm

(continued)

Table 2 *(continued).*

Frequency	Procedure	Tolerance
	Data transfer	
	Link to treatment planning	Functional and accurate
	Long term and short term storage	Functional
	Dosimetry	
	Axial and skin dose	Baseline
	Clinical process issues	
	Database integrity and maintenance	Baseline
	Documentation of imaging parameters	Up-to-date
	Review of daily and monthly test results	Complete

(Modified and reprinted from Table 7.3, p. 278, *The Modern Technology of Radiation Oncology, Volume 2*, J. Van Dyk (Ed.), with permission from Medical Physics Publishing.)

AAPM 2009) for this purpose. In general, the baseline data established during the acceptance testing could be used as the criteria for routine QAs of any image guidance system.

III.D.3 QA Phantoms and Measurements

Selection of QA phantoms and measurement methods should be judged by the basic principle that all measurements should be able to provide reliable values for the measured parameters and can be used to judge whether tolerance criteria have been achieved. Well-adapted QA tools and phantoms facilitate efficient and accurate QA procedures. Sometimes, QA test phantoms are provided by manufacturers of in-room kV imaging systems. For example, Varian provides an array of phantoms and tools both for calibration and for QA (Yoo, Kim et al. 2006). In-house developed and new commercial phantoms and software are also critical examples of the IGRT QA tools. For example, daily QA tests designed specifically for CBCT warm-up and verification of the geometric accuracy of the guidance system have led to the development of commercial products, such as the Penta-Guide phantom (Modus Medical Devices. London, ON, Canada) (Bissonnette 2007). This phantom cannot only be used to compare the accuracy of CBCT localization with that of portal imaging on a daily basis, but it can also assess the accuracy of remote-controlled couch motions and therefore the accuracy of the entire image-guidance process prior to the first treatment of the patient. Such a test assesses the entire process from beginning to end and inspires confidence that the overall process is accurate and robust. Apparently, QA phantoms and measurements devices play critical roles in QA for IGRT systems and processes. It is therefore important to also maintain a periodic QA program for QA phantoms and measurement devices.

An important implication of QA and quality improvement for an IGRT process is the compilation of uncertainty data to produce rational PTV margins. The use of an image-guided process can produce a substantial volume of data on patient positioning and organ motion uncertainty. A single treatment machine capable of image-guidance could reasonably produce 5000 patient fractions of data every year (assuming 20 IGRT patients per machine, 250 working days per year for a typical community radiation therapy clinic). However, this information will remain unused if processes are not developed to analyze and collate this data. This represents an

unprecedented opportunity to produce databases of patient uncertainty. The resultant database of patient uncertainty information can provide information about appropriate margin calculations and allow the design of rational and appropriate PTV margins for specific treatment methods. Some studies have suggested methods for using IGRT data for PTV margin design (van Herk, Remeijer et al. 2000).

III.E. System Integration and Data Management

As outlined previously, the successful and widespread introduction of image guidance has for most part been made possible by the automation of the image acquisition and rapid correction processes. As pointed out earlier, image-guidance procedures require accurate geometric calibration of the systems and the user's complete understanding of the mechanical characteristics of these systems. The geometric information generated by these systems, in turn, must be entirely compatible with the software used to interpret the images. The DICOM-RT standard provides a framework to communicate such data, including coordinate systems, back to the treatment planning, record-and-verify, or automatic couch control software. Thus, the acceptance and commissioning of image-guidance systems must document and validate the accurate transfer of geometric data to all other pertinent devices.

Special attention should be paid to the usage of radiation oncology information software in the context of IGRT. In a large radiation therapy department, images are generated from numerous sources. Radiographs, portal imaging, and kV- or MVCT images should be stored and shared in a single database for ease of use and for distributed access for review. However, the management of a large number of images for a single patient may become problematic, especially when several imaging studies (CT, positron emission tomography [PET], magnetic resonance imaging [MRI], and daily volumetric positioning images) are performed. The storage requirements become massive. Additional images, such as several DRRs, are generated during the planning process. The management of these massive amounts of images becomes more complex if changes occur within a treatment course to reflect different treatment phases or corrections. Users may select the wrong DRR as a reference image or mismatch studies or even patients. In combination with non-compliance to naming conventions, changes to a plan, or other communication failures, the large number of images can create confusion and result in treatment errors. Special attention must be brought to the management of the imaging database, including links to simulation, planning, and delivery imaging sources. These aspects will be discussed in section IV.

IV. IMAGE-GUIDED PROCESSES IN THE CLINICAL SETTING

IV.A. General Considerations/Identification of a Suitable Imaging Technology

The overall objective of in-room kV based image guidance is either to reduce the treatment margin, or PTV, or to assure that the prescribed margin is adequate. Before embracing image guidance, it is important for the practitioner to examine the clinical treatment objective, the necessary dose, and the necessary and achievable margin. It is useful to have a general discussion about the treatment strategies, the matching of treatment objective with the appropriate strategy, and the selection of the appropriate method of image guidance.

The selection of an appropriate image-guidance solution is a complex process that is a compromise between clinical objectives, product availability, existing infrastructure, and manpower. The deployment of a new technology requires a thorough understanding of the complete clinical process and the necessary infrastructure to support data collection, analysis and intervention. The most important considerations are clinical objectives and manpower. Table 3 lists many but not all of the factors that should be considered in this process.

An excellent example is the employment of fiducial markers for on-line prostate IGRT which has grown dramatically in recent years (Alasti, Petric et al. 2001). The clinical objective of this process is to increase the precision of radiation field placement with respect to the prostate gland. Gold markers implanted in the prostate provide a surrogate of the gland position that is visible in the portal images. Prior to radiation delivery, a pair of radiographic images using either MV portal or kV imaging devices are taken and compared to reference DRR images to identify potential positional deviations of the target. The position is then corrected by moving the treatment couch. This procedure could be completed within a 15-minute treatment time slot. This approach allows for a reduction of the PTV to CTV treatment margin. Alternatively, the use of EPIDs and orthogonal kV imaging in this process can be replaced with fast and low-dose kV CBCT imaging for fiducial-based marker guidance. One major consideration for CBCT imaging

Table 3. Considerations for the Deployment of an Image-Guided Process

Category	Factor
Clinical Considerations	Structures of interest (target, surrogates, normal structures)
	Strength of surrounding surrogates (bone, skin)
	Consideration of implanted markers as surrogates of target/normal tissue
	Frequency of imaging (prior to, during, after treatment)
	Dose escalation/normal tissue sparing
Technical Considerations	Desired level of geometric precision
	Uncertainties to be managed through the use of margins
	Method of intervention (degrees of freedom)
	Number of fractions for which guidance is required
	Techniques of managing organ motion
	Magnitude of dose gradients
Resource Considerations	Available treatment capacity (treatments/hour) on treatment system
	Application for all or some fractions (boost)
	Application for some or all patients
Organizational Considerations	Development of a structure for delegation of responsibility with respect to measurement, analysis, decision, and correction
	Identification of individuals responsible for program development
	Identification of individuals responsible for commissioning and performance characterization
	Identification of individuals responsible for performing quality assurance on the system and periodic verification or performance

is that volumetric changes in treatment target volumes and adjacent critical organs such as bladder and rectum need to be evaluated. The application of an appropriate margin requires recognition that the markers are a surrogate for prostate gland location. The validation of markers as appropriate surrogates for soft-tissue target is somewhat underpracticed in the community. Technically, if there are no marker shifts or organ deformation, the localization accuracy based on marker-marker matching between kV plane images and kV CBCT should be comparable. CBCT should always be used to assess deformation and marker movement. This may be more important for hypofractionated treatments with high dose per fraction and tight margins between CTVs and PTVs. However, for regular fractionated treatments when a sufficient margin between CTV and PTV is added, daily CBCT may not be necessary. It would be prudent not to image with CBCT for these cases considering excessive cumulative imaging dose.

The process for selecting an imaging device can be challenging. The principle goal for using image guidance is to improve target localization accuracy, so that treatment margin from CTV to PTV may be reduced. Several papers have also advocated optimizing plans directly on the CTV and applying the uncertainties for setup and motion during the optimization process without using a PTV (Chetty, Rosu et al. 2004; Trofimov, Rietzel et al. 2005; Baum, Alber et al. 2006; McShan, Kessler et al. 2006; Olafsson and Wright 2006). Therefore, use of a proper image guidance method must be carefully considered to achieve the necessary localization accuracy. Excessive use of IGRT should be avoided if such improvement is clinically insignificant. On the other hand, failure to achieve the required accuracy could be detrimental.

IV.B. Design and Implementation

The integration of a new system into the process for IGRT requires significant effort to design, implement, and maintain.

The design of the image-guidance procedure must begin with a review of the clinical objective. Once the clinical objective has been set and it is clear that the necessary technology is in place, a multidisciplinary task group consisting of therapists, dosimetrists, oncologists, and physicists should be assembled. The addition of computing support staff, if available, is also recommended. Well-trained medical physicists generally play leading roles in such implementation. This task group should set out to break the design elements down into three components: (1) system issues (infrastructure, connectivity, tools); (2) performance issues (detection, i.e., image quality, and guidance performance, i.e., geometry); and (3) operation issues (decision making, PTV margins, QA). Assuming no limitations due to hardware availability, the development of such a process could reasonably take 2 to 3 months to complete with significant reductions in this estimate if a similar process already exists within the clinical program. The implementation process would be considered complete when the procedure has been fully documented, its performance has been quantitatively assessed, a program of quality assurance has been established, and all relevant staff have been trained. The training could be offered by vendors or internal skilled physicists or other staff who are familiar with the details of the system and operations. Again, the design and implementation are team efforts with a focus on the principle improving the quality of patient care.

Careful assessment of the workload and additional resources required is necessary for the success of the implementation. Patient-related factors include the ability to tolerate the procedure and the additional radiation dose. Lengthy image-guided procedures may reduce the initial patient positioning uncertainty but may also increase the potential of intrafractional variation in patient positioning. While the dose from an individual kV imaging procedure is usually very low compared to the therapeutic dose, the dose from multiple, long fluoroscopic acquisitions or high-quality CBCT scans should not be dismissed. Furthermore, unlike MV portal imaging dose, kV imaging dose cannot be included in the treatment plan with current commercial treatment planning system, although some efforts have been made toward this direction (Ding, Duggan et al. 2008). It should be recognized that the intent is localization and verification of patient positioning, not diagnosis.

IV.B.1 Image Performance and Objectives

The clinical objective needs to be translated into an imaging task for the guidance system. Imaging systems have many parameters that can be set to alter the quality or acquisition frequency of the resulting images. A given set of operational parameters is often referred to as a "technique". The selection of the technique in a kV radiographic system has many variables than can alter the visibility of structures and the dose delivered during the imaging procedure. For example, visualization of clinical targets in the lung is possible at dramatically lower imaging doses (one-tenth) than soft-tissue structures in the pelvis; therefore permitting a much lower current-time product in the radiographic technique. The testing of a technique on phantoms and subsequently on a range of patient subpopulations will allow the development of robust procedures for image-guidance. It is recommended that standardized techniques be developed to produce images of consistent performance. Consistent imaging performance is critical in the construction of a robust image-guidance process.

In the case of automatic or semi-automatic image analysis systems, the imaging performance should be evaluated by testing the accuracy, precision, and robustness of the analysis method on the images produced by the specific technique. Identification of modes of failure and the establishment of a review mechanism that permits the operator to make sense of the result should also be provided.

IV.B.2 Image Acquisition

Other parameters that may need to be specified include the frequency of imaging: real-time, once or twice per treatment session, or weekly. The rate of image acquisition will depend upon the frequency of intervention that is intended or possible. For example, correction of respiratory motion would not only require a high frame rate (>5 frames/s) for imaging, but also require a similarly fast mechanism for correcting the patient and beam co-registration. The integration of other devices into the image-guidance procedure must also be considered in designing an appropriate image acquisition sequence. These systems include breath-hold devices, gating systems, and tracking systems.

The frequency of image acquisition must also consider the accumulation of imaging dose. The optimal imaging scenarios will use only enough imaging to achieve the necessary

accuracy and will take into account the range of radiation sensitivity and vulnerability in the patient population. For example, when performing SBRT, it is clinically feasible to perform imaging before and after positioning correction prior to the actual treatment, as well as during and after treatment to ensure positioning accuracy and document treatment delivery. However, such an imaging procedure is not practical for patients treated using conventional fractionations.

IV.B.3 Analysis Tools

The identification or development of a clinically useable and robust analysis tool is of paramount importance in the implementation of the image-guidance process. Many of the commercial vendors offer a specific tool set for analysis of the images. The performance of these tools needs to be tested for robustness and accuracy in the image guidance process. An image-guidance phantom can be employed for these tests. This phantom should imitate the image-guidance task as closely as possible, including the imaging task and other imaging and patient related parameters (mass, thickness, etc.). The basic tests of accurate scale and linearity should have been performed during acceptance of the device (see section IV.F).

IV.C. On-line and Off-line Strategies

The development of various mechanisms for measuring patient position has created valuable data for the correction of patient position. The use of these data to stratify treatment decision and to modify the treatment process is referred to as the *strategy*. Strategies are broadly divided into *on-line* and *off-line* approaches. The on-line approach adjusts the treatment parameters or patient position based upon data acquired during the current treatment session. This may be as simple as adjusting the couch position or as complex as full re-optimization of the treatment parameters based on changes in the shape and relative position of target and normal structures. The off-line approach is one in which the intervention is determined from an accumulation of information that may be drawn from previous treatment sessions or other times of measurement. The on-line approach is generally categorized as having greater capacity to increase precision with an associated increase in effort for the same level of accuracy as that achieved with off-line strategies. In general, clinical implementations typically operate with a hybrid of on-line and off-line approaches that are invoked under different tolerance thresholds. A familiar example is seen in conventional portal film practice in which the first treatment session is adjusted "on-line" (i.e., at the time of therapy in the treatment room) while subsequent corrections are applied off-line (physician review of portal images). Another example developed since the advent of EPIDs is to correct "gross errors" in an on-line fashion, as it is clear that any reasonable intervention would be an improvement. For a detailed review of the numerous strategies in clinical use, the reader is referred to recent reviews in the literature (Hurkmanns, Remeijer et al. 2001; Yin, Wang et al. 2006a).

In general, off-line strategies reduce interfraction systematic errors, while on-line strategies reduce both inter- and intrafraction systematic and random errors. The relative importance of systematic and random errors in the determination of PTV margins should be considered in the design of the clinical strategy. Geometric errors in radiation field placement are typically characterized by distributions of non-zero mean and variance. The mean describes the systematic discrepancy for an individual patient and the variance of the random component. Several

authors have highlighted the relative importance of these two categories of errors in determining appropriate PTV margins (van Herk, Remeijer et al. 2000, 2002).

Off-line and on-line strategies have significantly different requirements with respect to integration and coordination. More complex off-line procedures that employ increased frequency of imaging, alignment tools, and decision rules offer increased accuracy compared to conventional practice while maintaining efficiency (Yan, Vicini et al. 1997; Yan, Wong et al. 1997; Yan, Ziaja et al. 1998; Yan, Lockman et al. 2000). The overhead associated with the alignment tools and decision rules can be prohibitive unless properly integrated. The adaptive radiotherapy program at William Beaumont Hospital (Royal Oak, MI) (Yan, Lockman et al. 2000) was only made possible through software integration developed internally. Similarly, effort was also required from the procedure and policy perspectives to coordinate the actions of the off-line efforts with the radiation therapists operating the machine. On-line approaches require elevated levels of software and hardware integration for operation as the analysis and interpretation are performed at the time as therapy (Wu, Thongphiew et al. 2008). One advantage of the on-line approach may be in the capacity to focus these efforts at the treatment machine, as opposed to the development of clinicwide systems for coordination of an off-line approach. This issue requires further debate, and the relative merits of off-line and on-line approaches should be evaluated from the precision, accuracy, and efficiency perspectives. Ideally, all measured data should be analyzed to identify areas of improvement globally, such as the refinement of margin prescription. Regardless of the strategy applied, the need for quantification of geometric performance and assurance of continued performance requires appropriate allocation of manpower in the radiation oncology process.

IV.D. Margins, Accuracy, and Precision

Intimately related to the identification of a strategy, it is also imperative that the practitioners of IGRT be cognizant of treatment margin design. A starting point is to determine an appropriate margin for the procedure—an interesting and important challenge as such information is typically not available at the initiation of a new procedure. Indeed, imaging data need to be acquired and analyzed before an appropriate margin can be determined.

Treatment verification and localization can reduce, but not eliminate, geometric uncertainties. The common approach currently used for dealing with residual geometric uncertainties is to add a safety margin to the CTV to form the PTV and to add a safety margin to the organ at risk to form the planning organ at risk volume (PRV) (ICRU 1993, 1999). If geometric uncertainties can be reduced, a smaller PTV may be used, resulting in a possible reduction of normal tissue complications and/or the opportunity for dose escalation. The process of determining an appropriate PTV compels the radiation oncology professionals, especially the physicists, to consider important clinical issues, such as the nature and magnitude of uncertainties due to patient positioning and organ motion (both random and systematic), as well as the desired goals of image-guided treatment modifications.

The definition of an appropriate PTV is not a trivial task. A common approach is to use twice the standard deviation of measured geometric uncertainties. This assumes a Gaussian distribution of uncertainties, where two standard deviations include 95% of all displacements (Tinger, Michalski et al. 1998). The simplicity of this strategy results in generic PTV margins for

many situations. An improvement on these simple rules is the class of "margin recipes" that have been developed by several investigators (Bel, van Herk et al. 1996; Stroom, de Boer et al. 1999; McKenzie, van Herk et al. 2000; van Herk, Remeijer et al. 2000, 2002; Stroom and Heijmen 2002). These recipes are linear equations that describe the required margin in terms of the standard deviations of random and systematic uncertainties (the dose gradient or 3D "penumbra" of the dose distribution may also be included). These recipes are defined by specific clinically relevant criteria (e.g., 90% of patients receive 95% of the prescription dose). The strengths of margin recipes include the explicit separation of random and systematic uncertainties, the incorporation of dose gradients, and clinically meaningful criteria. However, they are not fully general. Recipes often assume Gaussian distributions of uncertainties, have one specific treatment goal, assume a large number of fractions, and do not consider adjacent critical organs. Therefore, it is important to understand the assumptions and decisions that have gone into the formation of a particular PTV margin recipe before applying it clinically.

One criticism of the methods described above is that they all use population-based data. Therefore, all individuals are planned with the same general PTV margin, regardless of their individual geometric uncertainties. Treatment verification and PTV definition can be used iteratively to produce individual-specific PTVs. One example is "adaptive radiotherapy" (Yan, Lockman et al. 2000; Martinez, Yan et al. 2001). This off-line strategy employs a generic PTV at the beginning of treatment. The patient position is imaged during the first few days of treatment, and the resulting patient-specific uncertainty information is used to define a modified PTV. The novel imaging technologies described in this document may be able to use similar strategies to even greater benefit than previously demonstrated. Note that those methodologies are not validated with hypofractionated treatment, such as SBRT.

IV.E. Decision-Making and Intervention

The introduction of image-guidance procedures will increase the amount and quality of data available over the course of therapy. This new information will need to be acted upon for the betterment of the patient. This raises the issue of decision-making for modification of the patient's treatment and which individuals are responsible for making and executing these decisions. The development of a specific image-guidance procedure should include an assessment of the new information made available, the decisions to be made, and the individuals or disciplines that are responsible for these decisions. The development of rigorous and documented strategies to deal with this information is central to the image-guidance process, as it will significantly impact (1) the appropriate PTV margins, and (2) the efficiency with which these processes are able to operate. The importance of communication and training of the strategy is of the utmost concern from a safety perspective.

IV.F. Quality Assurance Program for Image-Guided Processes

The development of a process will only be a worthwhile investment if the clinician can confidently depend upon the estimates of geometric precision produced by that process. Failure to provide confidence will have two outcomes: the failure to use sufficiently large PTV margins or the failure to reap the full capacity of the system. Both of these failures will result in a detriment to the patient. To achieve this confidence, the QA program for any image-guided therapy process

must evaluate the entire treatment process. This includes, although may not be limited to: imaging, treatment planning (including the production of reference images to guide corrections), verification imaging, image registration, patient position correction, and treatment.

A comprehensive QA procedure should be established for each institution for each image guidance system. To effectively perform QA procedures, one will need to specify QA performance parameters, establish criteria and frequencies of QA, identify tools and phantoms required for QA, and delegate all responsibilities to appropriate staff. In addition to regular examination of the devices, the image-guidance procedures themselves, including documentation of the training process, should be reviewed on a regular basis to verify that the procedures are consistent with the initial design or intended design after changes have been made to the procedure.

IV.G. kV Imaging Dose Considerations

The imaging techniques summarized in section I.A or Table 1 can be used individually or in combination throughout the treatment process. This can result in a significant cumulative imaging radiation dose to the patient. The concomitant dose should be carefully considered and documented when designing treatment imaging scenarios in order to remain faithful to the radiology principle of "As Low As Reasonably Achievable" (ALARA). Because the evaluation of cumulative imaging dose is a non-trivial problem, a separate AAPM Task Group 75 (Murphy, Balter et al. 2007) has produced a report analyzing the radiation dose delivered during IGRT. Readers are referred to the TG-75 report to pursue questions related to cumulative imaging dose. It is recommended that imaging doses are measured as part of the IGRT commissioning process.

IV.H. Manpower and Training

When implementing IGRT procedures, manpower needs should be carefully estimated by an interdisciplinary team including physicists, physicians, and therapists. The benefits of IGRT should also be communicated to hospital administrators, who also need to understand the need for adequate staffing and training. Properly trained staff in an IGRT department is also critical to secure high-quality patient care. These staff should include radiation oncologists, medical physicists (and/or dosimetrists), radiation therapists, administrators, and nurses. Such kind of training could be done through vendor's courses, related conferences offered by professional organizations, and internal in-services.

The process of IGRT is a team approach and effort. Radiation oncologists should be overseeing clinical operations about how IGRT applications can be used for improving patient positioning accuracy. Medical physicists leading the IGRT implementation should have a deep understanding of each of the IGRT elements, be capable of developing and implementing QA procedures, and be highly effective in communicating with all the members involved in the IGRT process. The therapists are the front-runners for execution of the developed IGRT programs, and the quality of their performance will have a substantial impact on the success of IGRT. The importance of the processes and the impact of clinical decisions need to be communicated to each staff member on the team. This process is open to errors in communication. The review of the guidance elements of a patient's treatment should be integrated into the chart rounds program within the institution to verify that the process is operating correctly.

V. NEW DEVELOPMENT

It is clear that in-room kV-based image guidance has taken hold in the radiation therapy community and may become a standard of care. There are many exciting developments along this direction, although many aspects of the practice are in their infancy. There are several noteworthy works in progress. These are only briefly discussed, as they are not yet available commercially or have very limited clinical users.

V.A. CBCT with a Mobile CT

Several investigators are collaborating with Siemens in the development of a mobile C-arm 3D CBCT system that can rotate isocentrically and can be used as an alternative to the CT-on-rails system. The C-arm approach was originally intended for minimally invasive orthopedic and trauma surgery and is available as a commercial product, such as the PowerMobil (Siemens Medical Solutions, Erlangen, Germany). For IGRT, the C-arm unit is equipped with a large-area flat-panel imager to provide CBCT with a larger FOV. Siewerdsen et al., evaluated the device and its imaging characteristics for applications in image-guided surgery (Siewerdsen, Moseley et al. 2005). They reported that soft-tissue contrast in the cone beam images was compromised compared to conventional CT, due primarily to the underlying noise inherent in cone beam reconstruction. In contrast, kV cone beam images were observed to be free of geometric distortion and to have spatial resolution of >10 lp/cm which is approximately equivalent in all three dimensions. Sorensen et al. subsequently adopted the device for in-room localization of radiotherapy patients, using an IR-tracking system similar to that of BrainLAB's ExacTrac to spatially register the cone beam images with the linac isocenter (Sorensen, Chow et al. 2006; Sorensen, Mitschke et al. 2007). Use of the device to acquire respiratory-gated cone beam images has also been demonstrated (Kriminski, Mitschke et al. 2005).

V.B. kV Imaging for Proton Treatment

The continuing development of particle therapy facilities around the world calls for the parallel development of image-guided target localization technologies. Particle therapy requires a particularly high geometric accuracy for target localization, especially in regions of tissue inhomogeneity. Kilovoltage imaging has been the principal tool for this purpose. In addition to traditional planar kV x-ray imaging, using either single or dual orthogonal source-detector configurations, CBCT technology is being implemented in proton treatment rooms. There are two ways to install CBCT in the proton room. One is to mount the x-ray tube and detector on the rotational gantry. The other way is to mount both the x-ray tube and detector to the ceiling of the treatment room via a robotic arm. The use of a robotic arm allows very flexible image positioning at a variety of couch positions, but precise knowledge of the geometrical relationship between the imaging and treatment geometry is very critical for such an installation. Figure V-B-1 illustrates a kV x-ray imaging system used at Loma Linda University Proton Treatment Center (a) and a CBCT imaging system with a robotic arm used at the Heidelberg University heavy ion particle treatment facility (b) (Haberer, Debus et al. 2004).

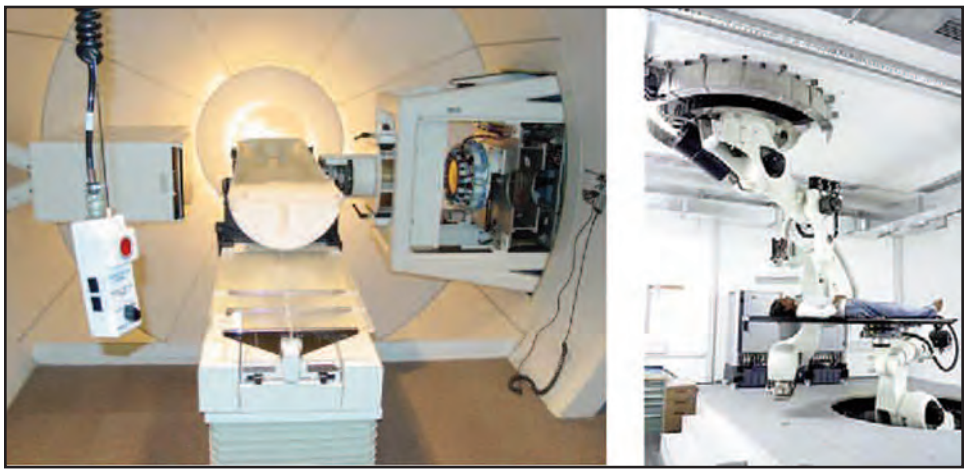

Figure V-B-1. (a) Illustration of a kV x-ray imaging system used at Loma Linda University Proton Treatment Center; (b) a CBCT imaging system with robotic arm used at Heidelberg University heavy ion particle treatment facility. (Courtesy of Michael Moyers, Ph.D.)

V.C. Dual X-Ray Tubes with Dual Detectors

The Integrated Radiotherapy Imaging System (IRIS), developed at Massachusetts General Hospital in collaboration with Varian Medical Systems, Inc., consists of two gantry mounted diagnostic kV x-ray tubes and two flat-panel a-Si detectors. As the entire system is rigidly mounted to the gantry, it co-rotates with the gantry, so the diagnostic beams maintain their positions relative to the therapy beam (and each other). The system is designed for three main functions: simultaneous orthogonal radiographs for 3D patient setup, CBCT for soft-tissue localization, and real-time orthogonal fluoroscopy for tumor/marker tracking. The IRIS is unique in its integration of all three image guidance functions with the therapy linac (Berbeco, Jiang et al. 2004).

Another type of dual-detector and dual-tube system is mounted to a 4D-IGRT therapy system (MHI-TM2000) developed by Kamino et al. (Kamino, Takayama et al. 2006) with Mitsubishi Heavy Industries, Ltd. Two sets of kV x-ray tubes and flat-panel detectors (FPDs) are mounted on an O-ring treatment unit as the on-board imaging subsystem. The lines of sight are orthogonal to each other. The resultant FOV at the isocenter is 21 cm (in the O-ring plane) $\times$ 16 cm (perpendicular to the O-ring plane). The imaging system provides a pair of radiographs, CBCT images useful for image-guided setup, and real-time fluoroscopic monitoring for motion tracking. The MHI-TM2000 IGRT system as shown in Figure V-C-1 is being installed in the Academic Hospital of the Free University of Brussels (AZ-VUB), Brussels, Belgium.

V.D. kV and MV Dual-Energy Imaging

In an effort to improve imaging efficiency and to reduce CBCT reconstruction artifacts due to the presence of high-density materials, Yin et al. has investigated the use of MV/kV aggregated imaging techniques. Promising results have recently been presented (Yin, Guan et al. 2005; Zhang and Yin 2007).

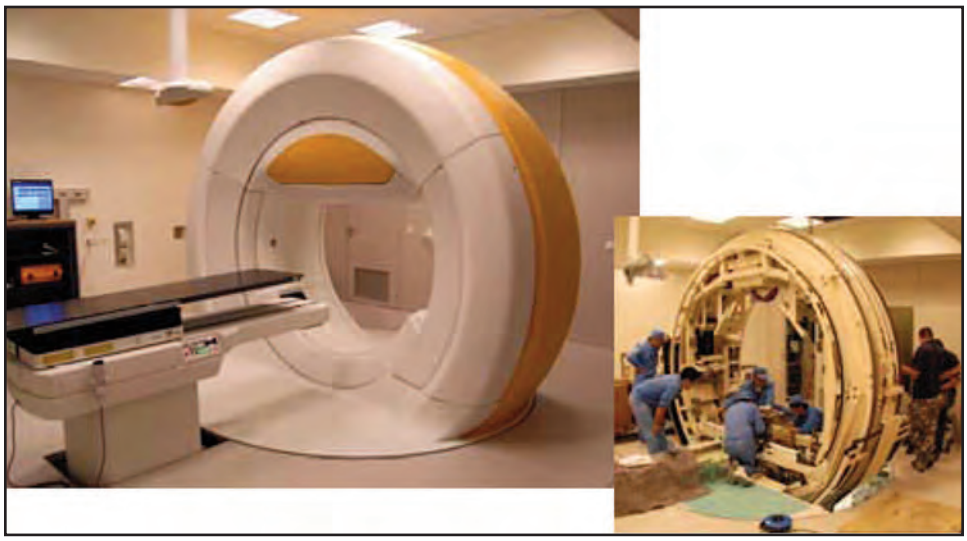

Figure V-C-1. Illustration of MHI-TM2000 image guidance system. The insert shows the physical size relative to people. (Courtesy of Dirk Verellen, Ph.D., Academic Hospital of the Free University of Brussels (AZ-VUB), Brussels, Belgium)

Recently, Siemens announced the In-Line kVision™ image-guidance system as shown in Figure V-D-1. kVision™ is a kV imaging device onboard the newly announced Siemens' ARTISTE treatment unit. It is pending U.S. FDA approval at the time of this writing. The treatment unit is equipped with In-Line MV CBCT and kV CBCT capabilities. In this kV imaging system, the retractable x-ray tube is mounted at the bottom of the accelerator gantry close to the portal vision detector, and the retractable a-Si flat-panel detector is mounted at the head of the gantry. The kV x-ray axis is in parallel and coincident to the treatment beam but at the opposite direction. This is different from the Elekta and Varian onboard kV imaging systems where MV and kV imaging systems are mounted at orthogonal directions. The imaging system is capable of performing radiographic and fluoroscopic imaging. It will also be capable of performing kV CBCT when it is commercially released.

As part of Siemens' IGRT solution including planar and tomographic MV imaging (MVision), kV imaging (kVision), and tomographic In-room CT (CTVision), the new In-Line system shares common image analysis tools in a dedicated workstation for image analysis, manipulation, and archiving. Technical information about the system is also included in Table 1 for comparison.

V.E. Digital Tomosynthesis

Digital tomosynthesis (DTS) is a method for reconstructing 3D slices from 2D cone beam x-ray projection data acquired with limited source angulation (e.g., 40 degrees). It has advantages over CBCT in terms of lower doses, short image acquisition times, and less gantry rotation clearance requirements. These images may be particularly suited for patient repositioning in the thorax and abdomen, where CBCT currently suffers from motion artifacts. Duke University has developed a unique technique to generate reference and on-board DTS images for 3D target

Figure V-D-1. Illustration of In-line kVision image-guidance system. (Courtesy of Siemens Oncology Systems)

localization (Godfrey, Yin et al. 2006). DTS images for all clinical sites show excellent soft-tissue contrast (Godfrey, Yin et al. 2007). Breath-hold DTS is also shown to be a potential alternative to on-board CBCT for sites prone to respiratory motion. Clinical feasibility of using DTS for target localization has been documented by its equivalency of localization accuracy compared with CBCT technology (Wu, Godfrey et al. 2007). A novel technique has also been developed to reconstruct CBCT images using limited scan angle projections (Ren, Zhang et al. 2008). Use of DTS technology will be especially useful to generate on-board 4D images due to short acquisition time and limited scan angles (Maurer, Godfrey et al. 2008; Maurer, Pan et al. 2009). Alternatively, Maltz et al. (Maltz, Sprenger et al. 2009) and Chang et al. (Change, Frederick et al. 2009) reported a study using Nanotube Stationary tomosynthesis for potential application in IGRT.

VI. SUMMARY AND CONCLUSION

The introduction of in-room kV imaging provides new opportunities to further improve treatment accuracy and precision. At the same time, there are challenges for its efficient and effective implementation. Each in-room kV imaging method has its strengths and limitations. The user is strongly advised to match the clinical objective with the appropriate technology or at least to apply the image guidance information within the bounds of its validity. Implementation of an in-room kV imaging technology requires rigorous characterization and validation of its performance. Quality assurance measurements with phantoms are requisite. Expertise must be developed and must be re-established from time to time. One must also be cognizant that in

actual clinical practice, uncertainties inherent to each guidance solution exist. There is uncertainty in the strength of the surrogate information as in the case of implanted fiducials, in the integrity of the information with time as in the case of CT guidance and in the residual error related to the implementation of the correction. In-room kV guidance clearly offers great potential for improving treatment accuracy. The promise of in-room kV guidance can only be realized with a radiation community that applies the technology with discipline.

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