IMAGING IN RADIATION THERAPY

SIYONG KIM* and TAE-SUK SUH[1]
Department of Radiation Oncology, University of Florida, Gainesville, USA
[1] Department of Biomedical Engineering, Catholic Medical Center, Seoul, Korea
* Corresponding author. E-mail : kims@ufl.edu

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Radiation therapy is an important part of cancer treatment in which cancer patients are treated using high-energy radiation such as x-rays, gamma rays, electrons, protons, and neutrons. Currently, about half of all cancer patients receive radiation treatment during their whole cancer care process. The goal of radiation therapy is to deliver the necessary radiation dose to cancer cells while minimizing dose to surrounding normal tissues. Success of radiation therapy highly relies on how accurately 1) identifies the target and 2) aim radiation beam to the target. Both tasks are strongly dependent of imaging technology and many imaging modalities have been applied for radiation therapy such as CT (Computed Tomography), MRI (Magnetic Resonant Image), and PET (Positron Emission Tomography). Recently, many researchers have given significant amount of effort to develop and improve imaging techniques for radiation therapy to enhance the overall quality of patient care. For example, advances in medical imaging technology have initiated the development of the state of the art radiation therapy techniques such as intensity modulated radiation therapy (IMRT), gated radiation therapy, tomotherapy, and image guided radiation therapy (IGRT). Capability of determining the local tumor volume and location of the tumor has been significantly improved by applying single or multi-modality imaging for static or dynamic target. The use of multi-modality imaging provides a more reliable tumor volume, eventually leading to a better definitive local control. Image registration technique is essential to fuse two different image modalities and has been in significant improvement. Imaging equipments and their common applications that are in active use and/or under development in radiation therapy are reviewed.

KEYWORDS : Radiation Therapy, Imaging Device, CT, MRI, PET, Ultrasonography

1. INTRODUCTION

Radiation therapy, often called radiotherapy, can be defined as the use of high-energy radiation such as x-rays, gamma rays, electrons, protons and neutrons to kill cancer cells and reduce the size of tumors. Shortly after the discovery of the x-ray by Wilhelm Conrad Roentgen and radioactivity by Marie and Pierre Curie about 100 years ago, the mysterious and powerful radiations were being used to treat cancer.[1-4] Continuous improvement of technology in related areas such as radiation biology, biomedical engineering and medical physics have made radiation therapy an important part of cancer treatment. At present, about half of all cancer patients are subject to radiation therapy during their cancer care treatment.[5]

When radiation particles are introduced to patient body, they start to interact with body cells and deposit energy in them. With enough energy absorbed, cells can be seriously damaged and even be dead.[6] Based on this principle, radiation therapy mainly attacks cancer cells, but it can also affect normal cells. The damage to normal cells is what causes side effects. Whenever radiation therapy is given it involves a balance between destroying the cancer cells and sparing the normal cells. Therefore, the goal of radiation therapy is simply giving the necessary radiation dose to cancer cells while keeping dose to normal cells as low as possible. In general, the more dose to the tumor, the better outcome obtained. However, as indicated in the goal of radiation therapy, the amount of dose can be delivered to the tumor is very often limited by tolerance dose to surrounding normal tissues.

Radiation therapy can be categorized in two types, external beam therapy and brachytherapy.[7] Radiation is introduced from outside to patient body in external therapy. In brachytherapy, radiation source is placed typically inside patient body, very close to the tumor lesion. This review is focused on external beam therapy that is more popular.

The most popular external beam machine is medical linear accelerator, called LINAC. A conventional commercial LINAC is shown in Fig. 1. Major parts of LINAC are gantry, collimator and table. All of three parts can be rotated with respect to a point in the space and this point is called isocenter. Both gantry and table determine the incident angle of any beam to the patient while collimator does

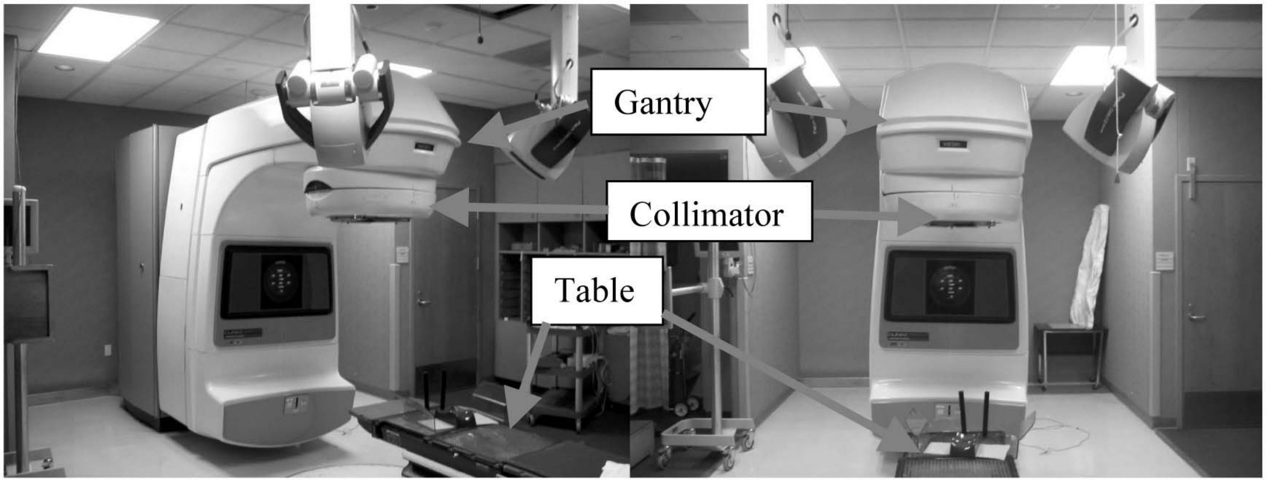

Fig. 1. A Typical Medical Linear Accelerator is Shown. Gantry, Table and Collimator can be Rotated at a Point in Space Called Isocenter. Gantry and Table Dictates the Direction of the Beam While Collimator Dictates the Shape of Each Radiation Beam

the shape of each beam.

A typical process of modern external beam radiation therapy consists of three major steps: imaging, treatment planning, and beam delivery.[7]. In the step of imaging, patient's structural information is obtained using an imaging device, mostly CT (Computed Tomography). This image set containing three-dimensional radiographic information of patient's anatomy is transferred to radiotherapy treatment planning (RTP) system for the next step.[8-16] During treatment planning stage, the tumor lesion is identified and the volume to be treated (called the target) is defined.[17,18] Normal structures, especially critical organs are also identified that are sensitive in causing severe complications with irradiation.[17,18] According to dose prescription and volumes defined, treatment parameters are determined such as beam energy, number of fields, size of each field, use of beam modifier and the amount of radiation to be delivered for each field (this parameter is called monitor unit, shortly MU). At the same time, dose distribution of the patient is calculated and dose to each volume (e.g., the target and critical organs) is evaluated. Once a plan that meets the criteria is obtained, necessary parameters of the plan are transferred to treatment machine. Finally, in delivery stage, the patient is set up on the treatment table as same as he/she was during the imaging step and the machine is operated according to the plan parameters to irradiate him/her as planned.

The target volume is, in general, larger than tumor volume. It includes certain amount of margin that accounts for any possible uncertainty.[17,18] The more uncertain the system is, larger margin is needed. Larger margin means more irradiated volume of not only target but also normal tissues. Therefore, it is very important to reduce the margin as much as possible. Several uncertainty sources are 1) many tumors are not clearly seen in images, 2) patient setup is not exactly reproducible and 3) patient is always in motion both externally and internally.[19] These uncertainties are deeply related with quality of imaging systems. As an example, improvement of imaging resolution can help clinical staffs to accurately define the tumor, resulting in reduction of margin in target volume.

Because of this, recently, many researches have been focused on developing and improving imaging techniques for radiation therapy. For instance, advances in medical imaging technology have accelerated the development of radiation therapy techniques such as intensity modulated radiation therapy (IMRT), gated radiation therapy, tomotherapy and image guided radiation therapy (IGRT). Single or multi-modality imaging for static or dynamic target has been applied in radiation therapy to determine the local tumor volume and location of the tumor. The use of multimodality imaging provides a more reliable tumor volume, eventually leading to a better definitive local control. Clinically, the best example of multi-modality imaging is seen in the rapid evolution of PET (Positron Emission Tomography)-CT imaging in radiation therapy planning. PET imaging has been incorporated into multi-modality in order to identify the metabolizing portions of the primary tumor and to detect a metastasis. Image registration technique is essential to fuse two different image modalities and has been in significant improvement. In this review article, imaging equipments and their applications that are commonly used and/or under development in radiation therapy will be briefly described.

2. IMAGING FOR PLANNING – TARGET DEFINITION

2.1 Computed Tomography (CT)

The CT system, invented by Godfrey Newbold Hounsfield in Hayes, England at THORN EMI Central Research Laboratories, is the most commonly used imaging device in radiation therapy. It provides three-dimensional anatomic image of the internals of an object.[20-24] Nowadays, many radiation therapy departments have their own CT. The CT commonly used for radiation therapy purpose is called 'CT simulator' and has two clear distinctions from conventional diagnostic CT: 1) shape of the table top is flat to get a patient image in the same condition as would be in treatment machine while a rounded table top is used in diagnostic CT for patient comfort and 2) gantry bore size is bigger to accommodate situations where overall diameter of imaging volume is large due to immobilization devices and special patient postures often needed for better treatments. Fig. 2 shows a modern CT simulator that consists of gantry and table. In general, a patient lies in the table and the table moves toward the gantry. Inside the gantry, x-ray tube and detector array, that are key parts of CT system, are placed in the opposite side facing each other. For data acquisition, both x-ray tube and detector array rotate around a single axis. Image is reconstructed using a large series of two-dimensional x-ray projection views taken during this revolution of x-ray tube and detector array. Image contrast among different internal structures can be obtained because each structure has its own capability of blocking x-ray beam (i.e., attenuation coefficient). In normal display, high-density part (e.g., bone) appears white while low-density appears black (e.g., lung). CT image is typically displayed in three views, axial (cross section in head to feet direction when a patient lies on the table), coronal (cross section in front to back direction) and sagittal (cross section in left to right direction) as shown in Fig. 3. CT image represents spatial information very accurately. This is one of the most important reasons that CT is the gold standard imaging device for radiation therapy in which accurate knowledge of spatial information of both external and internal body is mandatory. Images of CT contain information that can be easily used for radiation dose calculation because they are reconstructed based on attenuation coefficient of each small volume, called voxel. This is another advantage of using CT in radiotherapy. Currently, cases of external beam radiotherapy in which CT is not used are very rare.

Virtual Simulation and Treatment Planning

In modern radiation therapy, a treatment simulation is virtually accomplished. In this simulation process, called 'virtual simulation', virtual machines are prepared in the software program and necessary treatment parameters of the machine can be determined for the virtual body of patient, that is, the CT image set.

As described earlier, a typical radiotherapy process consists of 3 distinct steps: imaging, treatment planning, and beam delivery. In imaging step, a patient is placed on CT table with appropriate immobilization devices that help the patient stays still during both imaging and treatment. Once the patient is set up as needed, 3 radio-opaque balls are placed on the patient skin, and then the patient is scanned. These 3 balls are aligned so that they are on a plane that is normal to the direction of table movement. Skin spots of those balls are marked using permanent tattoo after the scan is finished. The role of 3 balls is to provide a reference point that can be utilized to correlate the patient body with the coordinates of both the virtual treatment machine and real machine. Position of each radio-opaque ball can be seen in the CT image and a reference point can be defined using

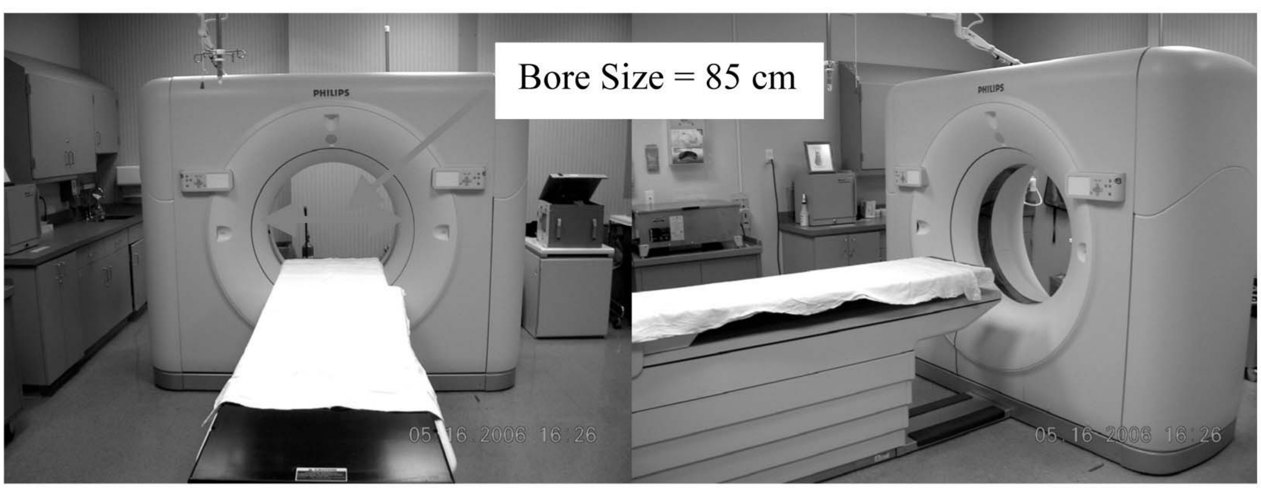

Fig. 2. A Modern CT Simulator Used in Radiation Therapy is Shown. Bore Size is Larger Than that of Normal Diagnostic CT to Accommodate Various Immobilization Devises and Patient Setups. Note Table Top is Flat

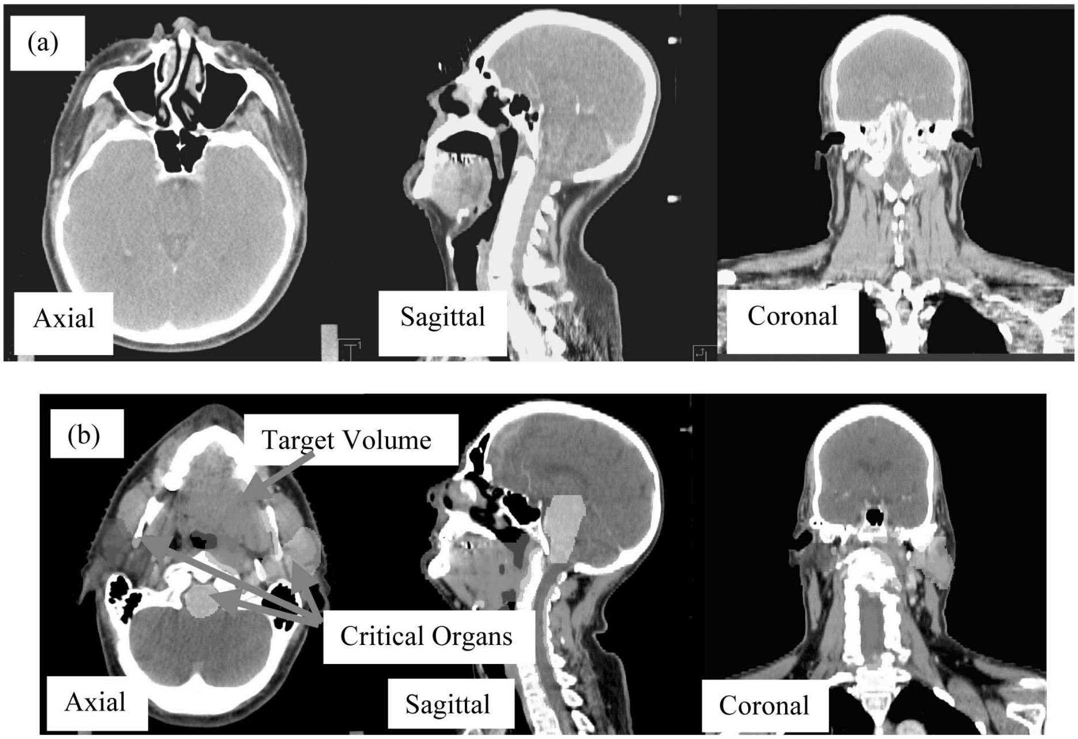

Fig. 3. CT Image is Typically Displayed in Three Views, Axial (Cross section in Head to Feet Direction When a Patient Lies on the Table), Coronal (Cross Section in Front to Back Direction) and Sagittal (Cross Section in Left to Right Direction). (a) CT Images of a Head and Neck Site (b) CT Images With Target and Critical Organ Volumes

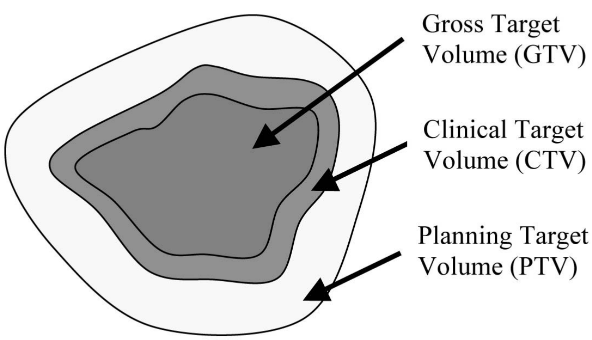

Fig. 4. Definition of Target Volumes in Radiation Therapy Planning (ICRU 50) is Illustrated

those 3 points. On the other hand, the patient can be aligned in the real treatment room as the same as in the CT using 3 skin tattoos.

The CT image set is transferred to the RTP system for treatment planning. The tumor lesion is identified and the target volume to be irradiated is defined. Adequate determination of volume is one of the most important tasks in radiotherapy. At first, tumor lesion that can be clearly detected in the image is identified and it is called gross target volume (GTV). Tumor cells are often dispersed around GTV and these are not visible in the image most cases. Based on physiologic information and clinical experience, a clinical margin is added to GTV to make so called clinical target volume (CTV). As the last step, addition of planning margin is made to account for uncertainties that can occur through the whole process of radiotherapy. This is called planning target volume (PTV) and it is the volume that is supposed to be irradiated to prescribed dose.[17,18] Fig. 4 illustrates how target volumes are defined. In addition to the target volumes, important normal structures that are to be avoided from unwanted over irradiation are also defined. Based on volumes and prescribed dose to the target, an optimal plan is obtained through an interactive process. To get necessary dose to the target while minimizing dose to normal structures, multiple fields of radiation are introduced to the target in many different directions. The amount of dose from a field can be different from those of others. Beam fluence shape of each field may vary also. Determi-

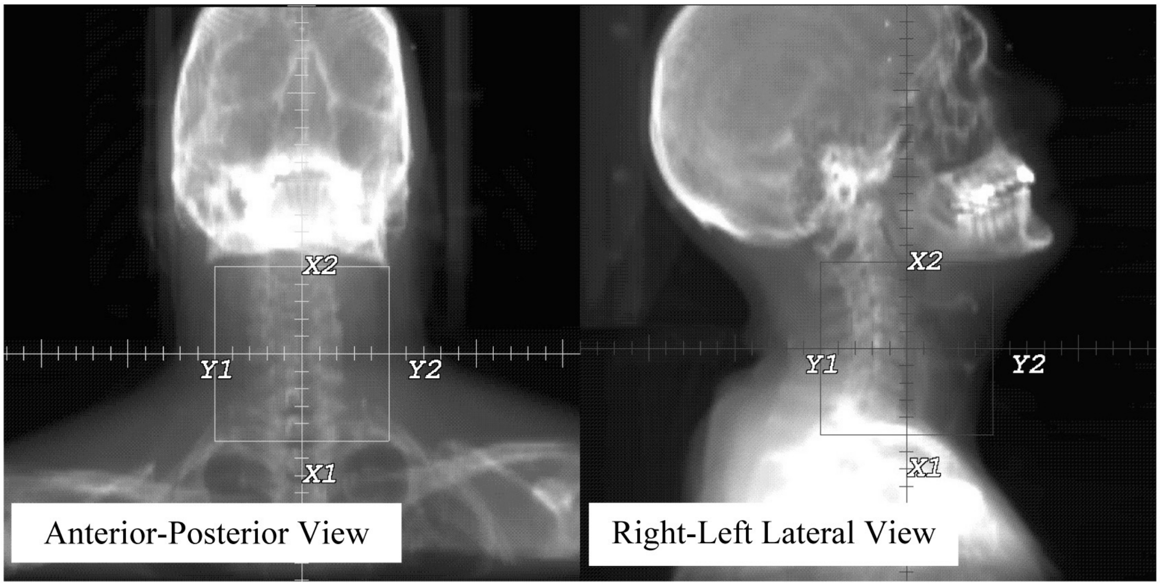

Fig. 5. A Set of Orthogonal DRR Images is Shown

nation of all these treatment parameters is accomplished during treatment planning stage. In general, patient dose distributions calculated with several sets of treatment parameters are evaluated and a plan that best fits the required criteria is selected.

Dose Delivery and Setup Verification

Once an optimal plan is obtained, all treatment parameters are transferred to treatment machine and radiation is delivered to the patient according to the plan parameters. Radiation therapy is not a single day treatment in most cases. Instead, the total dose is delivered in a small piece daily through several weeks to minimize radiation toxicity to normal tissue. Accuracy of patient setup is verified in the first day of treatment and at least once a week thereafter. In general, two orthogonal radiographic images (e.g., views in both anterior-posterior and left-right directions) are acquired and compared with images of digitally reconstructed radiography (DRR) provided during planning stage. DRR is an image processing technique in which radiographic images are generated by a mathematical software algorithm using a CT image set. A set of orthogonal DRR images is shown in Fig. 5.

2.2 Magnetic Resonant Image (MRI)

Similar to CT, MRI provides three-dimensional image of the internals of an object. It is based on the principles of nuclear magnetic resonance (NMR), a spectroscopic technique that has been used to investigate chemical and physical information of molecules in microscopic scale. Strong magnetic fields and non-ionizing radiation in the radio frequency (RF) range are applied in MRI. [25] Thus it is considered to be harmless to the patient while CT involves radiation dose that may increase the chance of cancer incidence. But patients can have symptoms of vomiting and nausea when magnetic field is too strong. A modern MRI is shown in Fig. 6.

MRI can demonstrate pathological or other physiological alterations of living tissues that cannot be seen in CT. [25] Therefore MRI is preferred in distinguishing pathologic tissue such as a brain tumor from normal surrounding tissues. A distinct strength of MRI is high contrast resolution.

Fig. 6. An MRI Scanner is Shown (Courtesy of Philips)

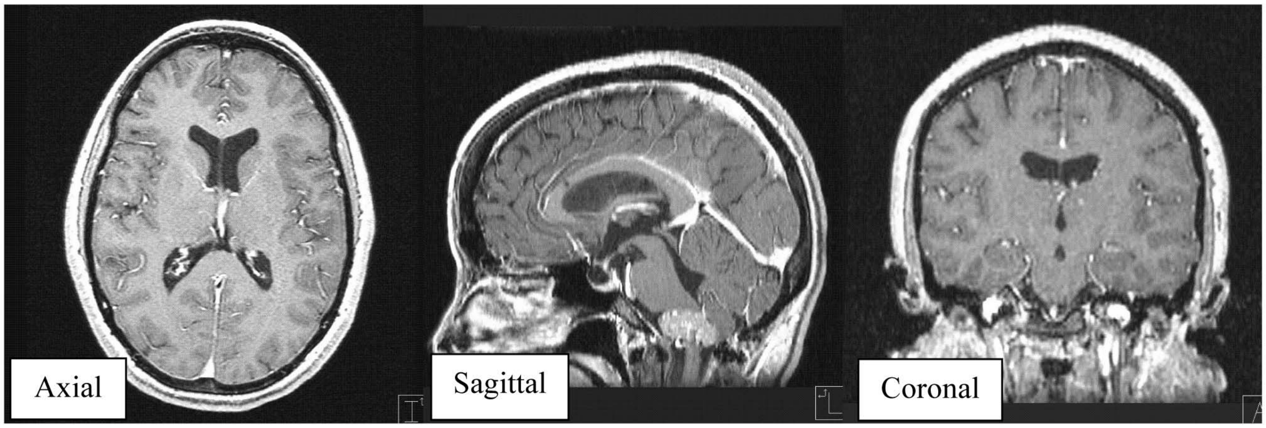

Fig. 7. An Example of MRI Images

In other words, it enables to distinguish the differences between two similar but not identical tissues. Fig. 7 shows examples of MRI images. However, MRI is inferior to CT in spatial resolution that is the ability to distinguish two structures in small distance from each other. Therefore, MRI image set is not directly used in radiation therapy. Instead, it is combined with CT image set and useful information (i.e., high contrast tumor lesion that is clearly seen in MRI image set but not in CT image set) is transferred to CT image set. This imaging process is called image fusion.[26,27] In the process of image fusion, images of the same subject but from different modalities are combined to enhance the capability of interpretation of acquired information. Use of such multi-modality imaging can provide a more reliable tumor volume, eventually leading to a better definitive local control. Clinically, a typical example of multi-modality imaging in radiation therapy is seen in MR-CT fusion in stereotactic radiosurgery (SRS). SRS is a special treatment procedure in which brain disease patients are treated in a single day treatment using radiation instead of physical surgery. Almost all patients get benefit from image fusion between MRI and CT image sets in stereotactic radiosurgery. Treatments of some head & neck tumors such as nasopharyngeal cancer also often require image fusion of MRI and CT.

2.3 PET or PET/CT

Positron emission tomography (PET) is an imaging process that acquires physiologic information based on the detection of radiation from the emission of positrons.[28-33] There are several materials that can be accumulated in a certain part of body when injected to a patient. A radioactive substance that emits positrons is attached to these materials (this process is called radio labeling) then, introduced to the patient together. The most commonly used material in PET imaging is 18F-Fluordeoxyglucose (FDG). Glucose is needed for metabolic process in living subject.[28,32] Cancer cells are abnormally active in growing, which means they absorb glucose a lot more than normal tissues do. Therefore, actively growing tumor lesions can be imaged using PET with FDG injected. Because PET imaging is based on body function, it enables physicians to detect alterations in biochemical processes that are not apparent with other imaging tests. PET imaging is most commonly used to detect cancer and to examine the effects of cancer therapy by characterizing biochemical changes in the cancer. Diagnostic value of PET imaging can be significantly enhanced when it is part of a larger diagnostic work-up, which often entails comparison of PET image with images from other modalities such as CT or MRI.[33-36]

Because PET imaging relies on chemical process of living body, it easily provides false results when a patient is in abnormal chemical balances. For instance, diabetic patients often cause inadequate diagnosis because of blood sugar or blood insulin levels.[37-41] Even patients who have eaten within a few hours prior to the examination can be adversely affected. This factor should be well understood and accounted for to minimize unwanted prediction of diseases.

It is not easy to use PET-only image set for radiation treatment planning due to the lack of detail information on patient anatomy that is necessary for accurate treatments. In addition, there is no simple method to fuse PET data with a radiation treatment planning CT. Recent development of a hybrid imaging modality, called PET-CT overcomes the limitation of PET-only studies for radiation treatment planning.[28] PET-CT is an imaging device that contains both PET and CT in a single machine. However,

Fig. 8. A Commercial PET-CT Device. In a PET-CT Process, CT and PET Scans are Performed in Series With the Same Patient Setup (Courtesy of Philips)

Fig. 9. An Example of PET-CT Fusion for the Lung Lesion. Bright Area Contoured With a Black Line is High Signal Region in PET Imaging

PET-CT enables to co-register both functional and morphologic information in a single imaging procedure.[28,42] This integrated system gets over the limitations of manual or software fusion of independent PET and CT images, resulting in a more robust set of images. For example, a PET-CT-based radiation treatment planning was performed and it was found that the spatial resolution of co-registered anatomic and functional images allowed for a more accurate delineation of tumor compared to CT alone.[28] Fig. 8 shows a commercial PET-CT device and an example of PET-CT fused image for lung lesion is shown in Fig. 9. In a PET-CT process, CT and PET scans are performed in series with the same patient setup.

Positron emission radioisotopes typically decay fast, thus the amount of exposure in PET imaging is relatively small. However, cautious risk-to-benefit analysis is needed for patients who are pregnant or breast-feeding.

2.4 Dynamic Imaging - Four Dimensional (4-D) Imaging

Both external and internal motions of patient cause increase of margin for volume definition, which inevitably hinders enhancing target dose to improve treatment results without increase of side effects. One of the most dominant sources for patient motion is breathing.[43-50] Respiration motion causes movement of internal structures, especially in the thorax and abdomen, making inaccurate delivery of radiation therapy to tumors in those areas such as lung and liver. As treatment techniques become more complicated and accurate, effects of breathing motion become more important. Thus, the management of patient motion, especially the respiration motion has been an important issue in radiation therapy.

Methods used in the management of the respiration motion in radiation therapy can be broadly separated into four major categories: special immobilization techniques, respiratory gating techniques, breath hold techniques and tumor tracking techniques. The immobilization technique is the simplest way to reduce the effect of movement due to the respiration of the patient by applying special immobilization devices such as body compressor.[51] However, there exists a residual motion because its approach is to minimize the motion but not to eliminate. The radiation delivery is performed although the target is still moving. Breath-hold techniques suspend respiration of the patient and allow treatment during this interval.[45,52-59] Breath-hold techniques are relatively simple and efficient but they can suffer from inconsistent pattern of patient breath-hold depending on patient condition. Respiration gating involves the administration of within a particular period of the breathing cycle of the patient with an assumption that patient motion is reproducible according to the phase of breathing cycle.[43,44,60-64] In other words, the beam is turned on only when the patient respiration signal is in a certain part of the respiratory cycle (generally end-inhale or end-exhale). In principle, a gating technique can offer complete elimination of motion effect. However, there are several issues such as extreme inefficiency of beam delivery and unexpected behavior of histerisis. Tumor tracking methods propose to track the tumor with the radiation beam as tumor moves during the respiration cycle.[65-69] Tumor tracking methods can overcome the inefficiency problem of gating techniques but how fast and accurately the machine can track the target is an issue.

These advanced techniques, especially respiration gating and tumor tracking, require acquisition of dynamic image data according to respiration cycle. In dynamic imaging, so called 4-D imaging, respiration signal, which is assumed to have a strong correlation with internal anatomy motion, is continuously obtained while the patient is imaged. Acquired image data are sorted based on phase of respiration cycle and a complete set of image is reconstructed for any given phase. Phased image sets show more clear quality of image because the effect of motion is eliminated. Fig. 10 shows

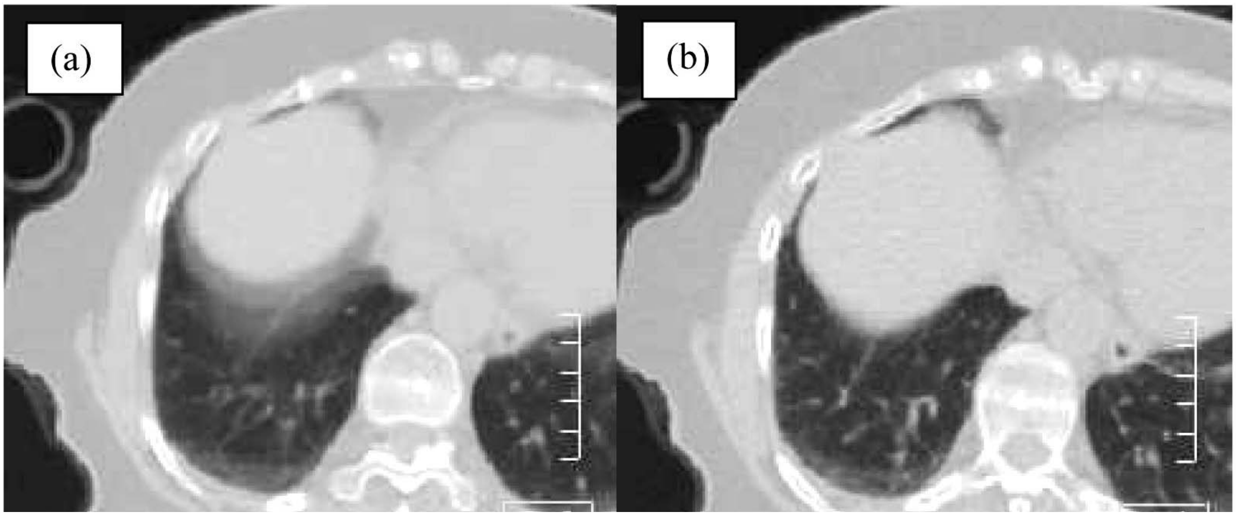

Fig. 10. Comparison of (a) Non-Phased CT Image (i.e., From Conventional CT Imaging Technique) and (b) Phased Image (i.e., From 4-D CT Imaging Technique) of the Chest Region; Phased Image is Clearer Than Non-Phased One Because of the Elimination of Motion Effect

the difference between conventional CT image and 4-D CT image.

3. IMAGING FOR PATIENT SETUP AND VERIFICATION

3.1 Ultrasonography (US)

Ultrasonography is an imaging technique that visualizes soft tissues using ultrasound wave.[70] The most important component of ultrasound imaging device is transducer that not only produces ultrasound beam but also receives reflected wave. Signal of reflections from interfaces between tissues with different sonic characteristics is primarily used to produce images. Ultrasonographic image is relatively familiar to public because of obstetric sonography that is commonly used during pregnancy.

US images muscle and soft tissue very well. It is particularly useful for delineating the interfaces between solid and fluid-filled spaces. Therefore, US is used for daily localization of target in radiotherapy, especially for prostate treatments. It is well reported that daily spatial variation of prostate within the body is relatively large, which means there exists a clinically significant positional discrepancy of the prostate between the static CT image made for planning and dynamic day-to-day condition of the patient.[71-74] In conventional therapy, this effect is taken care of by including enough planning margin during target definition with the price of increasing normal tissue dose. In advanced therapy, several approaches are implemented to minimize planning margin, thus normal tissue dose by improving target localization accuracy. Some clinics apply better immobilization techniques (e.g., rectal balloon) while others try daily localization using additional imaging techniques such as US.[75-80] Fig. 11 shows a commercial US system used for daily target localization in radiation therapy.

Fig. 11. SonArray Ultrasound Localizer for Daily Localization of Soft Organ is Shown (Courtesy of Varian)

US imaging rarely causes any discomfort to the patient and has no known long-term side effects. It is relatively small, flexible and inexpensive. However, US image quality is poor when there is gas between the transducer and the object. For example, lung imaging by US is not possible. Ultrasound wave hardly penetrate bone. Therefore, it is difficult to image objects behind bone such as brain. The quality of US strongly depends on skill of operator and it is one of obstacles in daily use of US in radiotherapy because most radiation therapy staffs are not trained for US.

3.2 Kilo-Voltage (KV) X-Ray Imaging Device in Treatment Room

The most commonly used radiation for modern external beam radiation therapy is x-ray in mega-voltage (MV) order. For patient setup verification, typically, two planar images orthogonal each other are obtained using MV x-ray. Unfortunately, the image quality of MV x-ray is poor due to the fact that there are very small differences in attenuation coefficient in human body at that energy range. Contrary to this, KV x-ray provides images of much better quality. Therefore, use of KV x-ray for imaging in treatment room was considered and has been in increase. Fig. 12 shows two planar images, one obtained using MV x-ray and the other KV x-ray.

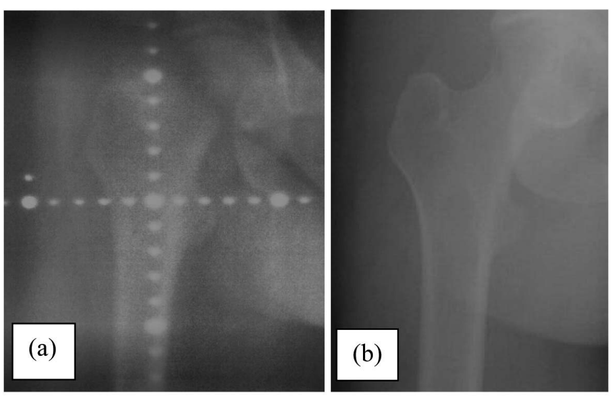

Fig. 12. Comparison Between (a) MV and (b) KV Planar Images for the Right Leg. A Better Quality of Image Can be Made With KV X-Ray

Planar Imaging

In this approach, typically two x-ray tubes and corresponding detectors are installed with a certain angle in the treatment room. Careful consideration is needed in placing both x-ray tubes and detectors so that they do not collide with any moving part of LINAC. Once the patient is set up on the table as planned, two KV x-ray planar images are acquired.[65-69, 81] These images are registered and compared with the reference images to determine the amount of adjustment needed. Finally, positional adjustment of the patient setup is accomplished mechanically. A commercial x-ray planar imaging system is shown in Fig. 13. Two x-ray tubes are installed on the floor and two flat panel detectors are placed on the ceiling.

Planar imaging performs very well for sites with bony structures. However, it is not easy to obtain necessary imaging contrast for soft tissues such as prostate. One solution is to implant radio-opaque objects into the target prior to the treatment.[82-86] Gold balls or gold seeds are most often the first choice for implanting marker because of high atomic number and bio-compatibility. With radio-opaque objects implanted, it is also possible to continuously trace the locus of the target during the whole process of the treatment using fluoroscopic imaging. Tracing the target will provide good understanding of target motion during irradiation and give information necessary for the method of beam delivery with tumor tracking. However, fluoroscopic imaging causes significant amount of extra irradiation of the patient.[87]

Serial Processing Volumetric Imaging

A set of x-ray tube and detector is added to the LINAC gantry in this approach as shown in Fig. 14. The gantry of x-ray tube is normal to the treatment gantry. Multiple planar images are obtained by cone shaped x-ray beam from the x-ray tube while the gantry rotates around the patient. Then, a volumetric image set is reconstructed using those planar images. The reconstructed image set is registered and compared with the reference CT image set to determine the amount of adjustment needed. Then, positional adjustment of the patient setup is made.

Images are displayed in three views, axial, coronal and sagittal as same as in conventional CT. This imaging technique is often called 'cone beam CT (CBCT)' because of its cone shaped beam geometry.[88-92]

CBCT provides 3-D information every day before the

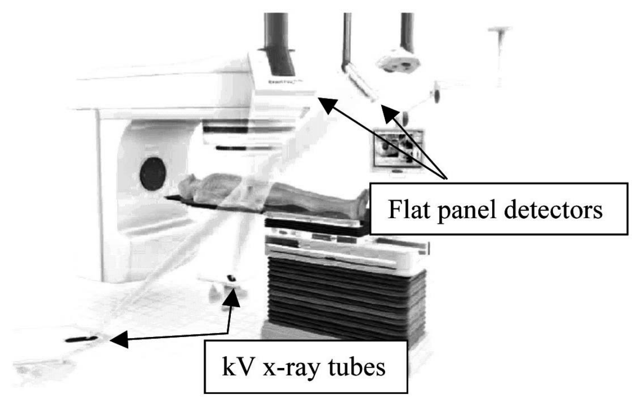

Fig. 13. A Commercially Available X-Ray Planar Imaging System. Two X-Ray Tubes are Installed on the Floor and Two Flat Panel Detectors are Mounted on the Ceiling (Courtesy of BrainLab)

beam is turned on, thus radiation therapy staffs are able to look at detail about the target and critical organs to make sure the patient setup is as close as possible to the plan. Fig. 15 shows an example of CBCT images of the lung lesion. It can be clearly seen that tumor mass is within the planned target volume.

Patient dose due to a CBCT procedure is about 2 to 5 cGy.[93] Although this amount of extra dose is much smaller than prescribed therapeutic dose of most cancer patients, considering significant consequence of long-term late effect by low dose exposure, it is necessary to cautiously implement the procedure.

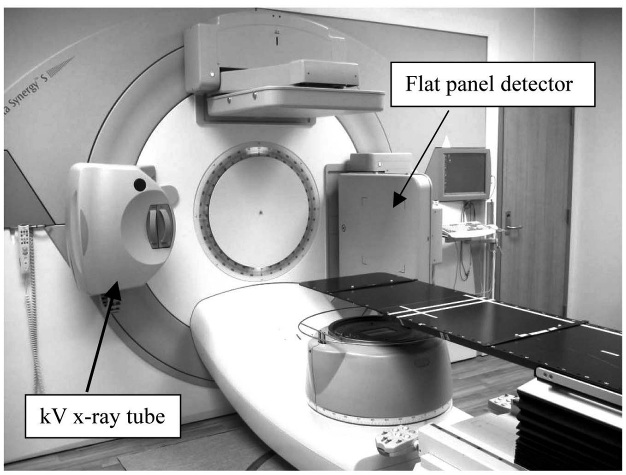

Fig. 14. A Serial Processing Volumetric Imaging System Incorporated Into LINAC; a Set of X-Ray Tube and Flat Panel Detector is Installed Orthogonal to the LINAC Gantry

In currently available CBCT approaches in radiation therapy, CBCT and treatment beam delivery are serial processes, which means CBCT cannot be performed while therapy beam is on because both CBCT and treatment beam delivery gantries rotate together. Therefore, it is not feasible to use CBCT for the purpose of monitoring patient motion during beam deliveries.

Parallel Processing Volumetric Imaging

A new concept of parallel processing both CBCT and treatment beam delivery, which is called beveled CT (B-CT), has been proposed by Kim in the University of Florida, Gainesville, Florida, USA.[94] In conventional CT currently available, the center of radiation is incident perpendicular to the axis of gantry as illustrated in Fig. 16. As shown in Fig 16, both x-ray source and detector are rotated within co-plane that is perpendicular to the axis of gantry. Because of this, there is no room to access to the region of interest of the patient. In B-CT, the incident angle of radiation is not perpendicular to the axis of gantry (see Fig. 17). As shown in Fig. 17, rotation plane of detector is different from that of x-ray source. However, the x-ray source is angled to the detector and the detector is angled to the source. Therefore, imaging x-ray beams are passing the patient with an angle with respect to the plane orthogonal to the gantry rotation axis. Image reconstruction can be performed to generate conventional image views by taking the geometry into account and a reconstruction algorithm is under development by Lee et al. in Catholic Medical Center, Korea.[95] This design allows medical staffs to access to the region of interest of the patient. Depending on situations, gantries can be mounted on rails and the width of access area can be adjusted. In this case, angles of x-ray source and detector are designed to be adjustable.

For an application of B-CT for radiation therapy, one more gantry, called RT gantry, is added in between CT

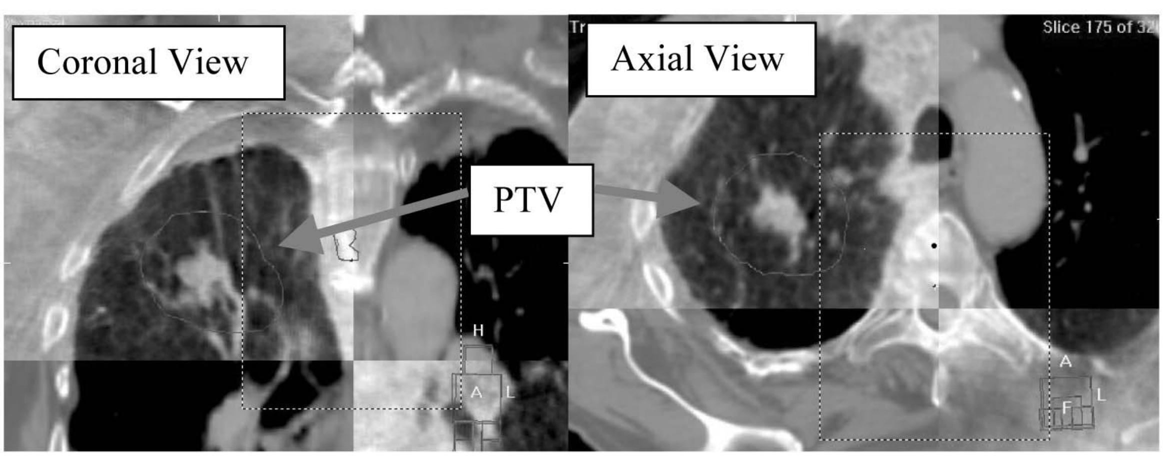

Fig. 15. A Checkerboard Display of Image Registration Between a Cone Beam and Reference CT Image Sets for the Lung Lesion. Image of CBCT is Slightly Fuzzier than Reference CT Image. However, it Clearly Shows that the Tumor is Within the PTV

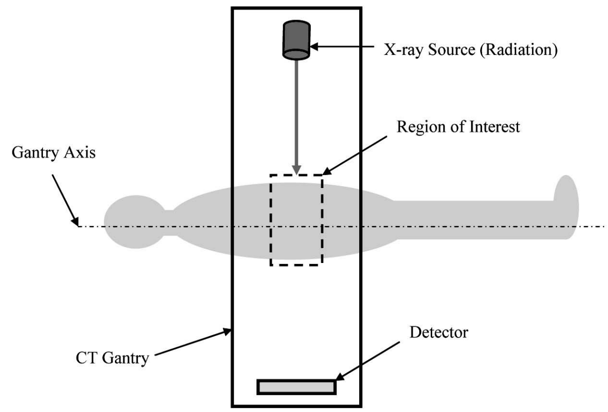

Fig. 16. In Conventional CT, Radiation is Incident Perpendicular to the Axis of Gantry (Side View)

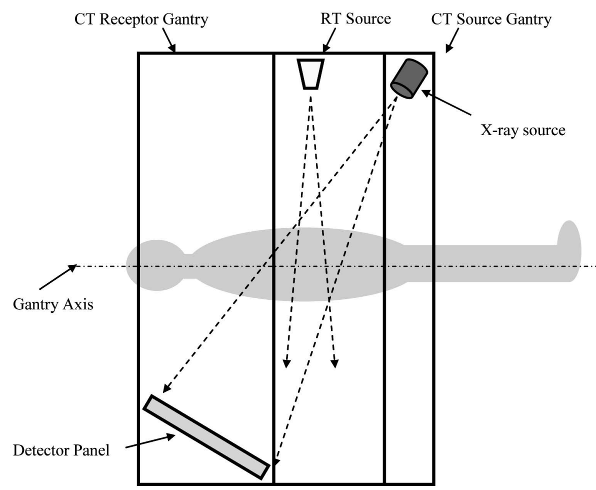

Fig. 18. RT Gantry is Located in Between CT Source Gantry and CT Detector Gantry. CT Gantries Rotate Independent of RT Gantry to Image the Patient During Beam Delivery

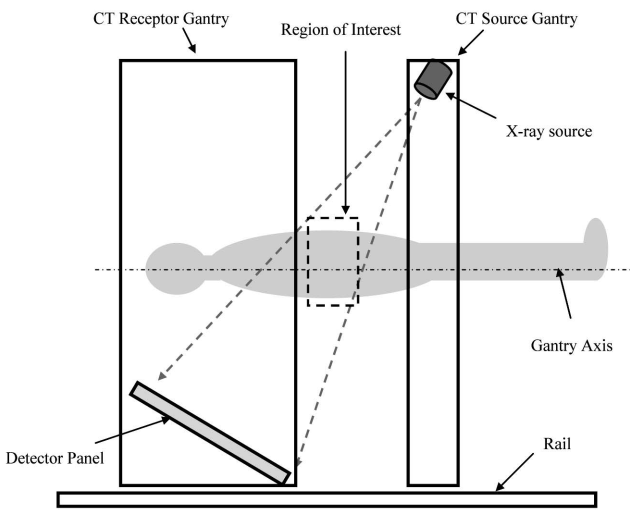

Fig. 17. A Simplified Side View of B-CT; X-Ray Source and Detector are Rotated in Their Own Rotation Plane While They are Angled to Face Each Other During Rotation. Mounted on the Rail, the Width of Access can be Adjusted

source gantry and CT detector gantry. Fig. 18 shows the side view of those gantries. As shown in Fig. 18, CT gantries can be rotated independent of RT gantry. Thus, CT imaging can be made any time even while the therapy beam is on.

The RT gantry contains multiple radiation treatment sources. Either linear accelerator or cobalt isotope can be utilized for radiation source. Each source is designed to rotate both concurrently and independently. Independent rotation is limited to the adjacent source. For field shaping, a multi-leaf collimator (MLC) is used for each source. In modern radiation therapy, one of the most time consuming steps is the rotation of the gantry. Therefore, by installing multiple sources, the amount of gantry rotation can be minimized, resulting in efficient beam delivery. This also decreases the chance of patient intra-fraction displacement, which is critical in modern high-precision radiation therapy. One of the disadvantages of current linear accelerator equipped with MLC system is that MLC system significantly increases machine down time because of its high failure rate. When MLC malfunctions, it is not possible to continue the high-precision therapy such as IMRT. However, in this approach, the treatment can be continued using any functioning MLC. The chance of all MLCs to malfunction at the same time is unlikely. Therefore, the machine down time due to MLC can be reduced close to zero. For each source, an electrical portal imaging device (EPID) is installed. Each EPID can be rotated independently. Therefore, it can be positioned either in or out of the treatment field as needed. In principle, EPID can be utilized for the reconstruction of delivered dose to the patient.

Another feature of the RT gantry is beam modifier slot. The number of beam modifier slots can be larger than that of sources. The slot is designed to rotate independently from the source. When IMRT is delivered using compensator block, all compensators can be mounted at the same time. Fig. 19 shows a transversal view of RT gantry with three sources, three EPIDs, and six beam modifier slots.

If RT gantry is replaced with PET gantry, simultaneous PET/CT (S-PET/CT) machine can be made. In current existing PET/CT, PET scan and CT scan are carried out in series. However, in S-PET/CT both scans can be done at the same time.

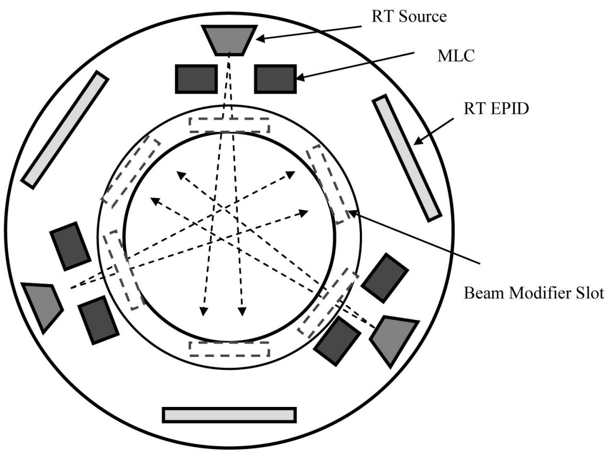

Fig. 19. A Transversal View of RT Gantry With 3 Sources and EPIDs. Number of Beam Modifier Slots Can be Larger Than that of Sources

When B-CT is applied in the operating room without anything in between two gantries, real time CT scan can be made with minimum interruption of operation procedure. Thus, real time CT image guided surgery can be performed.

3.3 MRI Device in Treatment Room

Use of CT in treatment room can provide a significant benefit, especially for sites with which bony structures can be utilized as the reference objects. However, the advantage of CT is reduced for soft tissues due to its relatively poor image contrast. To obtain soft tissue images of high quality, an effort on combining MRI and LINAC is undergoing in Utrecht University, Netherlands.[96-98] Fig. 20 shows a proposed design of the MR-LINAC hybrid machine in which MR occupies the inner ring and LINAC does outer ring. In principle, this approach can provide capabilities of superb soft tissue visualization, on-line patient monitoring with no extra radiation exposure, and tumor response assessment through the treatment course. However, answers on several issues, such as magnetic coupling between accelerator and MRI system, beam transmission through MRI system, and dose deposition in strong magnetic field, should be sought.

Another approach has been introduced by Dempsey in the University of Florida, Gainesville, Florida, USA.[99] In this method, a MR system is combined with Cobalt-60 treatment machine instead of LINAC to eliminate a potential problem of the effect of RF interference. Note that Cobalt-60 machine does not need RF power while a LINAC does. A design of prototype is illustrated in Fig. 21. It is expected that volumetric image sets are repeatedly acquired every 0.5-2.0 seconds using the open split solenoid super conducting MRI of 0.3 T (Tesla).

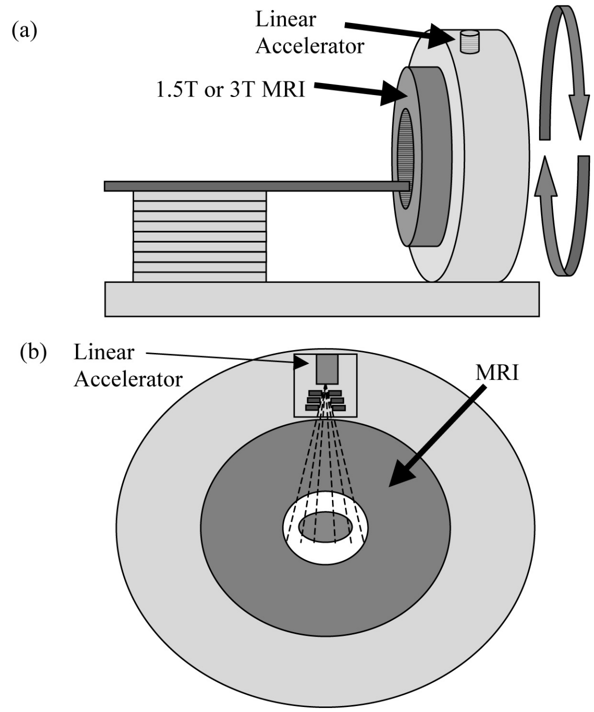

Fig. 20. A Proposed Design of the MR-LINAC Hybrid Machine in Which MR Occupies the Inner Ring and LINAC Occupies the Outer Ring; (a) Lateral View of the MR-LINAC Machine and (b) Sectional View of the MR-LINAC Machine

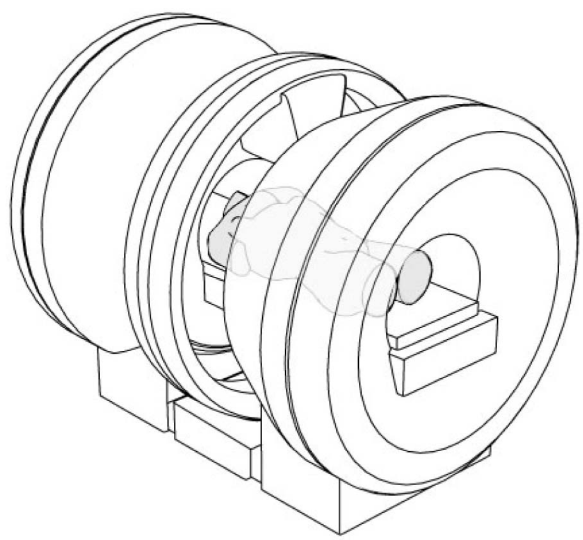

Fig. 21. A Proposed Design of the MR-Cobalt Hybrid Machine in Which a Donut Type of MR Occupies the Outer Gantries and Cobalt Treatment Gantry Occupies the Inner Gantry. A Volumetric Image Set Can be Acquired for Every 0.5-2.0 Seconds

4. SUMMARY

Each imaging modality has its own advantage associated with localization, morphology, pathology etc. The use of multi-modality imaging provides a more reliable definition of the local tumor and functional change in both diagnosis and therapy. Accurate and robust image registration methods are needed for proper application of upcoming imaging modalities. Dynamic imaging for moving organ provide a solution to treat the moving target using image guided RT based on measurement of respiration signal and tumor tracking.

New state of the art imaging modalities and their applications for radiation therapy will be continuously developed. New imaging modality such as nano-imaging or molecular imaging will be possible. Development of hybrid machine consisting of both imaging and therapy devices will bring a new paradigm of clinical practice of radiotherapy.

All these developments and implementations of advanced technologies totally rely on strong cooperation of many professional areas such as biology, engineering, medicine and physics.

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