การวางแผนการรักษาเทคนิคIMRTและVMATในผู้ป่วยมะเร็งศีรษะโดยใช้ภาพ Magnetic Resonance Imaging (MRI)

นายกิตติพล เดชะวรกุล

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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MAGNETIC RESONANCE IMAGING BASED TREATMENT PLANNING IN IMRT AND VMAT FOR HEAD REGION

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A Thesis Submitted in Partial Fulfillment of the Requirements
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ภาพถ่ายสนามแม่เหล็กกำทอนสามารถช่วยให้การระบุขอบเขตของเนื้องอกและเนื้อเยื่อปกติโรคมะเร็งในสมองดีขึ้น แต่อย่างไรก็ตามไม่สามารถให้ข้อมูลของคุณสมบัติทางรังสีได้เหมือนเช่นในกรณีของภาพเอกซเรย์คอมพิวเตอร์ซึ่งเป็นข้อมูลที่จำเป็นต่อการวางแผนการรักษา วิธีการที่สามารถแก้ปัญหานี้โดยวิธี bulk density โดยแทนค่าพิกเซลเดิมด้วยค่าความหนาแน่นเฉลี่ยในแต่ละพื้นที่ วัตถุประสงค์ของการศึกษานี้คือการประเมินความถูกต้องในการคำนวณปริมาณรังสีด้วยภาพถ่ายสนามแม่เหล็กกำทอนเปรียบเทียบกับการวางแผนการรักษาด้วยภาพเอกซเรย์คอมพิวเตอร์ในผู้ป่วยมะเร็งบริเวณศีรษะ ผู้ป่วยมะเร็งบริเวณศีรษะจำนวนสามสิบรายถูกจำลองการรักษาโดยเครื่องเอกซเรย์คอมพิวเตอร์และเครื่องถ่ายภาพสนามแม่เหล็กกำทอนโดยจัดท่าผู้ป่วยเหมือนกัน จากนั้นนำภาพจำลองการรักษาเข้าสู่เครื่องวางแผนการรักษา ภาพทั้งสองถูกซ้อนทับกันและทำการระบุขอบเขตของก้อนมะเร็งและเนื้อเยื่อปกติโดยแพทย์ ในขณะที่ขอบเขตของกระดูก และโพรงอากาศถูกระบุอัตโนมัติโดยเครื่องวางแผนการรักษา ทำการหาค่าของ CT number เฉลี่ยของก้อนมะเร็ง, กระดูกและโพรงอากาศ โดยแบ่งเป็น 3 ประเภทคือ 1. ค่า CT number เฉลี่ยเฉพาะผู้ป่วยแต่ละคน 2. ค่า CT number เฉลี่ยจากผู้ป่วยทั้งหมด 3. ความหนาแน่นจาก ICRU ฉบับที่ 46 และแปลงเป็นค่า CT number ทำการวางแผนการรักษาอ้างอิงด้วยภาพเอกซเรย์คอมพิวเตอร์ด้วยเทคนิคการฉายรังสีแบบปรับความเข้มและการฉายรังสีแบบปรับความเข้มรอบตัวผู้ป่วย และทำการวางแผนการรักษาด้วยภาพถ่ายสนามแม่เหล็กกำทอนโดยใช้ค่า bulk density ทั้ง 3 ประเภทและวางแผนการรักษาที่แทนค่าปริมาตรทั้งหมดด้วยค่าความหนาแน่นเทียบเท่ากับน้ำ ทำการเปรียบเทียบแผนการรักษาด้วยภาพถ่ายสนามแม่เหล็กกำทอนทั้ง 4 ประเภทเทียบกับการวางแผนการรักษาด้วยภาพเอกซเรย์คอมพิวเตอร์โดยใช้ D_95% ด้วยกราฟ DVH ผลการทดลองพบว่าจากแผนการรักษาของผู้ป่วยทั้ง 28 แผนการรักษา ทั้งเทคนิคการฉายรังสีแบบปรับความเข้มและการฉายรังสีแบบปรับความเข้มรอบตัวผู้ป่วย มีค่าความแตกต่างของปริมาณรังสีของแผนการรักษาด้วยภาพถ่ายสนามแม่เหล็กกำทอนด้วยค่า bulk density แบบเฉลี่ยเฉพาะผู้ป่วยแต่ละคนและแบบเฉลี่ยจากผู้ป่วยทุกคนเมื่อเปรียบเทียบกับแผนการรักษาด้วยภาพเอกซเรย์คอมพิวเตอร์มีค่าความแตกต่างของปริมาณรังสีเฉลี่ย 0.27% และมีค่าสูงสุดเท่ากับ 1.54% สำหรับความแตกต่างของปริมาณรังสีของแผนการรักษาด้วยภาพถ่ายสนามแม่เหล็กกำทอนด้วยค่า bulk density จาก ICRU มีค่าความแตกต่างของปริมาณรังสีเฉลี่ย 0.38% และมีค่าสูงสุดเท่ากับ 0.93% ในขณะที่แผนการรักษาด้วยภาพถ่ายสนามแม่เหล็กกำทอนโดยการแทนค่าปริมาตรทั้งหมดด้วยความหนาแน่นเทียบเท่ากับน้ำมีค่าความแตกต่างของปริมาณรังสีเฉลี่ย 1.68% และมีค่าสูงสุดเท่ากับ 3.83% โดยสรุปแล้วการวางแผนการรักษาด้วยภาพถ่ายสนามแม่เหล็กกำทอนในผู้ป่วยมะเร็งบริเวณศีรษะมีความถูกต้อง โดยค่าความแตกต่างของปริมาณระหว่างแผนการรักษาที่ใช้ค่า bulk density แบบเฉลี่ยเฉพาะผู้ป่วยแต่ละคนและแบบเฉลี่ยจากผู้ป่วยทุกคนมีค่าเทียบเท่ากัน ดังนั้นค่า bulk density แบบค่าเฉลี่ยจากผู้ป่วยทุกคนของขอบเขตการฉายรังสี กระดูกและโพรงอากาศของผู้ป่วยกลุ่มนี้สามารถแทนค่า bulk density แบบเฉลี่ยเฉพาะผู้ป่วยแต่ละคนได้ ส่วนค่าความแตกต่างของปริมาณรังสีในแผนการรักษาที่แทนค่าปริมาตรทั้งหมดด้วยความหนาแน่นเทียบเท่ากับน้ำไม่แนะนำให้ใช้ในผู้ป่วยมะเร็งบริเวณศีรษะ

ภาควิชา รังสีวิทยา	ลายมือชื่อนิสิต ....
สาขาวิชา ฉายาเวชศาสตร์	ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก ....
ปีการศึกษา 2556	

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KEYWORDS: MRI SIMULATION / TREATMENT PLANNING SYSTEM / IMRT / VMAT

KITTIPOL DACHAWORAKUL: MAGNETIC RESONANCE IMAGING BASED TREATMENT PLANNING IN IMRT AND VMAT FOR HEAD REGION. ADVISOR: ASSOC. PROF. SIVALEE SURIYAPEE, M.Eng., 86 pp.

MRI can improve delineation of tumor and normal tissues for radiation treatment planning in brain tumor. However, MRI cannot provide radiologic properties information as in the case of CT image. The approach can solve this problem by bulk density method. This method works by overriding the original pixel value over the interested area with average bulk density. The purpose of this study is to evaluate the dosimetric accuracy in MRI based compared with CT base treatment planning. Twenty eight brain tumor patients were scanned both CT and MRI simulator with the same position and then imported both of them to Radiotherapy Treatment Planning (RTP) unit. Registration images and delineation of tumor and OARs were created by radiation oncologist while bone and air cavity were defined with auto-segmentation in treatment planning. Determination of 3 types of bulk density: First, average individual bulk density: the average CT number of all slices for PTV, bone and air for each patient were undertaken. Second, average mean bulk density: the average individual bulk density for all slices and all patients for PTV, bone and air were calculated. And third, ICRU bulk density: recommendation from ICRU number 46 for PTV, bone and air were employed. CT full density plan were created in IMRT and VMAT as a reference plan of this study. MRI with 3 types of bulk density plans and MRI with water equivalent plan were created in both IMRT and VMAT. The plans were compared using D_95% in the dose volume histogram. The result of IMRT and VMAT plan, show that all the dose differences from CT full density plan of MRI average individual and average mean bulk density plan are within 0.27% and 1.54% for average and maximum dose difference, respectively, and the dose difference of MRI with ICRU bulk density plan were within 0.38% and 0.93% for average and maximum dose difference, respectively, The water equivalent plans were within 1.68% and 3.83% for average and maximum dose difference, respectively. The treatment planning of head region using MR image was quite accurate with bulk density method. The dose differences in both of average individual and average mean plan were comparable so the average bulk density for this group of study could be employed in the head planning instead of determining bulk density for individual. The ICRU bulk density can also be used in head planning. The MR water equivalent plan may not be suitable to use in head region.

Department: Radiology

Field of Study: Medical Imaging

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Student's Signature ....

Advisor's Signature ....

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LIST OF ABBREVIATION

ABBREVIATION	TERMS
ρ_e	electron density
3D	Three-Dimensional
AAA	Analytical and isotopic algorithm
BEV	Beams-Eye-View
cc	Cubic Centimeter
cm	Centimeter
CT	Computed Tomography
CT_F	Computed Tomography image based treatment planning with full density correction plan
CT_w	Computed Tomography image based treatment planning with water equivalent plan
DICOM-3	Digital Imaging and Communications in Medicine-3
DRRs	Digitally Reconstructed Radiographs
DVH	Dose Volume Histogram
G	gram
HU	Hounsfield Unit
ICRU	International Commission on Radiation Units and Measurements
IGRT	Image-Guided Radiation Therapy
IMRT	Intensity-Modulated Radiation Therapy

ABBREVIATION	TERMS
MLC	Multileaf collimator
mm	Millimeter
MR_B	Magnetic Resonance Imaging based treatment planning with bulk density plan
MR_W	Magnetic Resonance Imaging based treatment planning with water equivalent plan
MRI	Magnetic Resonance Imaging
MU	Monitor Units
MVCT	Megavoltage Computed Tomography
OARs	Organ At Risks
PET	*Positron Emission Tomography*
QA	Quality Assurance
VMAT	Volumetric-Modulated Arc Therapy

CHAPTER I

INTRODUCTION

1.1 Background and Rationale

Cancer of the brain is usually called a brain tumor. There are two main types: A primary and metastatic brain tumor. Brain tumors can be benign or malignant. Because brain is protected by skull which is limit space of brain, brain tumor is life-threatening. The various types of treatment are available depending on type and location and the treatment methods may be combined. Surgery is the first and most common treatment for most patients with brain tumors. Radiotherapy is reserved for inoperable cases. Multiple metastatic tumors are generally treated with radiotherapy and chemotherapy rather than surgery and the prognosis in such cases is determined by the primary tumor, but is generally poor[1-3]. The goal of radiation therapy is to selectively kill tumor cells while spare normal brain tissue safe[4]. The modern technique of radiotherapy such as intensity-modulated radiation therapy (IMRT) and volumetric-modulated arc therapy (VMAT) can create high gradient of dose distribution between tumor and organ at risks (OARs) to maintain the goal of radiation therapy concept.

IMRT is an advanced technique of high-precision radiotherapy that the computer-controlled linear accelerator with a multileaf collimator (MLC) is used to deliver precise radiation doses to a tumor. IMRT allows for the radiation dose to conform more precisely to the three-dimensional (3D) shape of the tumor by modulating or controlling the intensity of the radiation beam in multiple small volumes. IMRT can deliver higher radiation doses to the tumor while minimizing the dose to surrounding normal tissues, the IMRT plan is shown in Figure 1.1[5].

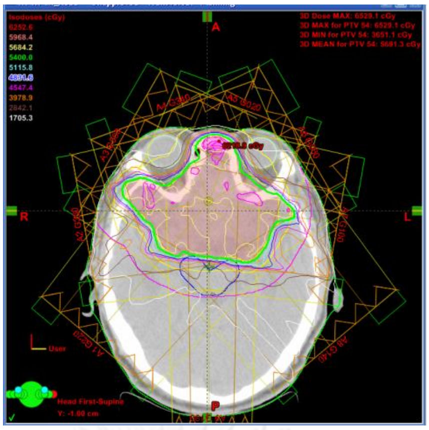

Figure 1.1 Intensity-modulated radiation therapy (IMRT) plan.

VMAT is an arc-based dose delivery approach that produces highly conformal dose distributions similar to those generated with static gantry (IMRT), the isodose distribution in treatment plan is shown in Figure 1.2. As many existing IMRT approaches, VMAT can be delivered with a standard linear accelerator that is equipped MLC. During arc beam delivery the dose rate, the speed of the gantry, and the position of the MLC leaves are varied dynamically. A major advantage of VMAT approach is the speed of dose delivery[6].

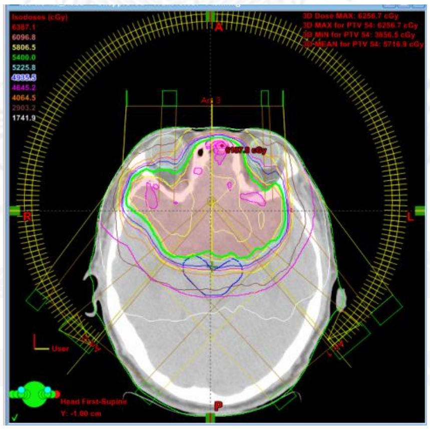

Figure 1.2 Volumetric modulated arc therapy (VMAT) plan.

Medical imaging is an important part of modern radiotherapy. It is necessary to define the tumor, OARs and normal tissues, to produce optimal dose distribution and also to verify the patient position. If the tumor is not properly visualized, Radiotherapy Treatment Planning (RTP) cannot create the dose distribution optimal to the tumor and OARs. Computed Tomography (CT) has been used as a basic imaging modality in radiotherapy over 30 years. CT is used to delineate target and OARs and the important role of CT in radiotherapy is to provide information for the attenuation of radiation by the patient's tissues in a form of CT numbers. It is known that corrections of tissue inhomogeneities can be performed on the basis of knowledge of the electron density in tissues. The RTP usually converts CT number to relative electron density (ρ_e) of incorporate voxel by voxel by determining the relationship between the two quantities. However, CT image alone does not always provide enough information for accurate delineation of the target volume especially in the soft tissue contrast area. Therefore the used of Magnetic Resonance Imaging (MRI) has challenged the utilization of CT for many tumor sites. As knowledge, MRI is acquired by a completely different physical process, which is related to the magnetic properties of each tissue. MRI is more advantages over CT because it produces better soft tissue contrast such as in brain tumor as shown in figure 1.3. MRI has a more range of available soft tissue contrast, depicts anatomy in greater detail, and is more sensitive and specific for abnormalities within the brain. MRI is the imaging modality of choice for the delineation of target volumes used in RTP. However, MRI cannot be calibrated to electron density as in the case of CT so in the beginning of MRI in RTP, only contouring, MRI must be registered to CT image to transfer contours of the tumor and OARs delineated on the MRI, and then dose calculation can be performed on the CT image.

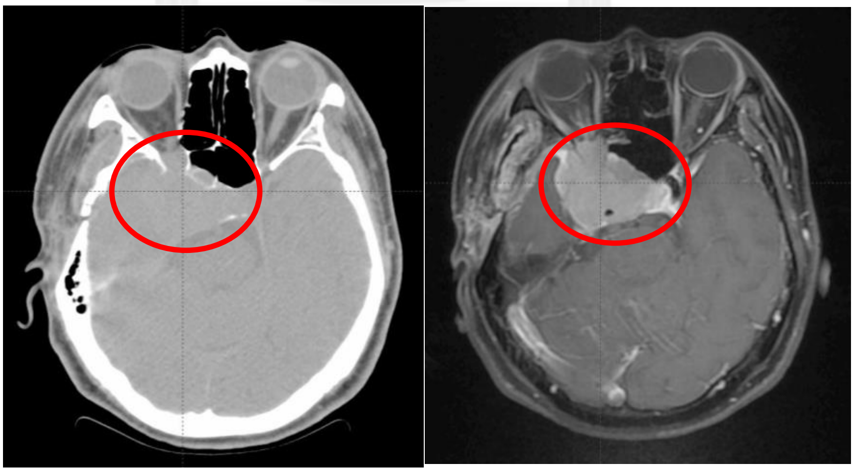

Figure 1.3 CT brain tumor (left) and MRI brain tumor (right) in the same patient.

Extra costs from imaging multimodality and registration error have motivated several authors studied about MRI based dose calculation in RTP. The lack of electron density of MRI is the main problem in RTP. The way to solve this problem is to use bulk density method, a method that could dose calculations be performed, using the MRI of applying bulk electron densities or CT number to the MRI. This involves overriding original pixel values with a single electron density value for each ROI. This method is to contour some regions such as bone, air or lung and assign a bulk densities or CT number for each region. The time and effort required for the manual contouring process is a limitation of this method. The purpose of this work is to study MRI based treatment planning using bulk density for individual patients, average value of all patient study, International Commission on Radiation Units and Measurements (ICRU) value and water value compared with the CT full density planning.

1.2 Research Objectives

To evaluate the dosimetric accuracy in MRI based compared with CT based treatment planning.

CHAPTER II
LITERATURE REVIEWS

2.1 Theories

2.1.1 Radiotherapy Treatment Planning (RTP)

The RTP process involves many steps: determine characteristics of the radiation beams used to deliver the radiation dose to the tumor or other organs in patient by decision the number, orientation, size, entry point, weighting, beam modification and type of the radiation beams. The treatment planning is performed with the assistance of a computerized treatment planning system that helps the medical physicist and radiation oncologist define the target volume, determine beam directions and shapes, calculate the associated dose distribution, and evaluate the dose distribution. The steps of RTP start from beam data acquisition and entry into the RTP, through patient data acquisition, to treatment plan generation and the final transfer of data to the treatment machine [7, 8]. Another issue of RTP is the inhomogeneity correction because the human body consists of a variety of tissues and cavities with different physical and radiological properties such as lungs, bones, teeth, sinuses, nasal and oral cavities. Optimization of radiotherapeutic impact requires correct accounting for this heterogeneity so that absorbed dose may be accurately determined in all irradiated tissues [9, 10]. The dose distribution is affected by these tissue inhomogeneities and since treatments are becoming increasingly conformal, as in the case of IMRT and VMAT, the opportunity for geometry misses of the target due to incorrect isodose coverage increases.

IMRT and VMAT are inverse treatment planning which employed dose optimization techniques and the degree of optimality of the final solution is generally determined by the form of objective function. The objective function is a function of the beamlet weights. A given objective function can be optimized using many different optimization algorithms, such as iterative methods, simulated annealing, filtered back projection, genetic algorithm, maximum likelihood approach, linear programming, etc. For all their complexity, the algorithms to optimize a multidimensional function are routine mathematical procedures. An iterative method is a widely used technique to optimize a multidimensional objective function by starting with an initial approximate solution and generating a sequence of solutions that converge to the optimal solution of the system. In addition to the prescription doses, the current planning system requires the user to pre-select the angular variables (gantry, couch, and collimator angles) and the relative importance factors of the involved structures [11].

2.1.2 Intensity Modulated Radiation Therapy (IMRT)

IMRT is an advanced mode of high precision radiotherapy that utilizes computer-controlled linear accelerators to deliver precise radiation doses to a tumor or specific areas within the tumor. IMRT allows for the radiation dose to conform more precisely to the three dimensional shape of the tumor by modulating or controlling the intensity of the radiation beam in multiple small volumes. IMRT also allows higher radiation doses to be focused to regions within the tumor while minimizing the dose to surrounding normal tissues and OARs. Treatment plan is created by using 3D image such as CT or MRI of the patient in conjunction with computerized dose calculations to determine the dose intensity pattern that will best conform to the tumor shape. Typically, combinations of multiple intensity-modulated fields coming from different beam directions produce a custom tailored radiation dose that maximizes tumor dose while also minimizing the dose to adjacent normal tissues. The treatment plan of IMRT is shown in Figure 2.1. The higher and more effective of radiation doses can be delivered to tumors with fewer side effects compared with conventional radiotherapy techniques. IMRT also has the potential to reduce treatment toxicity. Due to its complexity, IMRT does require slightly longer daily treatment times and additional planning and safety checks before the patient can start the treatment [5].

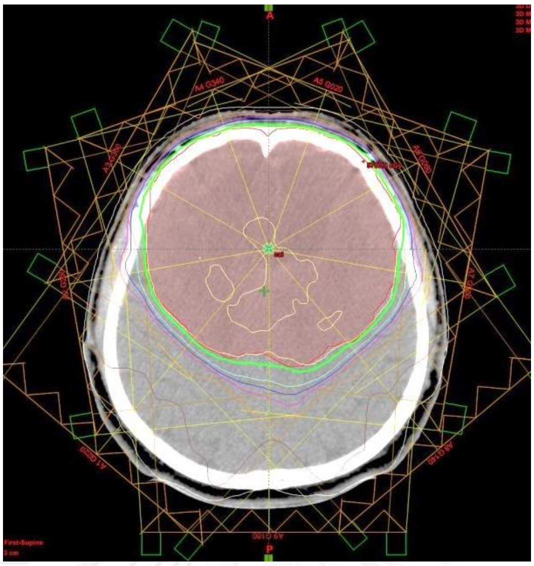

Figure 2.1 Intensity Modulated Radiation Therapy (IMRT) plan.

2.1.3 Volumetric Modulated Arc Therapy (VMAT)

VMAT delivers radiation by rotating the gantry of a LINAC through one or more arcs with the radiation continuously on. As it does so, a number of parameters can be varied. These include: MLC aperture shape, the fluence output rate, the gantry rotation speed and the MLC orientation. It is undisputed that VMAT can deliver highly conformal dose distributions similar to those created by other forms of IMRT. As such, it becomes a valued member of the IMRT delivery arsenal. The treatment plan of VMAT is shown in Figure 2.2. VMAT most operate by creating some form of fixed-field modulated beams, decomposing these into MLC components, redistributing those over small arcs and re-optimizing the outcome. In doing so, VMAT can take advantage of the above mentioned four variable parameters, but must do so while respecting the physical constraints of the LINAC and MLC such as the maximum gantry speed, maximum leaf speed, the MLC orientation constraints and the available subdivisions of fluence output rate. Provided that the gantry speed can be varied continuously, it does not require a continuous variation of fluence output rate to obtain a continuous variability of fluence output rate per degree. The minimum fluence output rate and the maximum gantry speed determine the constraining minimum fluence output rate per degree. Where there is a maximum fluence output rate and minimum gantry speed, there will be a constraining maximum fluence output rate per degree. VMAT can generate equivalently conformal dose distributions with fewer MU in a faster time. To have that is clearly advantageous these include: shorter treatments; better for patients in discomfort; less susceptibility to intra fraction motion; possibly less induced secondary cancers; quicker overall treatment slots [6].

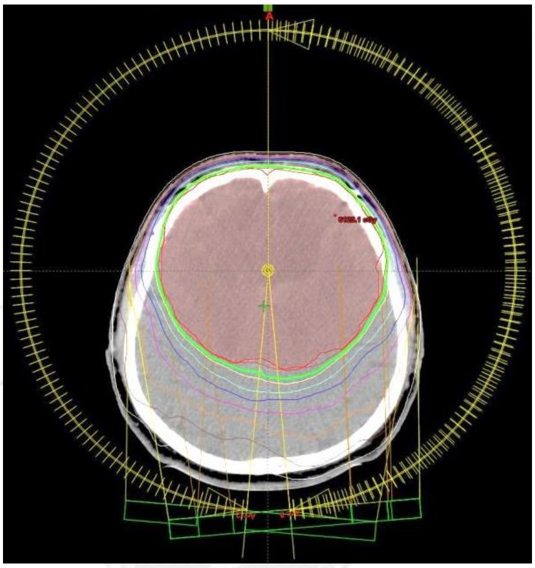

Figure 2.2 Volumetric Modulated Arc Therapy (VMAT) plan.

2.1.4 Treatment plan evaluation

For achieving goal of radiation therapy, it requires optimal dose distribution to the tumor, OARs and normal tissues, the complexity and conformal of the modern treatment planning, such as IMRT and VMAT, this has led to the need to quality assurance (QA) of treatment planning. The treatment plan evaluation is necessary methods which have many methods.

2.1.4.1 Dose distribution display

Analysis of displays of the dose distribution, particularly in association with the anatomical details shown in Figure 2.3, is one of the major ways that medical physicist and radiation oncologist make decisions about how the treatment plan should be optimized.

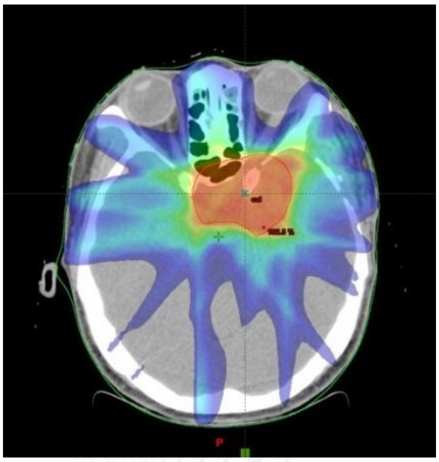

Figure 2.3 Dose distribution display in head region (color wash).

2.1.4.2 Dose Volume Histogram (DVH)

In modern radiation therapy, the specification of the absorbed dose to relevant anatomic volumes rather than to single points is critical to the communication of the treatment intent. The DVH summarized the information in the 3D dose distribution for the quantitative evaluation of treatment plan is shown in Figure 2.4. Visual inspection of DVHs can lead to identification of clinically important characteristics of an absorbed dose distribution, such as the presence (but not the location) of regions of high or low absorbed dose, which are difficult to assess rapidly and consistently from conventional isodose or color-wash presentations [7, 12].

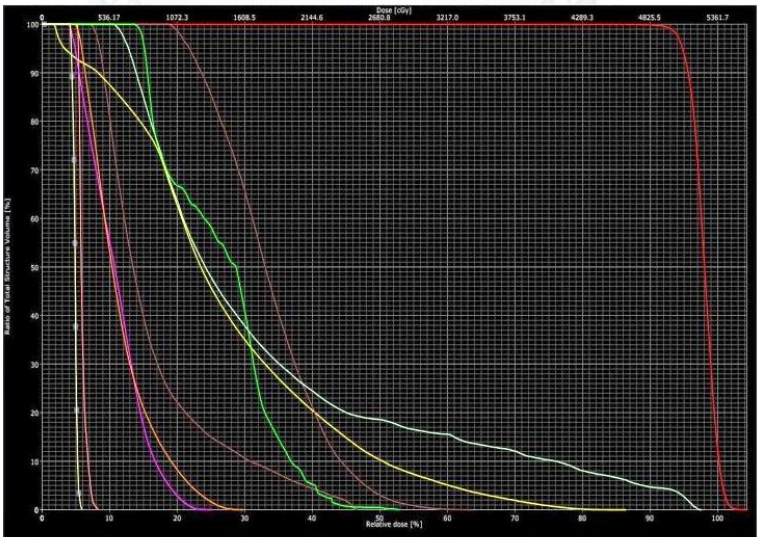

Figure 2.4 Dose Volume Histogram (DVH).

It is recommended that dose-volume specifications be used for reporting the treatment plan. For example $D_{95\%}$ is the minimum absorbed dose that covers 95% of the volume of the PTV. The ICRU number 83 [13], recommend for $D_{98\%}$ which represents near-minimum absorbed dose, $D_{95\%}$ represents the clinical relevance of the lowest PTV, absorbed dose can depend on their position within the PTV, $D_{2\%}$ represents near-maximum absorbed dose, they are shown in Figure 2.5.

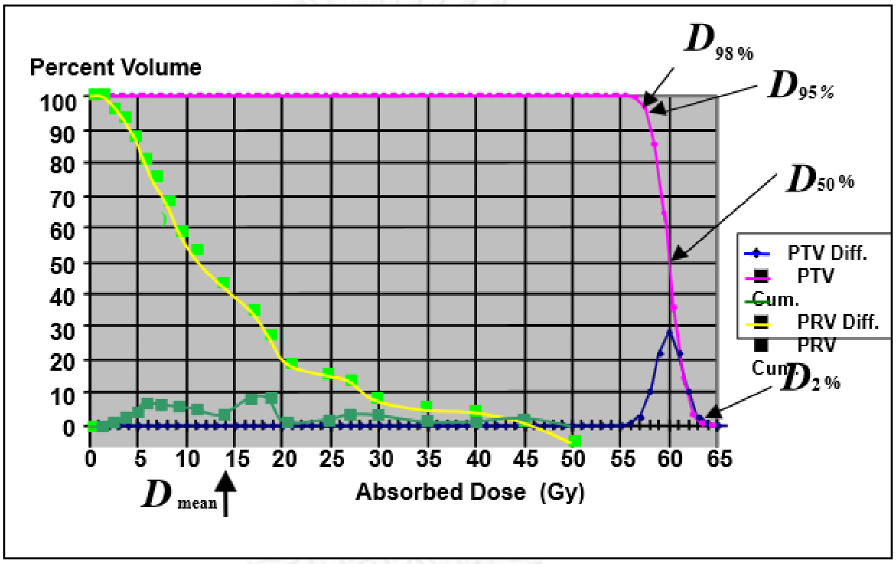

Figure 2.5 The recommendation of dose-volume specifications in DVH from ICRU number 83.

2.1.5 The role of CT and MRI in radiotherapy

CT provides the primary dataset for most aspects of conformal therapy treatment planning. The data from CT are used to construct geometric and physical models of the patient. The geometric models are used to define anatomic structures, target volumes and to aid in radiation beam placement and shaping. The physical models provide density information required by most dose calculation algorithms. The planning CT dataset is also used to generate graphical aids such as beams-eye-view (BEV) displays and digitally reconstructed radiographs (DRRs) for planning and treatment verification. The major drawback of CT data is the limited soft tissue contrast, which can hinder accurate tissue discrimination.

MRI now plays an important role in treatment planning for several tumor sites, offering several advantages over CT. The excellent soft tissue contrast provided by MRI, permits better discrimination between normal tissues and many tumors. A wide variety of MR imaging pulse sequences are available that can improve image contrast by enhancing or suppressing specific tissues such as fat and conditions such as edema. Also, MRI can be directly acquired along sagittal and coronal planes, offering better visualization of certain tissues. While these features make MRI an excellent choice as a primary dataset for treatment planning, several limitations have prevented the use of MR data alone. These drawbacks include the greater susceptibility of MR to spatial distortions and intensity artifacts, the lack of signal from cortical bone, and image intensity values that have no relationship to electron or physical density [14].

2.1.6 The effect of electron density in RTP

The dose calculation by RTP within the treated volume is an important step of contemporary treatment planning in radiotherapy. Many factors have an influence on the dose distribution, heterogeneity of the patient's body being one of them. For MV x-ray beams, Compton interaction predominates and the probability of a Compton interaction is inversely proportional to the energy of the incoming photon and is independent of the atomic number of the material. When one takes an image of tissue using photons in the energy range in which the Compton effect dominates (~25 keV-25 MeV), bone and soft-tissue interfaces are barely distinguishable. This is a result of the atomic number independence. The Compton effect is the most common interaction occurring clinically, as most radiation treatments are performed at energy levels of about 6-20 MeV. CT is fundamental, as it provides information on the attenuation of radiation by the patient's tissues in a form of CT numbers, expressed in Hounsfield units (HU) as in the following equation [15]:

$$HU_{tissue} = [(\mu_{tissue} - \mu_{water}) / \mu_{water}] \times 1{,}000$$

where μ is the linear attenuation coefficient of water and of the tissue. RTP usually converts HU values to ρ_e (relative electron density) by means of the predefined relationship between the two quantities, it is shown in figure 2.6, e.g., one given by Knöös et al [16].

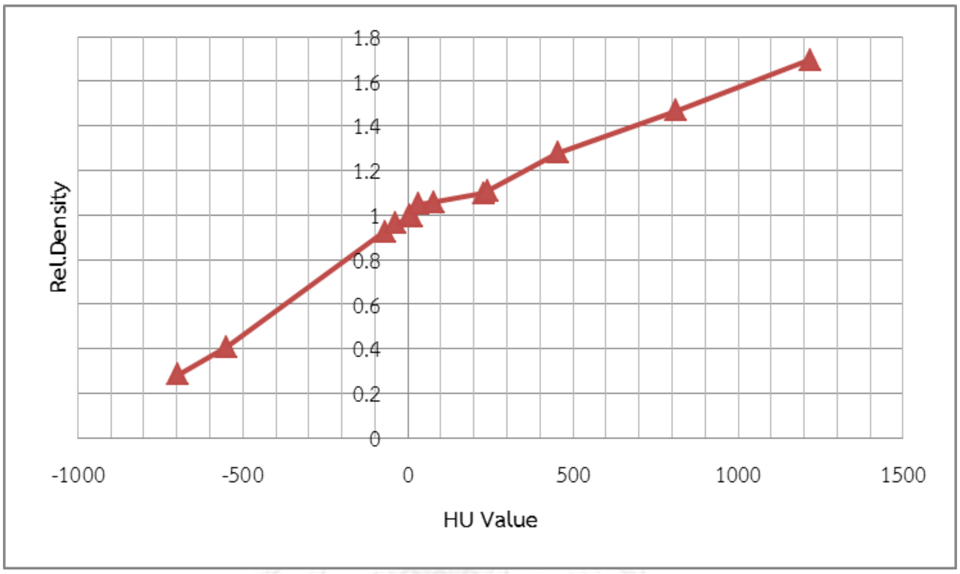

Figure 2.6 CT-to-density conversion curve.

2.1.7 Brain tumor[1]

Cancer of the brain (is usually called a brain tumor) is an intracranial solid neoplasm, a tumor (defined as an abnormal growth of cells) within the brain or the central spinal canal. There are two main types. A primary brain tumor starts in the brain. A metastatic brain tumor starts somewhere else in the body and moves to the brain. Brain tumors can be benign or malignant. Brain tumors include all tumors inside the cranium or in the central spinal canal. They are created by an abnormal and uncontrolled cell division, usually in the brain itself, but also in somewhere else. The intracranial are shown in Figure 2.7 such as lymphatic tissue, in blood vessels, in the cranial nerves, in the brain envelopes (meninges), skull, pituitary gland, or pineal gland.

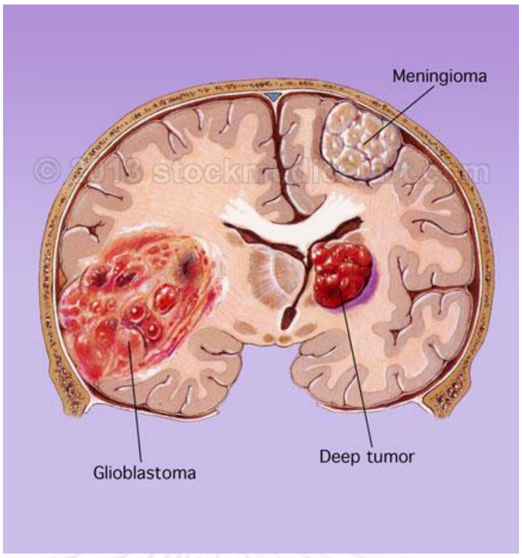

Figure 2.7 Tumor in intracranial [17]

Any brain tumor is inherently serious and life-threatening because of its invasive and infiltrative character in the limited space of the intracranial cavity. Its threat level depends on the combination of factors like the type of tumor, its location, its size and its state of development. Because the brain is well protected by the skull, the early detection of a brain tumor occurs only when diagnostic tools are directed at the intracranial cavity. Usually detection occurs in advanced stages when the presence of the tumor has caused unexplained symptoms.

The most common primary brain tumors are:

1) Gliomas (50.4%)
2) Meningiomas (20.8%)
3) Pituitary adenomas (15%)
4) Nerve sheath tumors (8%)

The various types of treatment are available depending on type and location and may be combined to give the best chances of survival:

A. Surgery: is the first and most common treatment for most patients with brain tumors. The primary objective of surgery is to remove as many tumor cells as possible, with complete removal being the best outcome.

B. Radiotherapy: is reserved for inoperable cases. The goal of radiation therapy is to selectively kill tumor cells while leaving normal brain tissue unharmed. Radiotherapy is the most common treatment for secondary brain tumors.

C. Chemotherapy: is a treatment option for cancer. However it is seldom used to treat brain tumors as the blood and brain barrier prevents the drugs from reaching the cancerous cells. Chemotherapy can be thought of as a poison that prevents the growth and division of all cells in the body including cancerous cells. Thus the significant side effects associated and experienced by patients undergoing chemotherapy.

2.1.8 Image registration[18, 19]

Registration is the determination of a one-to-one mapping between the coordinates in one space and those in another, such anatomical point are mapped to each other. Multiple image studies of the same patient are often used in treatment planning. The combination of images can often lead to additional clinical information not apparent in the separate images. Quantitative use of this information typically requires that these images be analyzed in a common coordinate system, so that, for example, the extent of a tumor delineated on MRI can be accurately placed in the context of a CT-based virtual simulation. Image registration can be applied to both serial studies of the same modality, for example, a planning and daily setup CT scan, or to image studies from different modalities-CT scan and MRI. Figure 2.8 shows a co-registered CT-MRI, each point in one image should map onto the corresponding point in the second image. The process is simplified if external markers can be attached to the patient, but this is often time-consuming and invasive; using internal anatomic markers, e.g. the rib cage, ventricles, bone surfaces, is more frequently used. The registration could be done interactively by a radiologist, assisted by software that gives feedback on the quality of the alignment, but automatic registration is generally preferred. Medical image registration has also been utilized in radiotherapy, mostly for brain tumors, and by cranio-facial surgeons to prepare for and simulate complex surgical procedures.

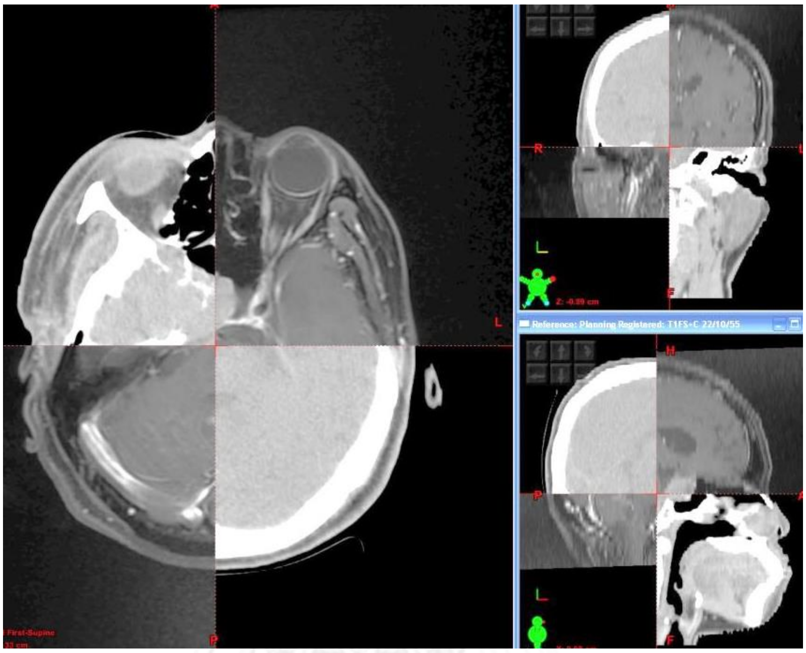

Figure 2.8 Registration between CT and MRI in head region.

2.1.9 Image segmentation[19]

Segmentation is the partitioning of an image into meaningful regions, most frequently to distinguish objects or regions of interest from everything else. In the simplest cases, there would be only these two classes and the segmented image would be a binary image. Segmentation is used, for example: For bulk density method, segmentation for some region is shown in figure 2.8 and overrides the original pixel value with bulk density value.

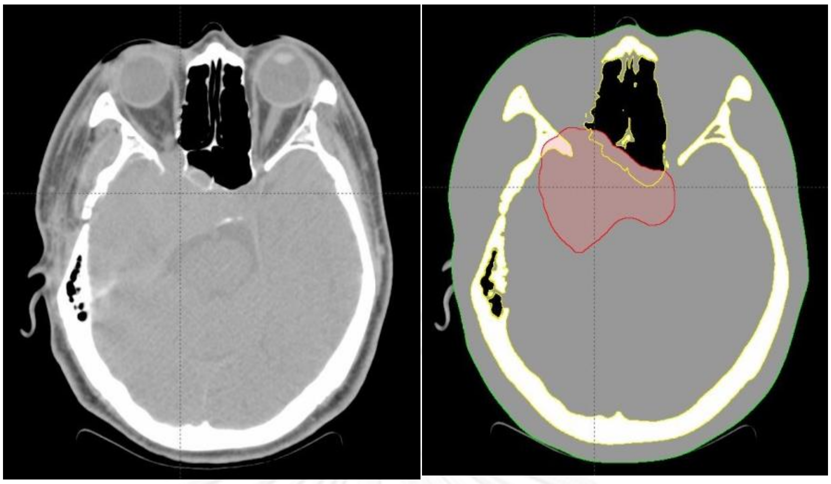

Figure 2.9 Before segmentation (left), after segmentation for PTV, bone and air in bulk density process (right).

2.2 Review of Related Literature

2.2.1 Lili Chen et al**[20]** investigated the dosimetric accuracy of MRI-based treatment planning for prostate IMRT in 30 IMRT plans for 15 patients using both MRI and CT data. The same internal contours were used for the paired plans. In MRI plan, all tissue set to a homogenous water equivalent material. The same energy, beam angles, dose constrains, and optimization parameters were used for dose calculations for each paired plans using a treatment optimization system. Their results showed that dose distributions between CT-based and MRI-based plans were equally acceptable based on our clinical. The DVHs from the CT-based were compared with MRI-based IMRT plans for the same patient. Again the differences were clinically insignificant. The differences for the bladder partially were due to the small differences in the structure volumes between the two image modalities. The absolute dose agreement for the planning target volume was within 2% between CT-based and MR-based plans. So MR imaging–based treatment planning meets the accuracy for dose calculation and provides consistent treatment plans for prostate IMRT.

2.2.2 Joakim H Jonsson et al[21]studied about the accuracy of dose calculation for four different treatment regions: prostate (n=10), thorax (n=10), brain (n=10), and head and neck (n=10). The dose calculation were performed using the same beam angle in four data sets: 1.The CT geometry with heterogeneity correction (the normal clinical geometry) 2. No heterogeneity correction on CT data (the patient external contour delineated on CT and the entire patient anatomy set to water) 3. Bulk density geometry based on CT data for all treatment regions and 4. Bulk density geometry based on MR data for the prostate and thorax regions. The electron densities were recommended from ICRU 46. For evaluation method, the shape differences of the DVHs and number of monitor units (MUs) were compared. Table 2.1 lists the mean values and standard deviations of the relative differences in MUs between the different calculation geometries and the standard CT geometry. The mean MU values of the bulk density assigned plans were within 1% of the CT plans for all patient groups. There was a consistent improvement of the calculation accuracy with bulk density assignment compared to calculations performed without inhomogeneity corrections, except in the head and neck plans where bulk density assignment gave the same result compared to calculations performed without the inhomogeneity correction.

Table 2.1 Percent difference of mean dose between bulk density geometry based on MR data, Bulk density geometry based on CT data, No heterogeneity correction on CT data compared with CT geometry with heterogeneity correction.

Treatment area	MR_{bulk}/CT		CT_{bulk}/CT		MR_{homo}/CT	
	Mean [range]%	Std.%	Mean [range]%	Std.%	Mean [range]%	Std.%
Prostate	0.2[-0.8;0.9]	0.5	0.8[-2.3;-1.6]	0.3	-1.6[-2.3;-1.6]	0.2
Thorax	0.2[-0.6;0.9]	0.4	1.4[-0.8;-6.5]	0.3	1.4[-0.8;-6.5]	2.1
Head&Neck	-	-	-0.3[-1.1;0.6]	0.3	-0.3[-1.1;0.6]	0.5
Brain	-	-		0.6	-1.5[-2.4;-0.7]	0.5

The dose calculation accuracy at the investigated treatment sites is not significantly difference when using MRI data of adequate bulk density assignments. With respect to treatment planning, MRI can replace CT in all steps of the treatment workflow, reducing the radiation exposure to the patient, removing any systematic registration errors that may occur when combining MR and CT, and decreasing time and cost for the extra CT investigation.

2.2.3 Jonathan Lambert et al [22] examined the dosimetric accuracy of prostate planning using MR alone with a large patient dataset of 39 patients. Fluke Biomedical #76-097, Everett, WA, USA was used to evaluate homogeneous of the MR scanner and spatial distortions due of the MR scanner. Each patient had three prostate pure gold fiducial markers of diameter 1.0 mm and length 3.0 mm inserted trans-rectally by an urologist 1–2 weeks prior to the acquisition of the planning images. Patients were scanned both for CT and MR images for planning, the interscan time was within 1 or 2 days with full bladder and empty rectum.

They imported and registered (CT and MR images) using fiducial marker. The target and organ at risk were defined in MR images and were planning in CT images. The dose was calculated in CT plan and was copied this plan to another 4 plan:

1. CT-based with bone correction
2. MR-based with bone correction
3. CT-based, uniform density
4. MR-based, uniform density

Table 2.2 Summary of average point dose results for the four electron density plans. The mean dose is the dose per fraction delivered by the plan, and the difference between this value and the full density CT plan is given as a percentage of the target dose delivered by the full density CT plan (200 cGy per fraction).

Plan	Mean dose (cGy)	%Variation from full density CT	Standard deviation (cGy)
CT-based with bone	200.2	0.1	1.2 (0.6%)
MR-based with bone	197.5	-1.3	1.6 (0.8%)
CT-based, uniform density	197.2	-1.4	1.7 (0.9%)
MR-based, uniform density	194.8	-2.6	1.7 (0.9%)

MR-alone bulk density planning is feasible provided bone is assigned a density, however, manual segmentation of bone on MR images will have to be replaced with automatic methods. The major dose differences for MR bulk density plans are due to differences in patient external contours introduced by the MR couch-top and pelvic coil.

2.2.4 A W Beawis et al [23]evaluated image distortion of MRI in phantom and patients. The phantom and all patients were scanned with 1.5T GE Signa scanner. The head coil cannot be used with head mask so all patients were scanned with body coil. The origin of reference lines were defined by using lasers. The water filled plastic tubes were positioned over these reference lines. The in-house software (ANALYZE^{TM}, Biomedical Imaging Resource, Mayo foundation) was used for evaluation. The phantom studied illustrated the accuracy of ±1mm within 10 cm field of view and ±2mm within 24 cm field of view. The patient studies of 24 cm field of view were undertaken by comparing between laser reference position and plastic tube position, resulted in: x co-ordinates (left-right direction) showed absolute mean difference of 0.7 mm. y co-ordinates (antero-posterior direction) showed absolute mean difference of 0.45 mm. z co-ordinates (supero-inferior direction) showed absolute mean difference of 1.0 mm. This study revealed that geometric distortions can be reduced by using small field of view.

CHAPTER III

RESEARCH METHODOLOGY

3.1 Research Design

This study is an analytical study

3.2 Research Design Model

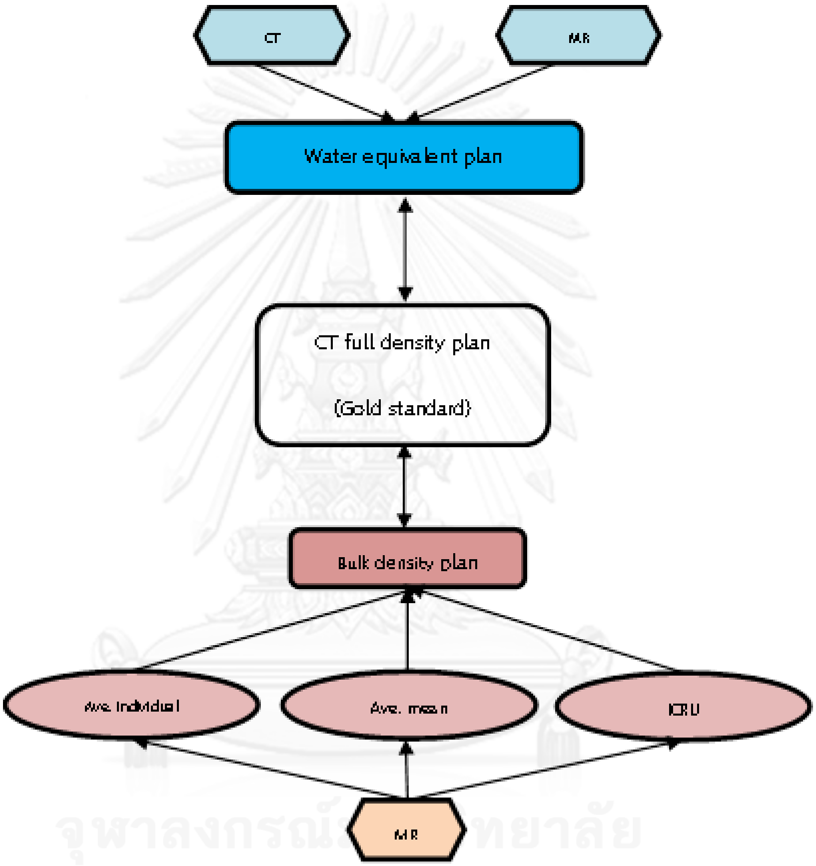

Figure 3.1 Research design model.

3.3 Conceptual framework

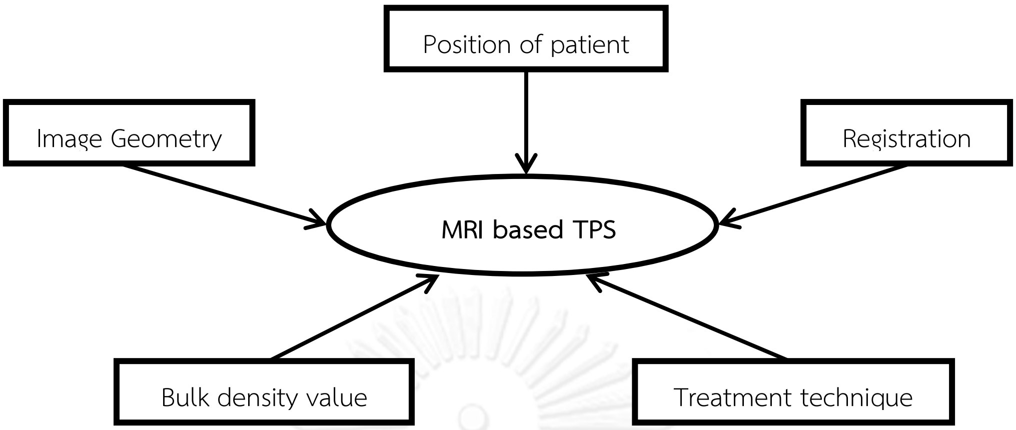

Figure 3.2 Conceptual framework.

3.4 Key Words

MRI based, Treatment Planning System, MRI simulation, IMRT, VMAT

3.5 Research question

What is the dosimetric accuracy in MRI based compared with CT based treatment planning in IMRT and VMAT for head region?

3.6 Materials

3.6.1 MRI simulator scanner

The 1.5T HDxt MRI scanner (GE Healthcare, Waukesha, WI, USA) is shown in figure 3.3. Bore diameter is 700 mm which allows immobilization devices to be employed with a larger aperture than a standard MR system. Additional, Signa Oncology Package such as flex coil and flat tabletop is an add-on for radiotherapy procedure. For optional coil, 6-Channel Flex coil shown in figure 3.4 is recommended for using with the Signa Oncology table and immobilization devices such as thermoplastic mask for brain cancer patient. The Signa Oncology table which can be used with a set of compatible patient positioning devices is shown in figure 3.5.

Figure 3.3 MRI scanner (HDxt 1.5T, GE Medical system, Waukesha, WI, USA.).

Figure 3.4 Signa Oncology Package: 6-Channel Flex coil.

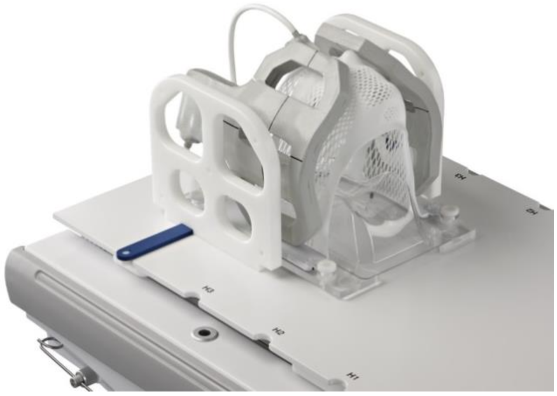

Figure 3.5 Signa Oncology Package: flat tabletop with flex coil.

3.6.2 CT simulator scanner

The 4 slice CT scanner (LightSpeed RT, GE Medical system, Waukesha, WI, USA.), which is shown in Figure 3.6, has the ability to simultaneous collecting 4 rows of scan data. The distance from tube to isocenter is 606 mm. The distance from the x-ray tube to detector focus is 1062 mm. Bore diameter is 800 mm which allows images to be reconstructed with a larger field of view than a standard CT system. Additional, raw image into 3D image can generate digital reconstructed radiograph (DRR) in many directions.

Figure 3.6 CT scanner (LightSpeed RT GE Medical system, Waukesha, WI, USA.).

3.6.3 MRI Phantom

Magphan® phantom which was designed for a wide range of precision performance evaluations of MRI scanners is shown in figure 3.7. Imaging performance is evaluated in the trans-axial, coronal and sagittal. The acrylic cylinder has an outer diameter of 20 cm and an inner diameter of 19 cm. Magphan® use a 10 cm test cube for image quality measurements, manufactured from 6mm-thick polycarbonate plastic. The test cube has an outer diameter of 10 cm. It contains the Slice Thickness Ramps, Sensitometry Vials, a High Resolution Test Plate and a Low Contrast Disk. The 3D configuration allows x, y, and z slice geometry measurements to be obtained from a single data acquisition. Geometric distortion can be measured in test plane number 3 by measuring between the 3 mm holes which are spaced in a pattern forming 2 cm, 4 cm, and 8 cm squares.

Figure 3.7 Magphan SMR 170 (The Phantom Laboratory Incorporated, Greenwich, NY, USA).

3.6.4 Radiotherapy Treatment Planning (RTP)

Eclipse treatment planning version 8.9.21 (Varian Medical System, Palo Alto, CF, USA.), which is shown in figure 3.8, is a comprehensive treatment planning system that simplifies modern radiation therapy planning for all kinds of treatment, including 3D conformal, IMRT, VMAT, electron, proton, and brachytherapy. Eclipse treatment planning reduces structure segmentation time from hours to minutes. Oncologist can accurately define targets and organs at risk on fused multimodality images with advanced drawing and editing capabilities. The IMRT and VMAT are planned by inverse planning using analytical and isotopic algorithm (AAA). The AAA is a Monte Carlo-based convolution superposition algorithm that covers the entire therapy range. The AAA accurately models dose deposition in regions with a high degree of tissue heterogeneity by accounting for the 3D density variations directly in the dose calculation.

Figure 3.8 Eclipse treatment planning: version 8.9.17 (Varian Medical System, Palo Alto, CF, USA.)

3.6.5 Quality Assurance software

ImsimQA^{TM} software version 2.0.47 (Modus Medical Devices Inc., London, Ontario, Canada): was developed due to the limitations of hard phantoms for testing modern radiation therapy and imaging software systems. ImsimQA provides extensive tools for generating infinite test image data, from any imported Digital Imaging and Communications in Medicine-3 (DICOM-3) images, and from virtual phantom library. The virtual phantom library which contains 15 3D anatomical and geometric virtual phantoms is shown in figure 3.9. All virtual phantoms can be transformed, deformed, re-orientated, structure density changed etc, to create DICOM-3 series in CT, MRI and Positron Emission Tomography (PET) which are then exported to the test clinical system. DICOM-3 images of any modality can be imported, edited and exported as new DICOM series. Supported modalities include CT, MRI, PET, megavoltage computed tomography (MVCT) and cone beam CT. RT Structure set can be imported, and edited prior to export. ImSimQA is used to test rigid and deformable image registration, Image-Guided Radiation Therapy (IGRT) treatment machines, auto-contouring and dose mapping in treatment planning applications. For image registration testing, varying setups of an initial DICOM image series can be created, without having to use valuable scanner time to create multiple scans for testing.

Figure 3.9 ImsimQA program version 2.0.47(Modus Medical Devices Inc., London, Ontario, Canada)

3.7 Methods

3.7.1 Geometrical distortion evaluation

3.7.1.1 Phantom study

A. Plane number 3 of Magphan phantom was scanned with MRI simulator by setting reference point at center of the phantom, it is shown in figure 3.10

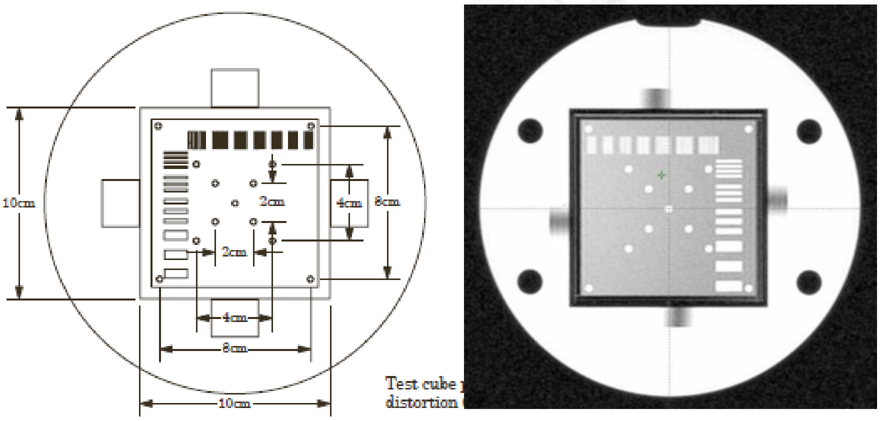

Figure 3.10 Plane number 3 of Magphan phantom.

B. Phantom images were recorded and transferred to RTP

C. The 3 mm holes which were spaced in a pattern forming of 2 cm, 4 cm and 8 cm in test plane number 3 of Magphan phantom were measured and 10 cm length of square was also employed. Four directions were measured by 2 observers, The measurement of distance between holes in plane number 3 is shown in figure 3.11

D. The measured distances and actual values were compared.

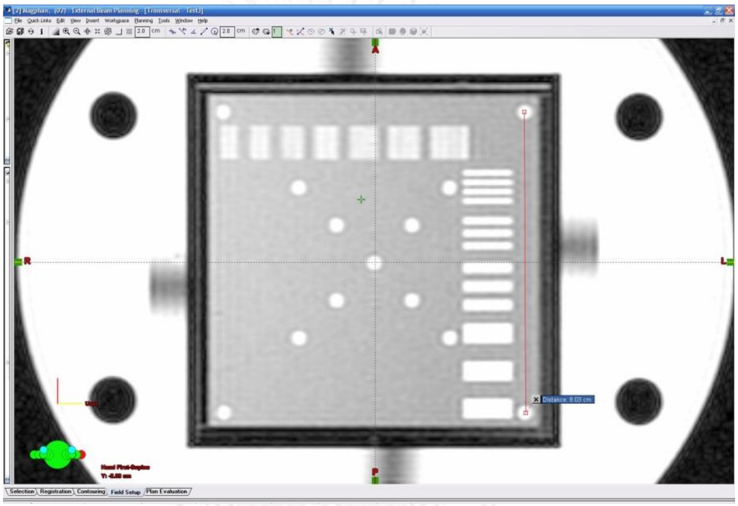

Figure 3.11 Measurement of distance between holes in plane number 3 of Magphan phantom.

3.7.1.2 Patient study

A. Three patients of head cancer were scanned for both of CT and MRI simulator in supine position and the thermoplastic mask to immobilize the patient was attached on the flat tabletop.

B. Patients were aligned by laser positioning system in both of CT and MRI simulator.

C. Patient images were recorded and transferred to RTP and the outer contour was created by RTP in both CT and MR image

D. The 13 directions of gantry angle with the selected isocenter were drawn in set up field as shown in table3.1 to determine the depth and SSD in each direction of gantry angle in axial and sagittal view for both of CT and MR images, they are shown in figure 3.12.

Table 3.1 The position of gantry and couch of setup fields.

Line no.	Gantry rotation (deg.)	Couch rotation (deg.)
1	0	0
2	45	0
3	90	0
4	135	0
5	180	0
6	225	0
7	270	0
8	315	0
9	180	270
10	225	270
11	270	270
12	315	270
13	0	270

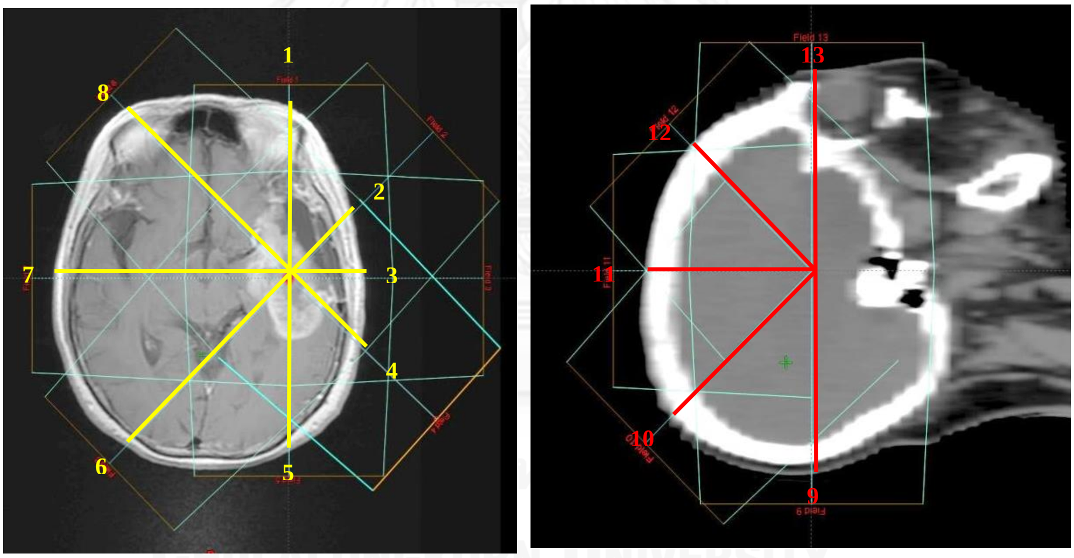

Figure 3.12 The direction of setup field around patient for co-planar, axial view (left) and non co-planar, sagittal view (right).

E. Source skin distance (SSD) was automatically calculated by RTP for each direction.

F. SSD were compared between CT and MR images.

3.7.2 Registration evaluation

A. Virtual head image was created by ImsimQA program for CT and T1 weighted and T2 weighted image of MRI, they are shown in figure 3.13

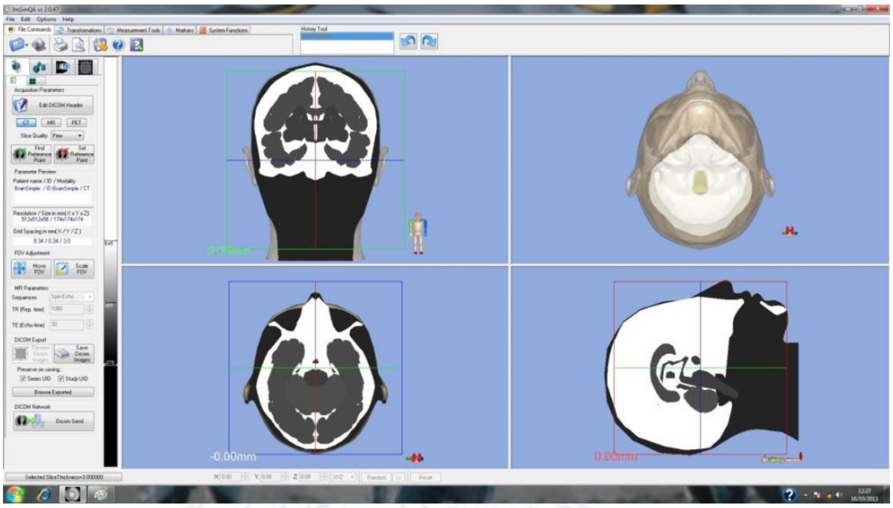

Figure 3.13 Virtual 3D head region image were created by ImsimQA program.

B. Setting CT image as reference image so both of T1 weighted and T2 weighted images were translated in 3 axis by known values in 4 set, they are shown in table 3.2

Table 3.2 The set of translate value in 3 axis for both of T1 and T2 images.

Set	axis	ImsimQA	
		T1(mm)	T2(mm)
1	X	5	5
	Y	0	0
	Z	0	0
2	X	0	0
	Y	5	5
	Z	0	0
3	X	0	0
	Y	0	0
	Z	5	5
4	X	5	5
	Y	-5	-5
	Z	5	5

C. Translated images between CT and MRI were exported into Eclipse treatment planning.

D. Translated images were registration between CT in T1 weighted image and also CT in T2 weighted image by using Pixel data command in Eclipse treatment planning.

E. Translate values were compared between known values and registration values from Eclipse treatment planning.

3.7.3 Planning evaluation

A. Thirty brain cancer patients were scanned both by CT and MRI simulator in supine position and immobilized with thermoplastic mask which attached with flat tabletop.

B. Patients were aligned with laser positioning system in both of CT and MRI simulator room.

C. Patient images were recorded and transferred to RTP for both CT and MR image

D. CT and MR images were registered by radiation oncologist.

E. Target and OARs were defined in MRI by radiation oncologist while bone and air were defined in CT image by automatic segmentation tool in RTP.

F. CT number of PTV, bone and air for all slices which contained PTV were collected by using area profile command in Eclipse treatment planning, they are shown in figure 3.14.

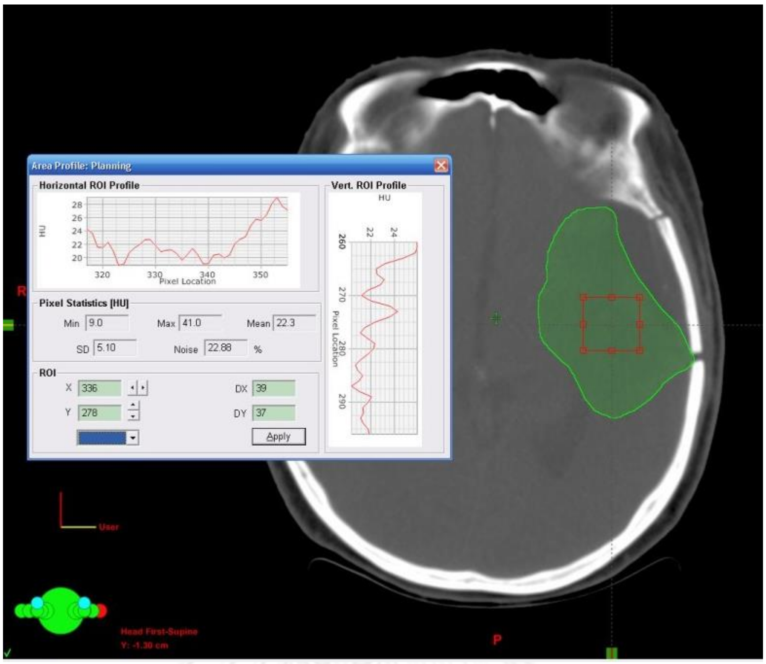

Figure 3.14 Determination of average CT number by Area Profile command for PTV in Eclipse treatment planning.

G. Average individual CT number (CT number for each patient) and average mean CT number (mean CT number for all patients) for PTV, bone and air were determined, they are shown in table 3.3.

Table 3.3 Average individual CT number (CT number for each patient) and average mean CT number (mean CT number for all patients) for PTV, bone and air.

Patient no.	CT number		
	PTV	Bone	Air
1	25.74	703.58	-909.58
2	30.84	1124.11	-925.57
3	27.25	801.37	-914.79
4	35.48	959.92	-952.66
5	29.70	1161.24	-808.90
6	36.50	945.22	-930.76
7	34.98	712.07	-872.08
8	43.34	1034.97	-925.13
9	30.22	1095.05	-845.62
10	40.18	871.63	-956.18
11	39.89	1017.66	-884.34
12	36.92	989.81	-941.77
13	37.00	922.95	-909.93
14	31.60	1047.93	-929.34
15	36.17	846.057	-921.23
16	41.84	913.78	-928.34
17	35.98	1021.30	-927.22
18	32.78	1168.55	-928.81
19	27.88	941.51	-935.64
20	28.79	711.53	-889.44
21	30.29	817.16	-850.39
22	33.44	730.57	-911.50
23	30.37	877.44	-868.21
24	27.19	939.59	-890.40
25	28.89	927.41	-892.40
26	22.81	1099.73	-887.75
27	28.37	1158.42	-924.48
28	23.18	1204.13	-919.16
29	19.69	885.05	-905.90
30	34.41	865.75	-917.46
Mean	32.06	949.85	-906.83
SD	5.73	143.92	32.94
%CV	14.53	19.16	2.07

H. The CT number from ICRU were determined by using recommendation of electron density from ICRU number 46[13] and then use S J Thomas's formula[24] for convert electron density to CT number for PTV, bone and air, they are shown in table 3.4.

Table 3.4 The calculation of CT number from electron density.

Organ	Electron density (g/cm^3)	CT number	Formulae
PTV (brain)	1.040	40	$\rho_e = \frac{HU}{1000} + 1, HU < 100$ $\rho_e = \frac{HU}{1950} + 1, HU \geq 100$
Bone	1.610	1090	
Air	~0	-1000	

Table 3.5 The prescription dose, number of beams and the characteristic of CT and MRI for treatment planning.

Pt. no	Prescription dose	Number of beams		PTV volume (cc)		Brain stem volume (cc)		Resolution (mm)		Slice thickness (mm)	
		IMRT	VMAT	CT	MRI	CT	MRI	CT	MRI	CT	MRI
1	6000/30	9	3	544.07	543.71	28.83	29.13	0.41	0.41	0.25	0.6
2	6000/25	9	3	183.68	179.85	29.1	28.65	0.47	0.49	0.5	0.6
3	5040/28	9	3	49.68	48.11	17.62	16.91	0.42	0.49	0.25	0.4
4	5040/28	9	3	135.69	134.76	26.09	25.94	0.46	0.49	0.25	0.35
5	4000/15	9	3	567.88	564.79	32.33	31.6	0.46	0.49	0.25	0.4
6	5040/28	9	3	109.75	107.39	21.52	21.59	0.48	0.59	0.25	0.4
7	1800/9	9	3	277.35	272.63	17.17	14.77	0.65	0.49	0.5	0.6
8	5400/27	5	3	6.7	6.1	26.7	26.5	0.49	0.49	0.25	0.4
9	6000/30	9	3	537.83	532.35	27.29	26.48	0.48	0.49	0.25	0.6
10	4500/25	9	3	12.57	11.69	26.52	26.05	0.45	0.49	0.25	0.4
11	5040/28	9	3	78.5	74.98	28.86	28.38	0.43	0.49	0.25	0.4
12	5040/28	9	3	107.97	106.16	28.02	27.34	0.49	0.49	0.25	0.4
13	5040/28	9	3	73.5	71.25	21.92	21.18	0.46	0.55	0.25	0.4
14	3000/10	9	3	1875.35	1873.15	34.04	32.24	0.48	0.49	0.25	0.4
15	5400/27	5	3	648.43	645.46	30.36	29.61	0.54	0.51	0.25	0.4
16	5400/27	9	3	63.31	60.48	25.41	24.39	0.45	0.53	0.25	0.4
17	6000/30	9	3	499.77	497.96	24.37	22.97	0.47	0.55	0.25	0.4
18	5040/28	9	3	38.55	37.74	23.2	22.95	0.42	0.49	0.13	0.4
19	5040/28	9	3	81.92	79.75	25.72	24.93	0.49	0.53	0.25	0.4
20	7000/35	9	3	236.93	234.65	38.67	38.07	0.82	0.68	0.5	0.4
21	5400/27	9	3	591.17	588.27	25.33	23.71	0.49	0.51	0.25	0.4
22	5400/27	9	3	97.73	96.26	25.92	24.26	0.48	0.49	0.25	0.4
23	6000/30	9	3	416.42	413.48	26.02	24.99	0.46	0.55	0.25	0.4
24	5400/27	9	3	119.07	117.71	38.01	36.64	0.49	0.49	0.25	0.4
25	6000/30	9	3	535.95	530.91	28.56	27.53	0.49	0.49	0.25	0.4
26	5400/27	9	3	491.61	489.04	22.63	21.74	0.45	0.49	0.5	0.4
27	5400/27	9	3	11.29	11	22.9	22.62	0.42	0.49	0.13	0.4
28	6000/30	9	3	573.53	563.53	30.04	27.94	0.46	0.49	0.25	0.4
29	4500/25	9	3	205.28	203.64	32.18	31.51	0.45	0.49	0.25	0.4
30	1600/1	9	3	11.14	10.06	19.5	19.46	0.49	0.49	0.25	0.4

I. CT based with full density plan was created by using 6MV in IMRT technique and numbers of beams are shown in table 3.5.

J. CT and MRI based with water equivalent plan were created by assigning whole volume with CT number =0 and planning with the same parameter as CT full density plan such as prescription dose, dose constraint, beam energy and number of beams using copy and paste plan command and re-calculate the dose.

K. MRI based with bulk density method using average individual CT number for PTV, bone, air and remaining tissues were assigned with water equivalent and planning with the same parameter as CT full density plan using copy and paste plan command and re-calculate the dose.

L. MRI based with bulk density method using average mean CT number for PTV, bone, air and remaining tissues were assigned with water equivalent and planning with the same parameter as CT full density plan using copy and paste plan command and re-calculate the dose.

M. MRI based with bulk density method using recommendation of electron density from ICRU number 46 converted to CT number is shown in table 3.4 for PTV, bone, air and the remaining tissues were assigned with water equivalent. The planning was performed with the same parameter as CT full density plan using copy and paste plan command and re-calculate the dose.

N. Percent dose differences from CT full density plan (ref.) were determined by

$$\left[\left(\frac{\text{dose(test)} - \text{dose(ref.)}}{\text{dose(ref.)}}\right)\right] * 100$$

O. Percent dose differences were compared using DVH at $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ of PTV and D_{1cc} of brain stem.

P. VMAT technique plan was also created using the same IMRT parameters of identical structures, bulk density values, prescription dose and optimization parameter etc.

3.8 Outcome Measurement

3.8.1 Geometrical distortion of phantom and patients images in co-planar and non co-planar of MRI.

3.8.2 Registration error in Eclipse treatment planning process.

3.8.3 The maximum of mean and mean dose difference between the CT full density and water equivalent plan together with the CT full density and bulk density plan in both of IMRT and VMAT.

3.8.4 The maximum of mean and mean dose difference from the CT full density between average individual bulk density, average mean bulk density and ICRU bulk density in both of IMRT and VMAT.

3.9 Data Collection

After study the image distortion in MRI and registration between CT and MRI, the dose difference between CT full density, water equivalent plan, the CT full density and bulk density plan were evaluated in both of IMRT and VMAT. The dose difference from CT full density plan in term of $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ of PTV and D_{1cc} of brain stem were recorded.

3.10 Data Analysis

The percent dose difference from CT full density plan was employed for evaluation of the dosimetric accuracy of all plans.

3.11 Benefit of the Study

3.11.1 Geometrical distortion in MRI was evaluated so that the image could be used in the clinical.

3.11.2 Image registration process in Eclipse treatment planning was evaluated to assure the accuracy to use in the clinical work.

3.11.3 The MRI with bulk density plans (CT number from average individual, average mean and ICRU) in head region were evaluated for using in the clinical work.

3.12 Ethical Consideration

Although this study used only planning from patient not directly operated to the patient, however, the proposal was approved by the Ethics Committee of Faculty of Medicine, Chulalongkorn University.

CHAPTER IV
RESULTS

4.1 Geometrical distortion evaluation data

4.1.1 Phantom study data

The average measured distance from 2 observers, four directions were compared with the actual distance (from manual). The differences between measured and actual distance are shown in table 4.1, 4.2, 4.3 and 4.4 for 2 cm, 4 cm, 8 cm and 10 cm, respectively. The average difference between measured and actual distance were 0.1, 0.3, 0.4 and 0.5 mm for 2, 4, 8 and 10 cm FOV, respectively. At the short distance from coordinate point, the average difference distance was small which mean that the geometrical distortion reduces when distance from coordinate point decrease.

Table 4.1 The difference between measured and actual distance of 2 cm in 4 directions.

Direction	Actual (cm)	Meas.No. 1 (cm)	Meas.No. 2 (cm)	Average measure (cm)	Difference (cm)	Ave. diff. (cm)
Front	2.00	2.02	2.04	2.03	0.03	0.01
Right		2.00	2.00	2.00	0	
Back		2.00	2.02	2.01	0.01	
Left		2.00	2.00	2.00	0	

Table 4.2 The difference between measured and actual distance of 4 cm in 4 directions.

Direction	Actual (cm)	Meas.No. 1 (cm)	Meas.No. 2 (cm)	Average measure (cm)	Difference (cm)	Ave. diff. (cm)
Front	4.00	4.02	4.04	4.03	0.03	0.03
Right		4.01	4.02	4.02	0.02	
Back		4.03	4.04	4.04	0.04	
Left		4.01	4.01	4.01	0.01	

Table 4.3 The difference between measured and actual distance of 8 cm in 4 directions.

Direction	Actual (cm)	Meas.No. 1 (cm)	Meas.No. 2 (cm)	Average measure (cm)	Difference (cm)	Ave. diff. (cm)
Front	8.00	8.07	8.03	8.05	0.05	0.04
Right		8.01	8.01	8.01	0.01	
Back		8.05	8.06	8.06	0.06	
Left		8.03	8.03	8.03	0.03	

Table 4.4 The difference between measured and actual distance of 10 cm (edge of phantom) in 4 directions.

Direction	Actual (cm)	Meas.No. 1 (cm)	Meas.No. 2 (cm)	Average measure (cm)	Difference (cm)	Ave. diff. (cm)
Front	10.00	9.94	9.93	9.94	-0.06	0.05
Right		9.99	9.97	9.98	-0.02	
Back		9.96	9.95	9.96	-0.04	
Left		9.94	9.94	9.94	-0.06	

4.1.2 Patient study

Geometrical distortion of MRI in patient image was evaluated by the calculation of SSD in Eclipse treatment planning. Three patient image set were evaluated by the eight directions for co-planar (line number 1-8) and 4 directions for non co-planar (line number 9-13). The difference of SSD between CT and MRI are shown in table 4.5, 4.6 and 4.7 for patient image set number 1, 2 and 3, respectively. The results showed that the difference of SSD for all patients was not more than 2 mm in both co-planar and non co-planar.

Table 4.5 The comparison of SSD in 13 directions between CT and MRI for patient image set number 1.

Line no.	Gantry/Couch position	CT (cm)	MRI (cm)	Diff. (cm)
1	G0/C0	91.1	91	0.1
2	G45/C0	89.1	89.1	0
3	G90/C0	89.5	89.5	0
4	G135/C0	89.6	89.7	-0.1
5	G180/C0	92.3	92.3	0
6	G225/C0	94.1	94.2	-0.1
7	G270/C0	94.9	94.9	0
8	G315/C0	94.6	94.6	0
9	G180/C270	92.3	92.3	0
10	G225/C270	91.4	91.4	0
11	G270/C270	93.1	93.2	-0.1
12	G315/C270	92.4	92.4	0
13	G0/C270	91.1	91	0.1

Table 4.6 The comparison of SSD in 13 directions between CT and MRI for patient image set number 2.

Line no.	Gantry/Couch position	CT (cm)	MRI (cm)	Diff. (cm)
1	G0/C0	91.8	92	-0.2
2	G45/C0	95.7	95.8	-0.1
3	G90/C0	96.5	96.5	0
4	G135/C0	95.4	95.3	0.1
5	G180/C0	92	91.8	0.2
6	G225/C0	88.9	88.8	0.1
7	G270/C0	88.6	88.7	-0.1
8	G315/C0	88.8	88.9	-0.1
9	G180/C270	92	91.8	0.2
10	G225/C270	91.6	91.4	0.2
11	G270/C270	92.9	92.9	0
12	G315/C270	92.6	92.8	-0.2
13	G0/C270	91.8	92	-0.2

Table 4.7 The comparison of SSD in 13 directions between CT and MRI for patient image set number 3.

Line no.	Gantry/Couch position	CT (cm)	MRI (cm)	Diff. (cm)
1	G0/C0	90.7	90.7	0
2	G45/C0	94.4	94.5	-0.1
3	G90/C0	95	95	0
4	G135/C0	93.8	93.7	0.1
5	G180/C0	90.3	90.2	0.1
6	G225/C0	88.5	88.5	0
7	G270/C0	88.5	88.6	-0.1
8	G315/C0	88.7	88.7	0
9	G180/C270	90.3	90.2	0.1
10	G225/C270	91.7	91.7	0
11	G270/C270	93	93.1	-0.1
12	G315/C270	92.4	92.4	0
13	G0/C270	90.7	90.7	0

4.2 Registration evaluation data

Image registration between CT and MRI was evaluated by ImsimQA program. CT image (as a reference), T1 weighted and T2 weighted image of MRI in head region were created by ImsimQA program, and then the MRI images were translated in 3 axes for 4 set as shown in table 4.8. The new translate images, which created by ImsimQA program, were registered with Eclipse treatment planning. Registration error was evaluated by comparing translate values from ImsimQA program and registration values from RTP. The results showed the registration error within 1 mm in both T1 weighted and T2 weighted image.

Table 4.8 The comparison of registration error between translate values from ImsimQA program and registration values from RTP of T1 weighted and T2 weighted image in 4 set.

Set	axis	ImsimQA		RTP		Registration error	
		T1(mm)	T2(mm)	T1(mm)	T2(mm)	T1(mm)	T2(mm)
1	X	5	5	4.94	4.76	-0.06	-0.24
	Y	0	0	0.19	0.11	0.19	0.11
	Z	0	0	0.06	0.08	0.06	0.08
2	X	0	0	0.16	0.18	0.16	0.18
	Y	5	5	4.98	5.13	0.02	0.13
	Z	0	0	0	0.09	0	0.09
3	X	0	0	0.16	0.16	0.16	0.16
	Y	0	0	0.14	0.12	0.14	0.12
	Z	5	5	5.12	5.99	0.12	0.99
4	X	5	5	4.82	4.85	0.18	-0.15
	Y	-5	-5	-4.98	-4.85	0.02	0.15
	Z	5	5	5.97	4.90	0.97	-0.10

4.3 Planning evaluation data

The aim of this study was to analyze 30 cases of patient but the case number 8* and number 29* were excluded due to large percent dose difference in all options of planning. So the analyze data was included only 28 cases.

The dose difference of water equivalent plan of both CT and MRI together with 3 types of MRI based treatment planning in IMRT plan with bulk density (average individual, average mean and ICRU) plans compared with CT full density plan were evaluated by the dose-volume specific of $D_{98\%}$, $D_{95\%}$, $D_{50\%}$ and $D_{2\%}$ of PTV and D_{1cc} of brain stem, they were shown in table 4.9-4.13 for IMRT plan and 4.14-4.18 for VMAT plan, respectively.

The agreement of image characteristic between CT and MR images were investigated by comparing the percent dose differences in $D_{98\%}$, $D_{95\%}$, $D_{50\%}$ and $D_{2\%}$ of PTV and D_{1cc} of brain stem from CT full density of CT and MRI water equivalent plan. The result showed the percent dose difference within 1.68% and 8.25% for average and maximum dose difference, respectively in all dose-volume specifications between CT and MRI water equivalent plan for IMRT and VMAT. The comparison of dose differences in $D_{98\%}$, $D_{95\%}$, $D_{50\%}$ and $D_{2\%}$ of PTV and D_{1cc} of brain stem from CT full density plan between CT and MRI with water equivalent plan which are shown in figure 4.1-4.5 for IMRT plan and 4.6-4.10 for VMAT plan, respectively, revealed mostly comparable between CT and MRI water equivalent. However, the large dose differences for both CT and MRI water equivalent plan were observed in case number 8 for only MRI water equivalent plan in case number 29 for D_{1cc} of brain stem, while the CT water equivalent plan was close to CT full density plan. These 2 cases were deleted from the analyzed data.

The $D_{95\%}$ of PTV which was the prescribed dose was selected to compare the dose difference of using bulk density in MRI planning with the CT full density plan, the mean dose differences between average individual MRI bulk density plan and CT full density plan were 0.27±0.58%, 0.22±0.51% and the maximum dose differences were within 1.46%, 1.54% for IMRT and VMAT plan, respectively. The mean dose differences between mean MRI bulk density plan and CT full density plan were 0.27±0.52%, 0.22±0.47% and the maximum dose differences were within 1.38%, 1.28% in IMRT and VMAT plan, respectively. The mean dose differences between MRI with ICRU bulk density plan and CT full density plan were -0.38±0.38%, -0.36±0.33% and the maximum dose differences were within 0.93%, 0.92% in IMRT and VMAT, respectively. The mean dose differences between mean MRI water equivalent plan and CT full density plan were 1.68±1.16%, 1.53±0.99% and the maximum dose differences were within 3.83%, 3.38% in IMRT and VMAT plan, respectively.

Table 4.9 The percent dose difference in $D_{98\%}$ for all plans and 30 patients in IMRT.

Pt. no	CT_W	MR_W	MR bulk		
			Individual	Mean	ICRU
1	-1.55	1.19	0.13	-0.39	-0.94
2	1.06	-0.81	-0.34	0.05	-0.65
3	2.87	2.98	0.70	0.31	-0.72
4	3.21	3.06	0.59	0.93	-0.30
5	2.94	1.93	-1.07	-0.76	-1.52
6	0.25	0.09	-0.10	-0.14	-0.49
7	1.22	0.98	0.08	-0.54	-1.35
8*	11.89	11.40	1.74	2.21	1.23
9	2.01	1.83	-0.14	0.10	-0.58
10	-0.68	-0.07	0.73	0.46	-0.01
11	2.07	2.00	0.15	0.34	-0.63
12	2.20	2.56	0.02	0.22	-0.66
13	3.46	3.77	0.90	0.83	-0.18
14	1.40	1.51	-0.30	-0.17	-0.42
15	0.10	-0.12	-0.16	-0.21	-0.30
16	4.18	4.11	1.04	1.01	0.18
17	1.06	0.74	-0.81	-0.66	-1.10
18	3.81	3.77	0.50	1.08	0.16
19	3.06	2.90	0.91	1.04	-0.05
20	2.67	2.89	0.87	0.16	-0.58
21	1.77	1.92	0.42	0.19	-0.41
22	1.31	1.35	0.66	0.24	-0.58
23	0.31	-0.16	0.26	0.20	-0.26
24	2.16	2.25	-0.30	-0.34	-0.91
25	1.15	1.43	0.47	0.42	-0.24
26	2.48	2.54	-0.09	0.13	-0.66
27	1.22	0.98	-0.08	0.49	-0.19
28	0.88	0.84	-0.25	0.24	-0.41
29*	1.52	1.56	0.49	0.40	-0.18
30	2.08	2.84	1.40	1.27	0.14
Avg.(28)	1.74	1.76	0.22	0.23	-0.49
SD	1.34	1.30	0.57	0.53	0.42

*excluded

Table 4.10 The percent dose difference in $D_{95\%}$ for all plans and 30 patients in IMRT.

Pt. no	CT_W	MR_W	MR bulk		
			Individual	Mean	ICRU
1	-1.03	1.30	0.22	-0.24	-0.79
2	0.99	-0.30	-0.14	0.20	-0.48
3	2.86	2.94	1.46	1.06	0.09
4	1.78	1.61	0.12	0.22	-0.55
5	2.51	2.20	-0.62	-0.19	-0.83
6	-0.09	-0.23	-0.21	-0.28	-0.57
7	1.24	1.13	0.37	-0.10	-0.71
8*	10.16	10.35	2.27	2.77	1.25
9	2.17	2.08	-0.10	0.13	-0.53
10	-0.29	0.02	0.66	0.38	-0.11
11	2.15	2.14	0.19	0.36	-0.57
12	1.73	1.78	-0.18	-0.06	-0.74
13	3.11	3.27	0.87	0.80	-0.07
14	1.38	1.46	-0.27	-0.15	-0.40
15	-0.19	-0.34	-0.20	-0.26	-0.35
16	3.09	3.16	1.04	1.00	0.11
17	1.19	1.05	-0.54	-0.40	-0.89
18	3.81	3.83	0.83	1.38	0.50
19	2.86	2.69	1.26	1.29	0.42
20	2.18	2.97	0.95	0.19	-0.49
21	1.58	1.64	0.15	-0.04	-0.57
22	0.95	0.96	0.40	0.01	-0.70
23	0.05	-0.14	0.32	0.27	-0.19
24	2.45	2.42	-0.31	-0.36	-0.93
25	1.57	1.71	0.38	0.33	-0.33
26	2.23	2.32	-0.04	0.18	-0.52
27	1.30	1.22	-0.18	0.45	-0.28
28	1.17	1.20	-0.11	0.28	-0.40
29*	1.61	1.60	0.47	0.35	-0.37
30	2.12	2.84	1.37	1.24	0.12
Avg.(28)	1.60	1.68	0.27	0.27	-0.38
SD	1.16	1.16	0.58	0.52	0.38

*excluded

Table 4.11 The percent dose difference in $D_{50\%}$ for all plans and 30 patients in IMRT.

Pt. no	CT_W	MR_W	MR bulk		
			Individual	Mean	ICRU
1	-0.07	1.46	0.09	-0.29	-0.67
2	1.78	0.09	0.18	0.44	-0.29
3	1.56	1.65	0.78	0.45	-0.29
4	1.52	1.48	0.37	0.34	-0.22
5	2.43	2.46	-0.03	0.34	-0.20
6	0.14	0.08	-0.08	-0.14	-0.46
7	1.78	1.81	0.61	0.33	-0.31
8*	3.06	2.99	0.04	0.36	-0.68
9	2.27	2.28	0.29	0.47	-0.07
10	-0.08	0.12	0.67	0.36	-0.17
11	2.04	2.07	-0.12	0.06	-0.69
12	1.83	1.88	-0.20	-0.14	-0.76
13	1.88	1.88	-0.05	-0.09	-0.79
14	1.59	1.56	-0.23	-0.11	-0.28
15	0.31	0.48	0.17	0.14	0.05
16	1.47	1.39	0.15	0.07	-0.68
17	1.63	1.59	0.15	0.26	-0.35
18	2.77	2.78	0.25	0.75	-0.08
19	1.16	1.09	-0.10	-0.19	-0.71
20	1.48	2.20	0.49	-0.13	-0.61
21	1.51	1.52	-0.02	-0.21	-0.59
22	1.49	1.42	0.49	0.11	-0.63
23	1.28	1.13	0.16	0.09	-0.44
24	2.52	2.37	-0.27	-0.32	-0.89
25	2.16	2.18	0.41	0.35	-0.29
26	1.93	1.90	0.01	0.14	-0.31
27	1.51	1.45	-0.32	0.23	-0.54
28	2.02	2.04	0.20	0.41	-0.14
29*	1.84	1.90	0.41	0.25	-0.37
30	2.34	2.40	0.83	0.72	-0.46
Avg.(28)	1.58	1.60	0.17	0.16	-0.42
SD	0.74	0.72	0.32	0.29	0.25

*excluded

Table 4.12 The percent dose difference in $D_{2\%}$ for all plans and 30 patients in IMRT.

Pt. no	CT_W	MR_W	MR bulk		
			Individual	Mean	ICRU
1	0.00	1.43	0.12	-0.17	-0.51
2	1.84	-0.16	-0.08	0.17	-0.43
3	1.62	1.67	0.76	0.54	-0.13
4	0.95	1.07	0.61	0.53	0.15
5	2.83	2.71	-0.07	0.27	-0.06
6	0.68	0.73	0.19	0.13	-0.20
7	1.87	1.91	0.57	0.40	-0.38
8*	3.03	3.01	0.28	0.45	-0.54
9	2.22	2.54	0.18	0.34	-0.03
10	0.22	0.46	0.99	0.74	0.25
11	2.88	2.79	0.01	0.16	-0.62
12	1.82	1.91	0.25	0.30	-0.51
13	1.65	1.79	0.06	-0.01	-0.66
14	1.33	1.37	-0.12	-0.06	-0.23
15	0.78	1.52	0.79	0.77	0.46
16	1.72	1.63	0.33	0.27	-0.53
17	1.42	1.53	0.25	0.33	-0.13
18	2.79	2.89	0.27	0.68	-0.04
19	1.61	1.63	0.39	0.35	-0.49
20	1.96	2.97	0.53	0.07	-0.42
21	1.21	1.21	-0.02	-0.13	-0.39
22	1.83	1.82	0.62	0.21	-0.55
23	1.22	1.26	0.40	0.36	-0.06
24	2.43	2.27	0.01	-0.02	-0.62
25	1.85	1.86	0.31	0.25	-0.21
26	1.68	2.21	0.14	0.14	-0.11
27	0.36	0.34	-1.06	-0.59	-1.15
28	1.94	2.08	0.12	0.36	-0.06
29*	1.59	1.78	0.27	0.15	-0.28
30	2.66	2.64	0.84	0.73	-0.39
Avg.(28)	1.62	1.72	0.26	0.25	-0.29
SD	0.76	0.78	0.40	0.30	0.33

*excluded

Table 4.13 The percent dose difference in D_{1cc} for all plans and 30 patients in IMRT.

Pt. no	CT_W	MR_W	MR bulk		
			Individual	Mean	ICRU
1	-0.16	4.77	3.60	3.22	2.56
2	2.30	0.13	0.26	0.47	-0.32
3	1.47	1.23	0.52	0.13	-0.42
4	1.21	1.47	0.61	0.55	0.13
5	2.38	3.11	0.85	1.32	0.36
6	0.61	0.57	0.38	0.29	0.03
7	1.69	1.49	0.48	0.15	-0.44
8*	0.85	-2.03	-2.29	-2.20	-2.68
9	1.80	6.16	4.40	4.58	3.78
10	0.58	-0.19	-0.07	-0.49	-0.77
11	2.62	2.64	-4.53	0.27	-0.53
12	2.12	2.72	0.68	0.70	-0.01
13	2.12	2.41	0.30	0.27	-4.54
14	1.20	0.46	-1.03	-0.92	-1.14
15	1.20	1.41	0.50	0.43	0.10
16	1.66	3.04	1.82	1.77	0.96
17	0.47	5.54	5.74	5.87	5.31
18	2.53	1.75	-0.67	-0.21	-0.93
19	1.59	1.37	0.07	0.03	-0.70
20	2.50	-0.31	-1.98	-2.81	-3.33
21	0.73	-8.25	-8.66	-8.73	-9.36
22	1.70	1.56	0.69	0.36	-0.34
23	1.14	-1.15	-2.05	-2.15	-2.81
24	2.66	2.43	-0.13	-0.16	-0.84
25	2.09	-0.17	-1.53	-1.59	-2.47
26	1.63	-1.83	-2.99	-2.79	-3.21
27	1.98	1.05	-1.32	-0.77	-1.41
28	1.69	0.29	-1.17	-0.92	-1.62
29*	-0.10	-22.90	-21.77	-21.45	-21.87
30	2.56	0.43	-0.40	-0.48	-2.97
Avg.(28)	1.65	1.22	-0.20	-0.06	-0.89
SD	1.74	2.62	2.65	2.54	2.65

*excluded

Table 4.14 The percent dose difference in $D_{98\%}$ for all plans and 30 patients in VMAT.

Pt. no	CT_W	MR_W	MR bulk		
			Individual	Mean	ICRU
1	-0.82	1.01	0.13	-0.29	-0.74
2	1.26	-0.87	-0.42	-0.13	-0.63
3	3.27	3.39	0.85	0.62	-0.66
4	3.68	3.58	0.95	1.28	0.02
5	2.44	1.49	-1.15	-0.90	-1.57
6	0.61	0.68	0.44	0.42	0.13
7	1.05	1.07	0.13	-0.27	-1.02
8*	13.42	13.83	2.13	2.53	1.25
9	1.96	1.49	-0.33	-0.10	-0.70
10	-0.71	-0.56	0.13	-0.16	-0.66
11	1.31	1.26	-0.21	-0.08	-0.63
12	2.70	2.93	0.13	0.32	-0.53
13	3.70	3.83	0.83	0.77	-0.16
14	0.98	0.92	-0.43	-0.33	-0.60
15	0.86	0.58	0.02	-0.03	-0.25
16	3.14	3.06	0.71	0.73	-0.10
17	0.91	0.64	-0.36	-0.27	-0.59
18	3.37	3.50	0.40	0.92	0.06
19	2.79	2.76	1.12	1.23	0.21
20	2.19	1.02	-0.36	-0.74	-1.09
21	1.58	1.76	0.44	0.26	-0.41
22	1.92	1.82	0.49	0.10	-0.65
23	0.88	0.02	-0.08	-0.12	-0.42
24	2.58	2.34	-0.41	-0.46	-1.04
25	1.48	1.54	0.54	0.48	-0.14
26	1.38	1.22	-0.39	-0.26	-0.71
27	1.81	1.89	-0.15	0.38	-0.29
28	0.97	1.04	0.11	0.40	-0.22
29*	1.37	1.31	0.39	0.27	-0.17
30	2.39	2.95	1.28	1.16	0.16
Avg.(28)	1.77	1.66	0.16	0.18	-0.47
SD	1.17	1.24	0.57	0.57	0.42

*excluded

Table 4.15 The percent dose difference in $D_{95\%}$ for all plans and 30 patients in VMAT.

Pt. no	CT_W	MR_W	MR bulk		
			Individual	Mean	ICRU
1	-0.69	1.11	0.19	-0.21	-0.65
2	1.23	-0.37	-0.19	0.08	-0.38
3	2.75	2.83	1.54	1.28	0.19
4	2.07	1.98	0.27	0.38	-0.39
5	2.15	1.86	-0.48	-0.15	-0.75
6	0.14	0.14	0.16	0.11	-0.12
7	1.16	1.24	0.38	0.02	-0.61
8*	11.79	12.05	2.57	2.98	1.16
9	2.07	1.94	0.00	0.22	-0.40
10	-0.49	-0.46	0.10	-0.20	-0.70
11	1.31	1.30	-0.21	-0.08	-0.62
12	2.23	2.30	0.06	0.19	-0.53
13	3.04	3.13	0.63	0.57	-0.21
14	1.05	1.05	-0.35	-0.26	-0.51
15	0.71	0.56	0.04	-0.03	-0.35
16	2.18	2.30	0.98	0.97	0.13
17	0.90	0.71	-0.22	-0.12	-0.44
18	3.31	3.38	0.38	0.90	0.04
19	2.05	1.95	1.26	1.27	0.53
20	2.04	1.73	0.24	-0.18	-0.52
21	1.36	1.47	0.26	0.09	-0.46
22	1.22	1.15	0.30	-0.12	-0.72
23	0.69	0.16	0.13	0.08	-0.23
24	2.73	2.56	-0.30	-0.35	-0.92
25	1.43	1.46	0.31	0.26	-0.30
26	1.60	1.44	-0.36	-0.23	-0.62
27	1.81	1.86	-0.26	0.28	-0.38
28	1.16	1.12	0.06	0.32	-0.31
29*	1.67	1.66	0.39	0.22	-0.40
30	2.41	2.85	1.19	1.07	0.04
Avg.(28)	1.56	1.53	0.22	0.22	-0.36
SD	0.96	0.99	0.51	0.47	0.33

*excluded

Table 4.16 The percent dose difference in $D_{50\%}$ for all plans and 30 patients in VMAT.

Pt. no	CT_W	MR_W	MR bulk		
			Individual	Mean	ICRU
1	-0.19	1.48	0.12	-0.28	-0.72
2	1.59	-0.09	-0.04	0.21	-0.28
3	1.27	1.26	1.01	0.67	0.00
4	1.67	1.61	0.30	0.27	-0.30
5	2.37	2.35	-0.15	0.21	-0.31
6	0.22	0.21	0.15	0.10	-0.17
7	1.75	1.69	0.58	0.29	-0.34
8*	3.54	3.53	0.37	0.59	-0.66
9	2.42	2.47	0.27	0.48	-0.14
10	-0.12	-0.16	0.23	-0.08	-0.59
11	1.58	1.55	-0.15	-0.02	-0.54
12	1.95	1.99	0.03	0.11	-0.58
13	1.86	1.86	-0.01	-0.06	-0.77
14	1.53	1.52	-0.22	-0.10	-0.27
15	0.91	0.80	0.06	-0.02	-0.44
16	0.43	0.53	0.02	-0.06	-0.65
17	1.39	1.35	-0.04	0.06	-0.36
18	2.91	2.90	0.37	0.84	0.00
19	0.89	0.83	0.05	-0.04	-0.59
20	1.15	1.56	0.20	-0.23	-0.56
21	1.48	1.49	-0.03	-0.22	-0.60
22	1.25	1.18	0.32	-0.07	-0.65
23	1.08	0.94	-0.06	-0.14	-0.46
24	2.58	2.46	-0.11	-0.15	-0.76
25	2.02	2.03	0.36	0.30	-0.30
26	1.87	1.76	-0.23	-0.09	-0.40
27	1.85	1.72	-0.34	0.20	-0.50
28	1.88	1.87	0.13	0.38	-2.91
29*	1.92	1.98	0.43	0.28	-0.38
30	2.48	2.56	0.93	0.82	-0.29
Avg.(28)	1.50	1.49	0.13	0.12	-0.52
SD	0.78	0.77	0.32	0.30	0.51

*excluded

Table 4.17 The percent dose difference in $D_{2\%}$ for all plans and 30 patients in VMAT.

Pt. no	CT_W	MR_W	MR bulk		
			Individual	Mean	ICRU
1	-0.29	1.39	0.07	-0.33	-0.74
2	1.18	-0.20	-0.16	0.04	-0.32
3	1.40	1.49	1.09	0.69	0.13
4	1.49	1.51	0.52	0.47	-0.02
5	3.49	3.40	-0.02	0.45	0.09
6	0.60	0.51	0.41	0.34	0.05
7	1.27	1.12	-0.20	-0.11	-1.05
8*	3.25	3.20	0.41	0.59	-0.61
9	2.46	2.78	0.15	0.38	-0.09
10	0.34	-0.03	0.58	0.34	-0.10
11	2.60	2.57	-0.08	0.06	-0.42
12	1.77	1.89	0.24	0.28	-0.40
13	1.72	1.74	0.04	0.00	-0.74
14	1.69	1.70	-0.09	-0.01	-0.18
15	1.18	1.08	0.20	0.15	-0.26
16	1.28	1.50	0.31	0.24	-0.49
17	1.40	1.51	0.15	0.24	-0.12
18	2.43	2.39	0.16	0.72	0.15
19	1.39	1.39	0.15	0.09	-0.57
20	0.75	1.32	0.44	0.23	0.01
21	1.64	1.69	0.04	-0.13	-0.48
22	1.53	1.50	0.32	-0.09	-0.65
23	0.83	0.91	0.28	0.24	-0.06
24	2.56	2.54	-0.18	-0.20	-0.79
25	2.01	2.09	0.34	0.28	-0.23
26	2.10	2.40	-0.06	0.05	-0.10
27	0.44	0.40	-0.99	-0.52	-1.16
28	2.55	2.66	0.13	0.44	-0.06
29*	1.30	1.46	0.26	0.16	-0.21
30	2.37	2.44	0.87	0.73	-0.38
Avg.(28)	1.58	1.63	0.17	0.18	-0.32
SD	0.83	0.85	0.38	0.30	0.35

*excluded

Table 4.18 The percent dose difference in D_{1cc} for all plans and 30 patients in VMAT.

Pt. no	CT_W	MR_W	MR bulk		
			Individual	Mean	ICRU
1	-0.38	2.21	2.46	2.07	1.47
2	2.06	-0.84	5.21	-0.43	4.83
3	1.36	1.34	0.85	0.54	-0.13
4	1.79	1.91	0.49	0.44	0.00
5	1.93	1.02	-1.14	-0.72	-1.48
6	0.11	0.15	0.74	0.65	0.48
7	1.51	1.07	0.19	-0.08	-0.64
8*	2.70	1.22	-0.92	-0.73	-1.80
9	1.84	5.24	3.55	3.74	3.01
10	-0.46	-1.16	-0.18	-0.58	-0.87
11	2.94	2.90	-4.04	0.15	-0.55
12	1.91	1.89	0.27	0.35	-0.41
13	1.93	1.84	0.18	0.13	-1.83
14	1.65	1.70	-0.42	-0.22	-0.38
15	0.95	0.76	0.32	0.22	-0.24
16	1.00	1.88	-3.84	0.82	-4.52
17	1.19	3.14	2.27	2.35	1.89
18	2.50	1.38	-0.87	-0.46	-1.30
19	1.21	1.05	0.27	0.21	-0.16
20	0.53	0.76	-1.22	-1.81	-2.21
21	0.69	-4.66	-5.09	-5.17	-5.93
22	1.48	0.75	-0.15	-0.48	-1.05
23	1.33	-0.96	-2.13	-2.13	-2.66
24	2.93	2.76	0.12	0.09	-0.76
25	1.98	1.23	-0.33	-0.39	-1.00
26	1.22	-5.00	-5.77	-5.52	-6.02
27	2.52	1.92	-0.67	-0.21	-0.94
28	1.46	0.35	-0.83	-0.58	-1.37
29*	0.17	-19.70	-19.10	-18.96	-19.46
30	2.04	3.10	2.04	1.90	0.50
Avg.(28)	1.47	0.99	-0.28	-0.18	-0.80
SD	0.85	2.12	2.39	1.88	2.27

*excluded

The graphs shown the dose difference between CT and MRI with water equivalent plan from CT full density plan in IMRT for $D_{98\%}$, $D_{95\%}$, $D_{50\%}$ and $D_{2\%}$ for PTV and D_{1cc} for brain stem are illustrated in figure 4.1-4.5, respectively. The results revealed that the CT and MRI water equivalent plan compared with CT full density plan were mostly the same deviation and the mean percent dose differences between CT and MRI were within 0.5%.

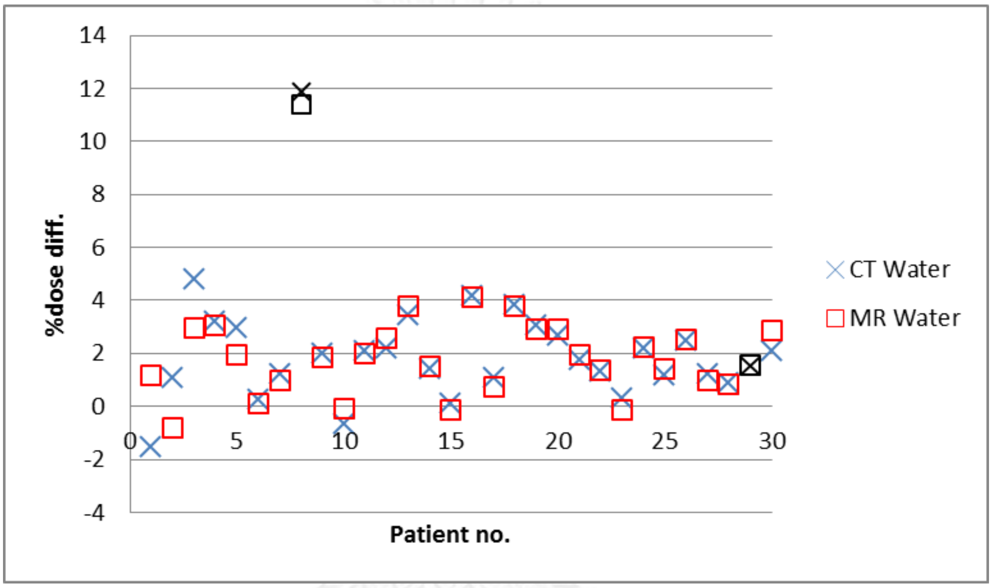

Figure 4.1 The comparison of dose difference in $D_{98\%}$ from CT full density plan between CT and MRI with water equivalent plan for IMRT.

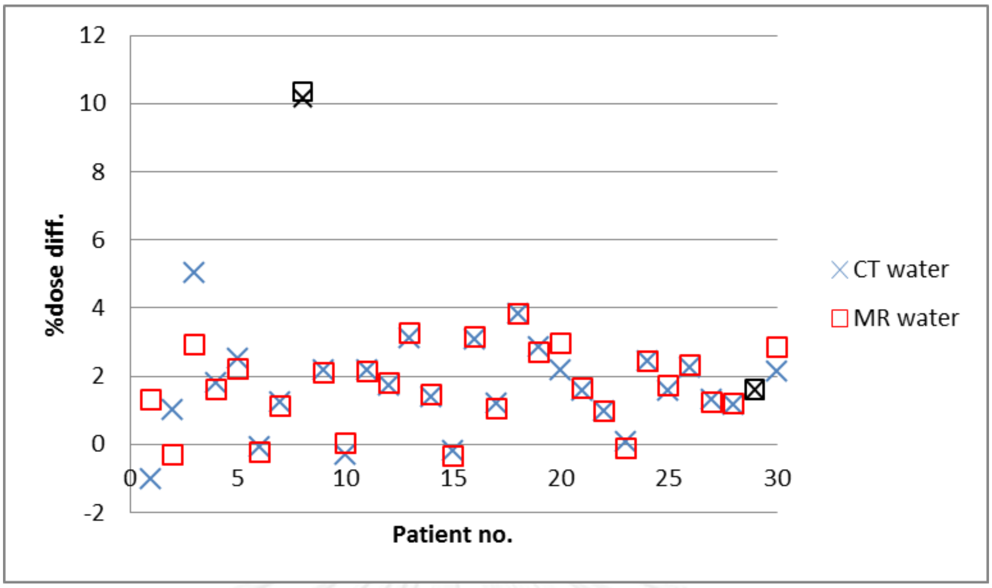

Figure 4.2 The comparison of dose difference in $D_{95\%}$ from CT full density plan between CT and MRI with water equivalent plan for IMRT.

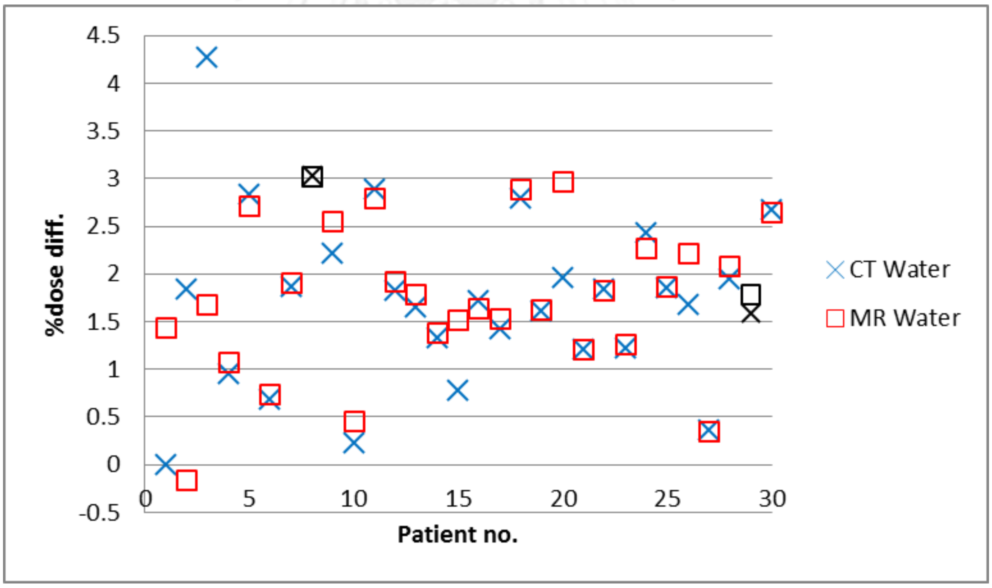

Figure 4.3 The comparison of dose difference in $D_{50\%}$from CT full density planbetween CT and MRI with water equivalent plan for IMRT.

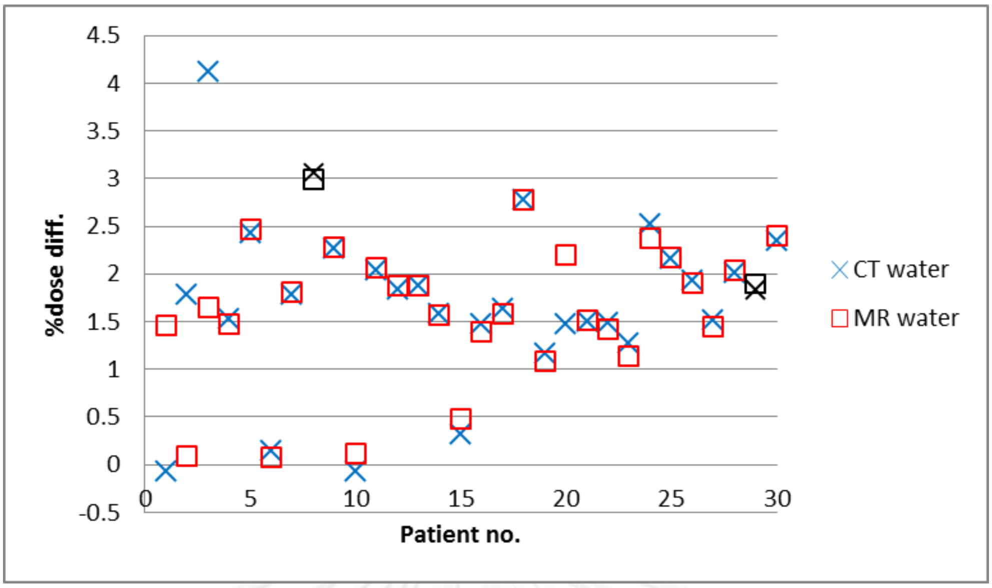

Figure 4.4 The comparison of dose difference in $D_{2\%}$ from CT full density plan between CT and MRI with water equivalent plan for IMRT.

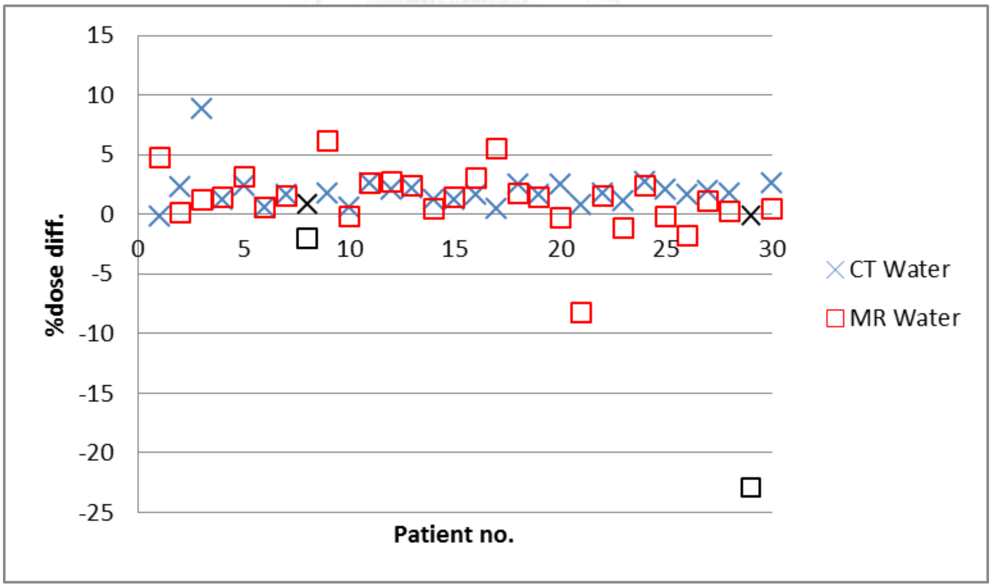

Figure 4.5 The comparison of dose difference in D_{1cc} from CT full density plan between CT and MRI with water equivalent plan for IMRT.

The graph shown the dose differences between CT and MRI with water equivalent plan from CT full density plan in VMAT for $D_{98\%}$, $D_{95\%}$, $D_{50\%}$ and $D_{2\%}$ for PTV and D_{1cc} for brain stem are illustrated in figure 4.6-4.10, respectively. The results were similar to those of IMRT plans. The results revealed that the CT and MRI water equivalent plan compared with CT full density plan were mostly the same deviation and the mean percent dose differences between CT and MRI were within 0.5%.

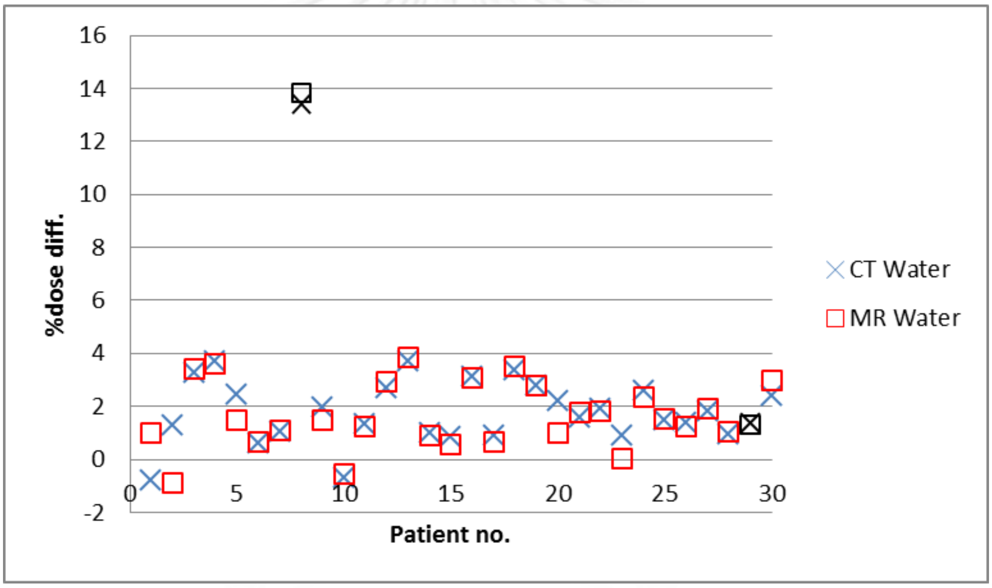

Figure 4.6 The comparison of dose difference in $D_{98\%}$ from CT full density plan between CT and MRI with water equivalent plan for VMAT.

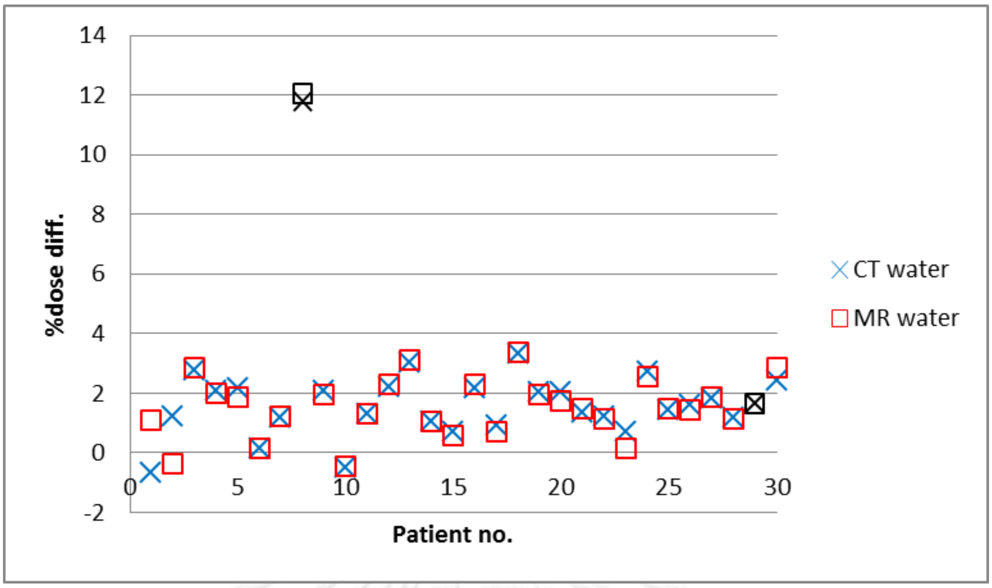

Figure 4.7 The comparison of dose difference in $D_{95\%}$ from CT full density plan between CT and MRI with water equivalent plan for VMAT.

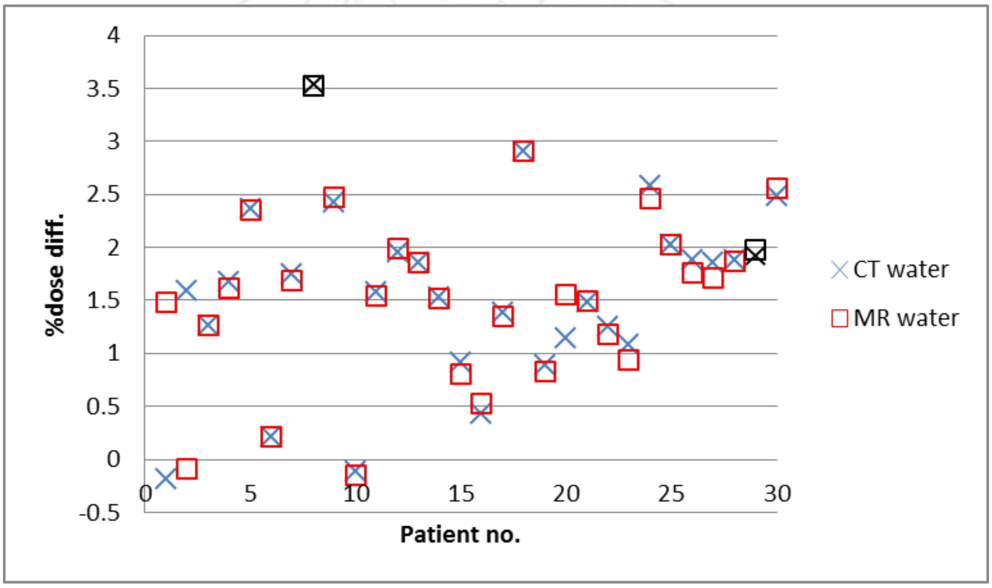

Figure 4.8 The comparison of dose difference in $D_{50\%}$ from CT full density plan between CT and MRI with water equivalent plan for VMAT.

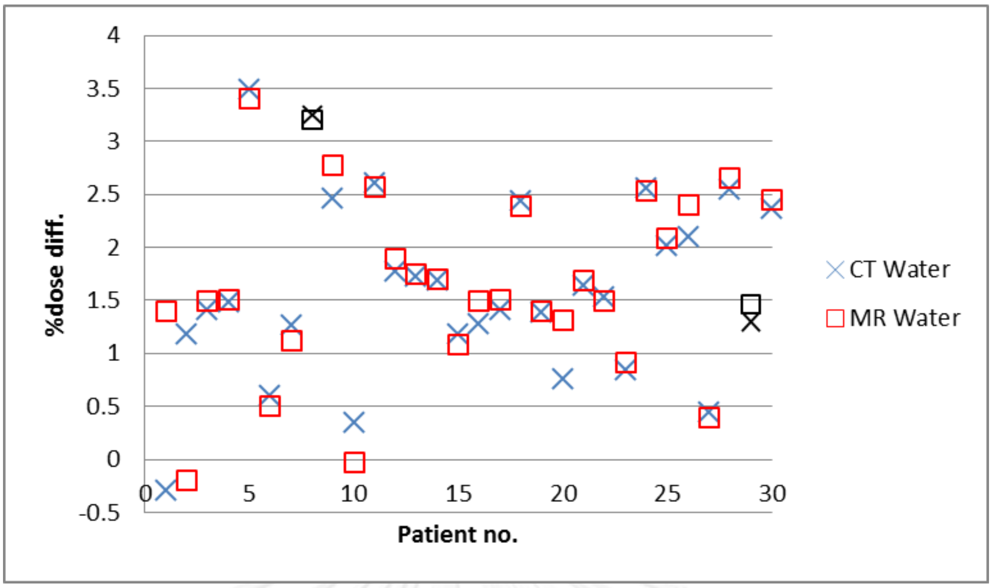

Figure 4.9 The comparison of dose difference in $D_{2\%}$ from CT full density plan between CT and MRI with water equivalent plan for VMAT.

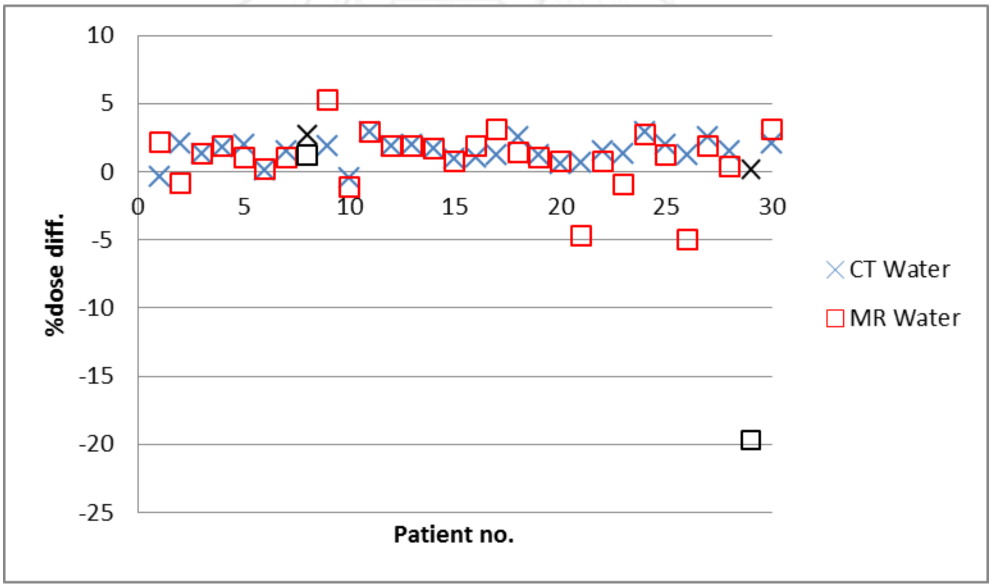

Figure 4.10 The comparison of dose difference in D_{1cc} from CT full density plan between CT and MRI with water equivalent plan for VMAT.

The graph shown the dose difference of MRI based treatment planning between average individual, average mean and ICRU bulk density plan from CT full density plan in IMRT for $D_{98\%}$, $D_{95\%}$, $D_{50\%}$ and $D_{2\%}$ for PTV and D_{1cc} for brain stem are illustrated in figure 4.11-4.15, respectively. The graphs revealed that the dose difference of average individual and average mean bulk density were mostly within 3% for all patients. The dose differences of average mean bulk density were slightly higher than average individual bulk density with the trend of the same deviation (close standard deviation). The ICRU bulk density plan showed the difference in the negative direction which demonstrated that the doses from CT full density plan were larger than the dose from MRI bulk ICRU density plans. The less standard deviation of MR bulk ICRU plans demonstrated the small variation between patients, this made the attraction to some user.

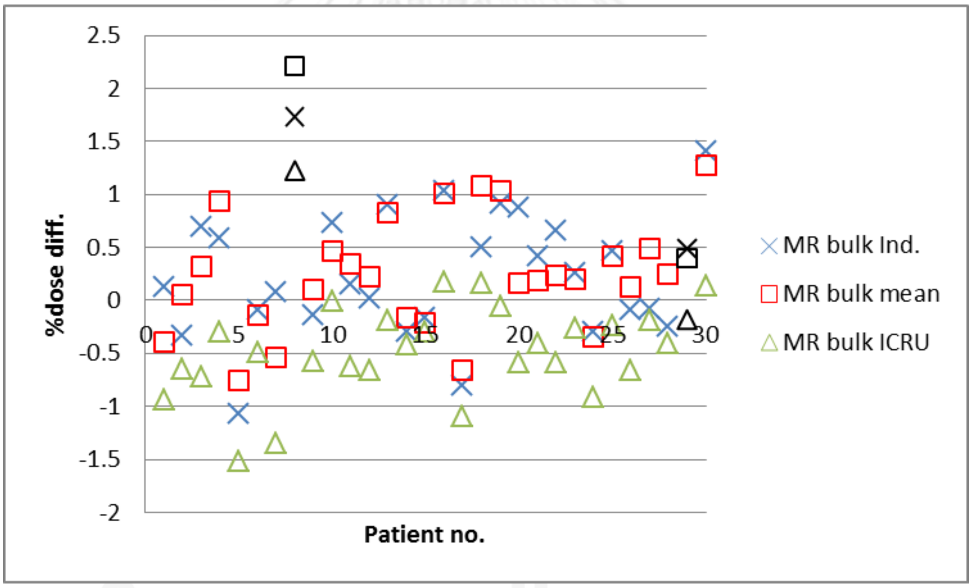

Figure 4.11 The comparison of dose difference in $D_{98\%}$ from CT full density plan between average individual, average mean and ICRU of MRI with bulk density plan for IMRT.

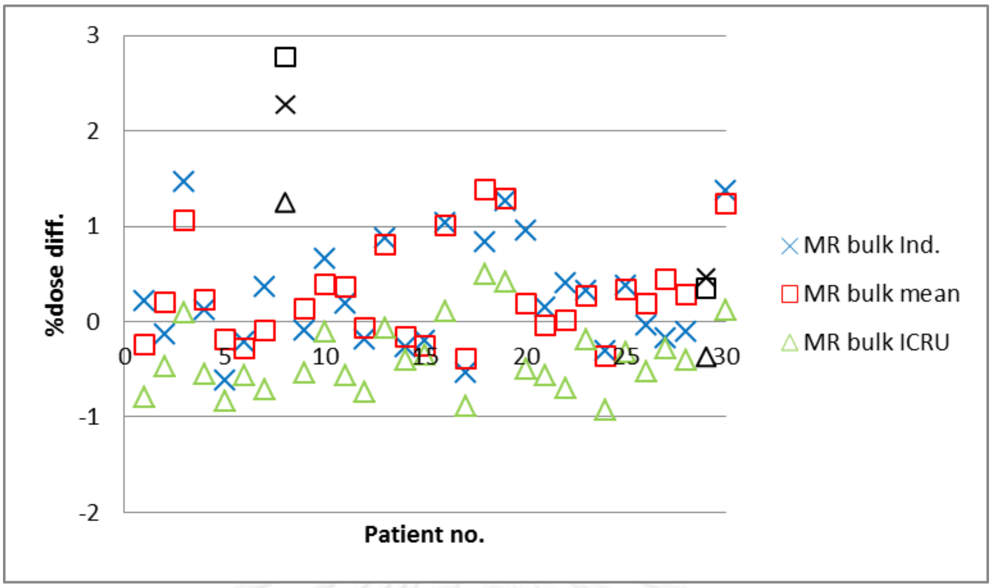

Figure 4.12 The comparison of dose difference in $D_{95\%}$ from CT full density plan between average individual, average mean and ICRU of MRI with bulk density plan for IMRT.

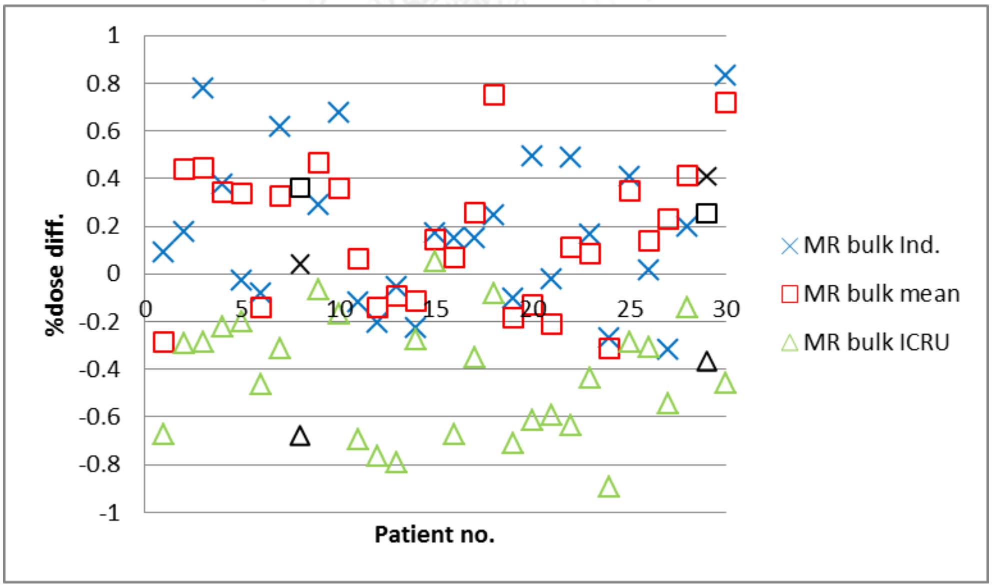

Figure 4.13 The comparison of dose difference in $D_{50\%}$ from CT full density plan between average individual, average mean and ICRU of MRI with bulk density plan for IMRT.

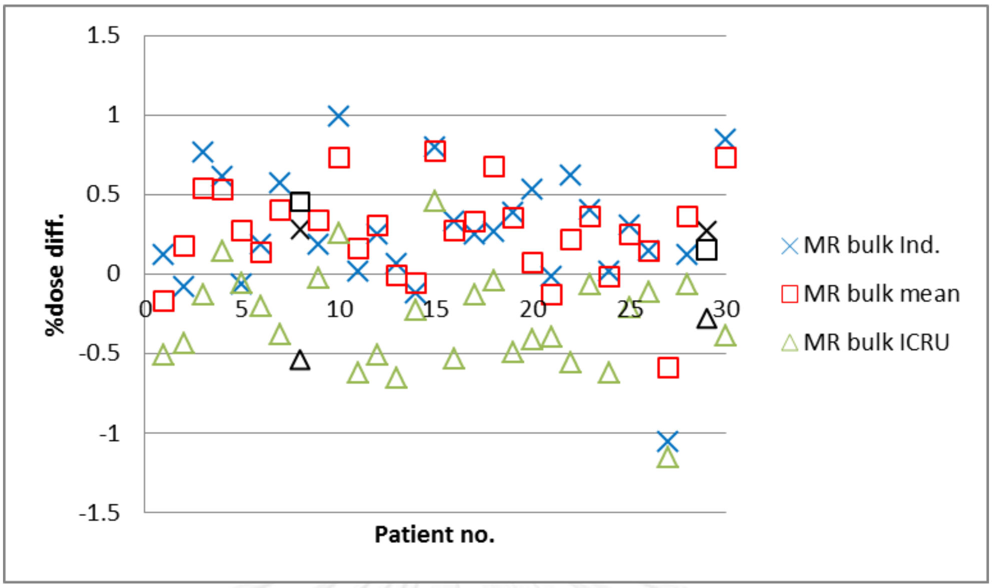

Figure 4.14 The comparison of dose difference in $D_{2\%}$ from CT full density plan between average individual, average mean and ICRU of MRI with bulk density plan for IMRT.

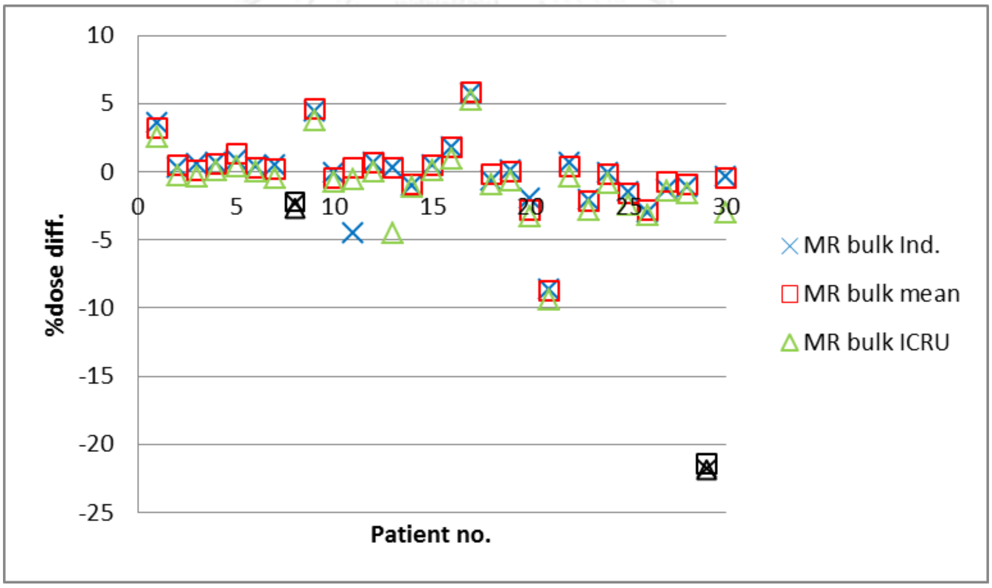

Figure 4.15 The comparison of dose difference in D_{1cc} from CT full density plan between average individual, average mean and ICRU of MRI with bulk density plan for IMRT.

The graph shown the dose differences of MRI based treatment planning between average individual, average mean and ICRU bulk density plan from CT full density plan in VMAT for $D_{98\%}$, $D_{95\%}$, $D_{50\%}$ and $D_{2\%}$ for PTV and D_{1cc} for brain stem are illustrated in figure 4.16-4.20, respectively. The dose differences of average individual and average mean bulk density plan mostly were comparable for all patients, which was the same as IMRT techniques. Most of the dose difference of average mean bulk density plan was slightly higher than average individual bulk density. The graph of ICRU bulk density plan was separated from average individual and average mean bulk density plan which the result demonstrated the same trend as IMRT.

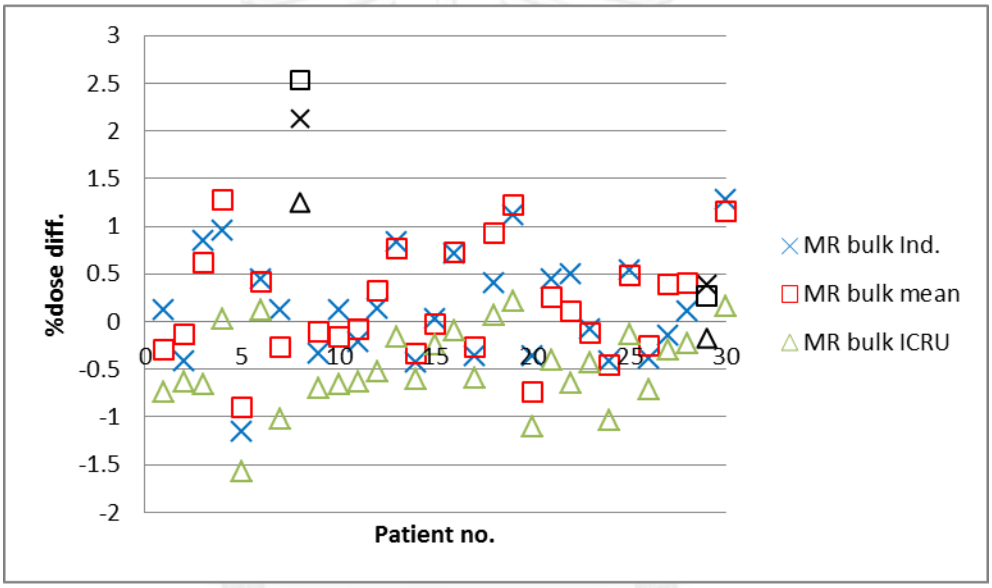

Figure 4.16 The comparison of dose difference in $D_{98\%}$ from CT full density plan between average individual, average mean and ICRU of MRI with bulk density plan for VMAT.

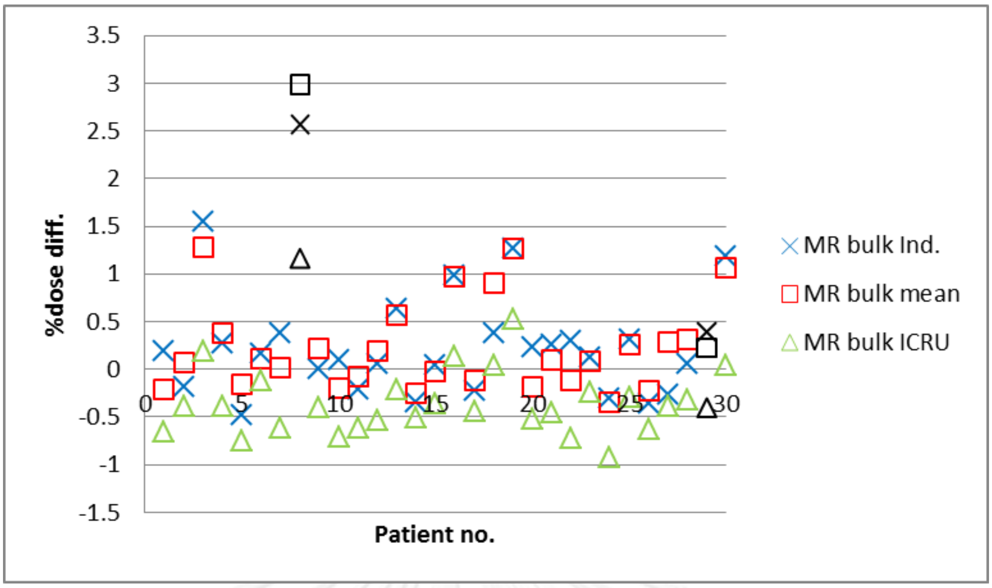

Figure 4.17 The comparison of dose difference in $D_{95\%}$ from CT full density plan between average individual, average mean and ICRU of MRI with bulk density plan for VMAT.

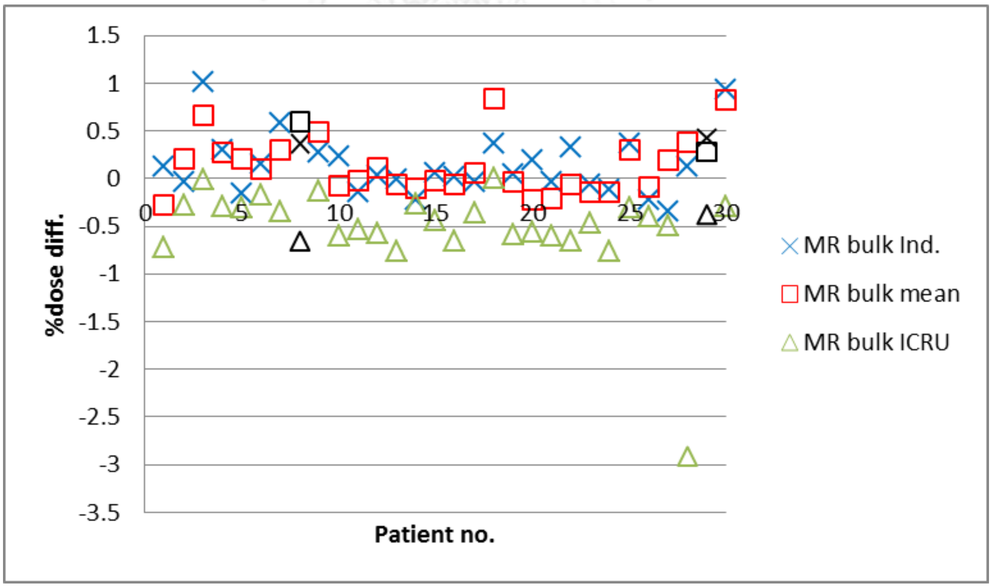

Figure 4.18 The comparison of dose difference in $D_{50\%}$ from CT full density plan between average individual, average mean and ICRU of MRI with bulk density plan for VMAT.

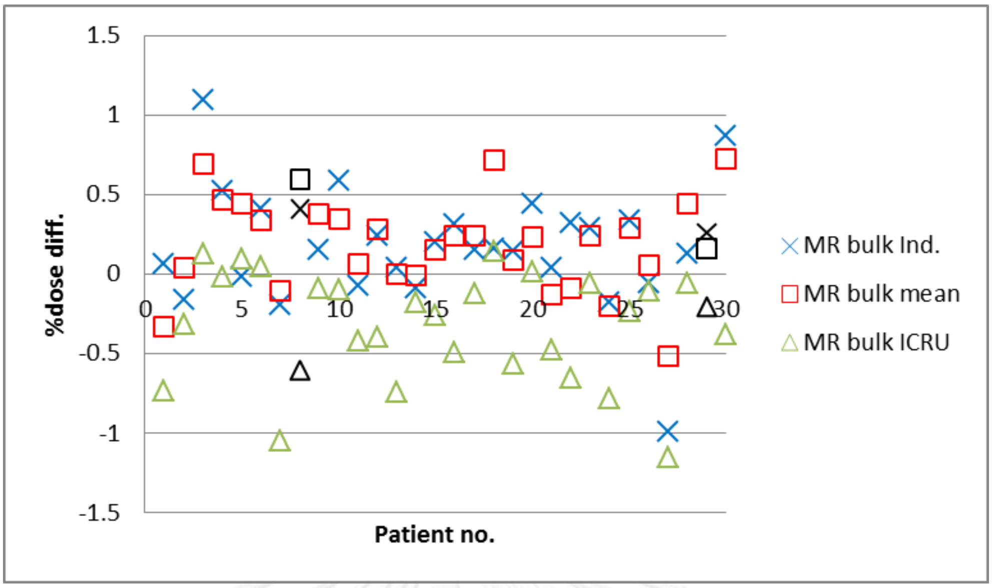

Figure 4.19 The comparison of dose difference in $D_{2\%}$ from CT full density plan between average individual, average mean and ICRU of MRI with bulk density plan for VMAT.

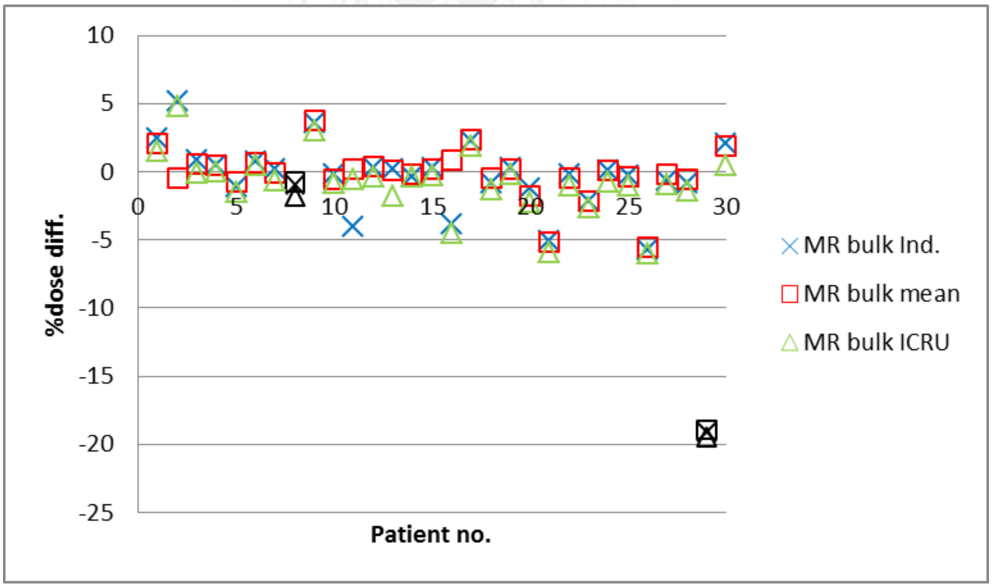

Figure 4. 20 The comparison of dose difference in D_{1cc} from CT full density plan between average individual, average mean and ICRU of MRI with bulk density plan for VMAT.

CHAPTER V

DISCUSSION AND CONCLUSIONS

5.1 Discussion

5.1.1 Geometrical distortion of MRI

The geometrical distortion evaluation of MRI from this study show the distortion effect in MRI of less than 1 mm in 10 cm FOV for phantom study using measuring tool in RTP with 2 observers. Our results are consistent with previous studies. Beavis et al [23] reported maximum distortion errors were within 1 mm for a 10 cm FOV and within 2 mm for a 24 cm FOV. For patient study, both of co-planar and non co-planar are evaluated in clinical condition by using SSD calculation of RTP and the result show that the image distortion is within 2 mm in 16 cm FOV approximation. The requirement for geometrical distortion in RTP is 2 mm so the geometrical distortion of MRI in head region is acceptable. The distortion effect shows in table 4.1-4.4 for the different distance between measured and actual distance of 2 cm, 4 cm, 8 cm and 10 cm, respectively, it increases when increasing FOV, because the non-linearity in the gradient fields are more pronounced at the radial edges of the field. Head region may have less effect from geometrical distortion. The geometrical distortion is more pronounced for the external contours so this will effect in dose calculation of RTP.

5.1.2 Image registration

Most modern treatment planning systems allow the use of one or more dataset for structure delineation and visualization. In order to transfer anatomic outlines and other geometric information from these dataset to the planning CT, the transformation between the two dataset is required. As the explanation in chapter 1, MRI provides superior soft tissue contrast relative to CT and the ability to image directly along arbitrary planes can aid in the visualization and delineation of certain anatomic structures, such as the PTV, optic nerves and chiasm. The accuracy for automatic registration of Eclipse treatment planning is evaluated by using ImsimQA program for creation and translation of virtual image of CT, T1 weightedand T2 weighted image of MRI. The results show the registration error is within 1 mm for all set, they are shown in table 4.8

and the large registration error are in Z-axis of set number 3 in T2 weighted image and Z-axis of set number 4 in T1 weighted image. This large error may attribute to the registration algorithm of treatment planning.

From the comparison of DVH between CT and MR water equivalent plan, the difference in DVH may be caused from many factors such as geometrical distortion, registration error and the difference of pixel size between CT and MR image. The difference in pixel size between CT and MR image result in the difference in structure volumes, it is shown in table 3.5 for PTV and brain stem. This effect also was investigated by L Chen et al [25] who studied MRI based treatment planning in prostate cancer. For structures with a relatively small volume, such differences may have noticeable effect on the DVH comparison between CT and MRI water equivalent plan.

For all 28 patients investigated, the mean of dose differences in $D_{95\%}$ are less than 1.7% between CT and MRI water equivalent plan for IMRT and VMAT. The example of DVH agreement of CT and MRI water equivalent plan is shown in figure 5.1.The image geometry, registration error and voxel size are less affect in our study except the organ that have small volume.

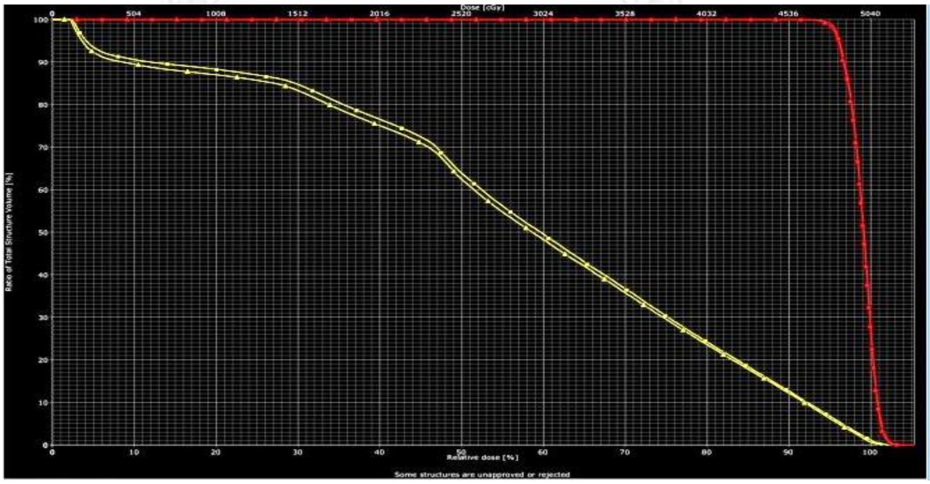

Figure 5.1 The comparison of DVH of PTV (red line) and brain stem (yellow line) of CT water equivalent plan and MRI water equivalent plan.

5.1.3 Planning evaluation

MRI with average individual bulk density plan in RTP is evaluated by comparing with CT full density plan. Figure 5.2 displays an example of isodose distribution on the CT full density and MRI with average individual bulk density plan of the same patient. It can be seen that the isodose distribution of two plans look very similar. The comparison of DVH display only PTV and brain stem are shown in figure 5.3. The two plans have slightly difference in DVH shape. This effect is increased with increase difference in volume size and high dose gradient.

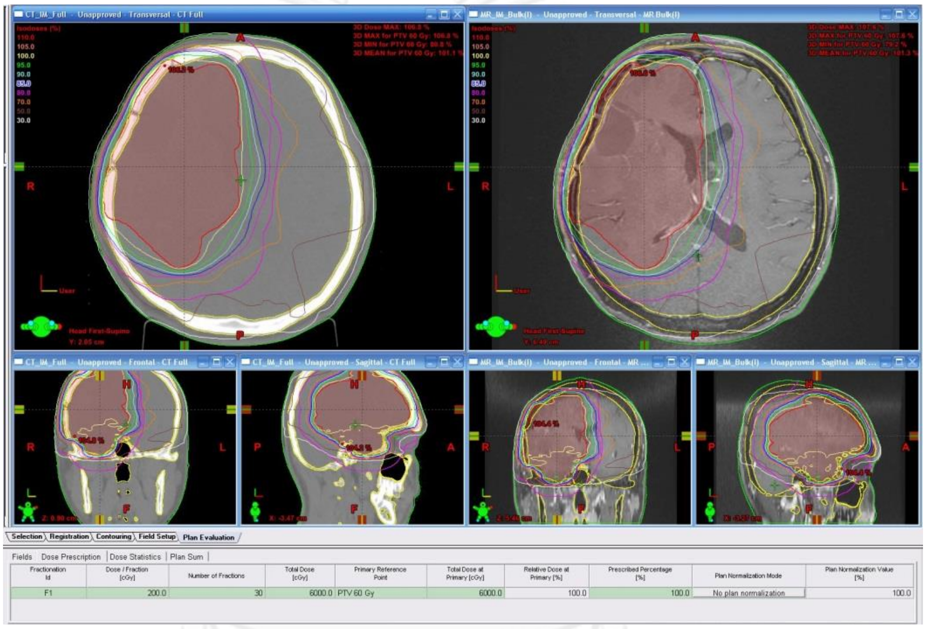

Figure 5.2 The comparison of dose distribution of CT full density plan (left) and MRI with individual bulk density plan (right).

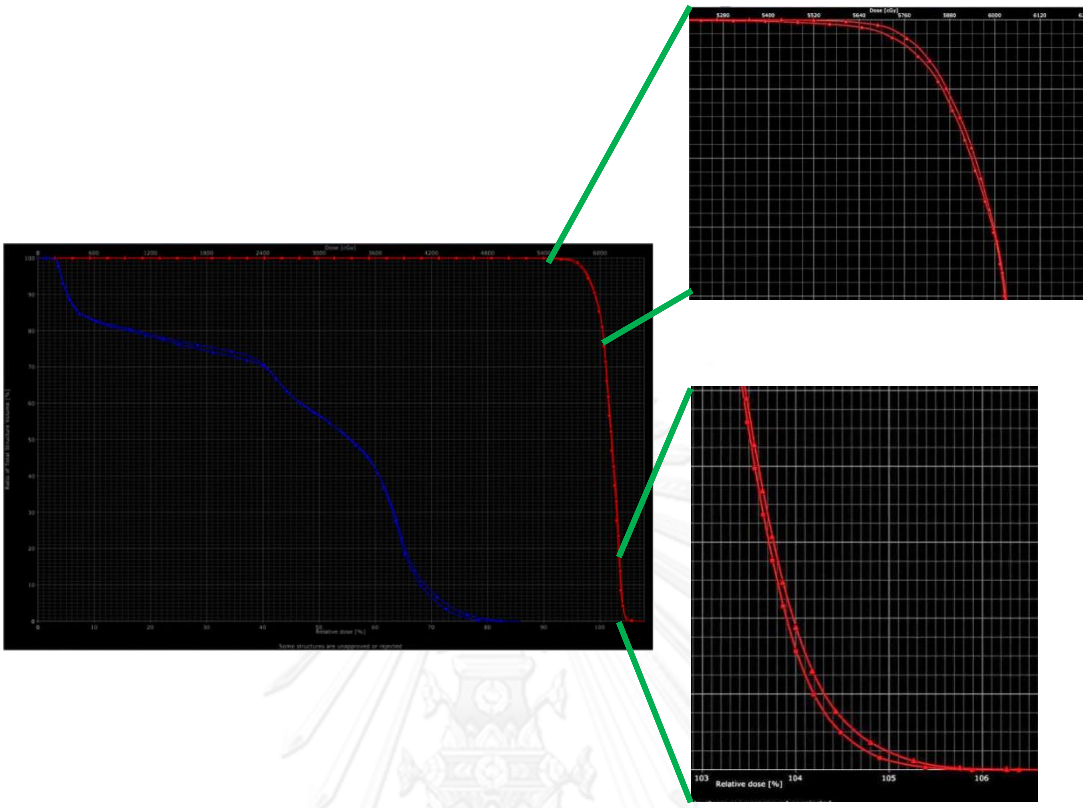

Figure 5.3 The comparison of DVH of PTV (red line) and brain stem (blue line) of CT full density plan and MRI with average individual bulk density plan.

The three types of MRI bulk density plan are observed and the comparison of dose differences in $D_{98\%}$, $D_{95\%}$, $D_{50\%}$ and $D_{2\%}$ for PTV and D_{1cc} for brain stem from CT full density plan between 3 types of bulk density plan is shown in figure 4.11-4.15 for IMRT and 4.16-4.20 for VMAT, respectively. The graphs show that the percent dose difference of MRI with average individual bulk density plan from CT full density plan is approximate close to the MRI with average mean bulk density plan. While the ICRU bulk density plan showed the difference in the negative direction which demonstrated that the doses from CT full density plan were larger than the dose from MRI bulk ICRU density plans. MRI with ICRU bulk density plan has less variation than another. Table 5.1 shows the summary of the percent dose differences in $D_{95\%}$ of PTV for all patients that are less than 2%. The numbers of patient that have dose difference less than 2% of 3 types of bulk density plan are 100% for IMRT and VMAT plan while water equivalent plan are 57.14% and 75% for IMRT and VMAT, respectively. From the results, three types of bulk density plans can be used in RTP with 2% uncertainty while the water equivalent plan may not recommend to use in head region. However, when the PTV has inhomogeneity effect including small size of PTV as case number 8 and very small dose in OAR as case number 29, the deviation from CT full density plan will be excess. These 2 cases are excluded from the analyzed data.

Table 5.1 The number of patient that have dose differences less than 2% from CT full density plan.

Plan	Percent dose difference in $D_{95\%}$ of less than 2% (in 28 patients)	
	IMRT	VMAT
MR bulk density (ave. Ind.)	28(100%)	28(100%)
MR bulk density (ave. mean)	28(100%)	28(100%)
MR bulk density (ICRU)	28(100%)	28(100%)
MR water equivalent	16(57.14%)	21(75%)

The large percent dose difference of PTV in case number 8 due to the PTV is very small and mainly consists of air which is shown in figure 5.4. The deviation occur in both CT and MRI plan but reduce from more than 10% for water equivalent plan to 2% for bulk density plan because of inhomogeneity correction of bulk density method.

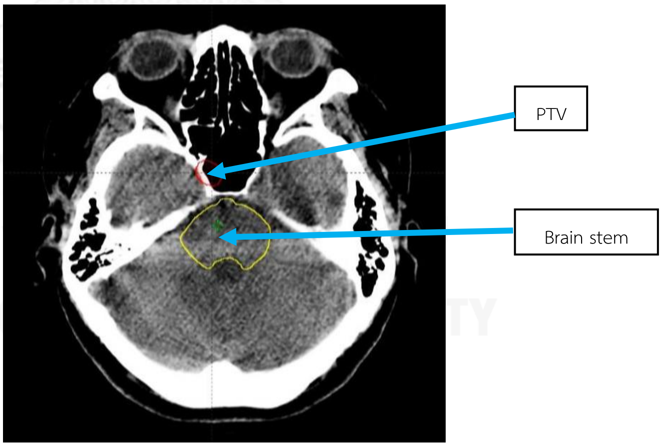

Figure 5.4 CT image of case number 8 in axial view.

The large percent dose difference of case number 29 in brain stem of MRI both water and bulk density plan is mainly caused from low dose area including the mismatch of resolution between CT and MR image. The voxel size of CT is smaller than MRI, they are 0.05 mm^3 and 0.10 mm^3 for CT and MR image, respectively.

5.2 Conclusions

The delineation of tumor and OARs in brain tumor in radiotherapy using MRI is advantage than CT image due to its superior soft tissue contrast. This work evaluates for image geometry of MRI in both of phantom and patient based on radiotherapy procedure. The result of this study shows that the geometrical distortion of MRI in RTP can be accepted with the 2 mm requirement. The comparison of dose difference in $D_{98\%}$, $D_{95\%}$, $D_{50\%}$ and $D_{2\%}$ for PTV and D_{1cc} for brain stem from CT full density plan between CT and MRI water equivalent plan demonstrate indirectly the influence of the geometrical distortion, registration process and voxel size. The maximum of mean dose difference is less than 0.5% in all dose-volume specifications.

The dosimetric accuracy for 3 types of MRI based treatment planning with bulk density method is evaluated in $D_{98\%}$, $D_{95\%}$, $D_{50\%}$ and $D_{2\%}$ for PTV and D_{1cc} for brain stem by comparing with CT full density plan. The results show that the dosimetric accuracy in $D_{95\%}$ of MRI average individual, average mean and ICRU bulk density method is acceptable within 2% for 100% of study cases for average individual, average mean bulk density and ICRU bulk density in both IMRT and VMAT plan. The water equivalent plan shows the dose difference of less than 2% for 57.14% and 75% of study cases in IMRT and VMAT plan, respectively. The bulk density for 3 types of bulk density (average individual, average mean and ICRU) can be used in treatment planning so MRI can be replaced CT image in treatment planning.

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APPENDICE

Appendix A: Percent dose data

1. Average individual bulk density (IMRT)

Pt. no.	PTV (%)																Brain stem (%)			
	$D_{98\%}$				$D_{95\%}$				$D_{50\%}$				$D_{2\%}$				D_{1cc}			
	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W
1	96.34	94.85	96.46	97.49	97.48	96.48	97.69	98.75	100.70	100.62	100.79	102.16	102.53	102.53	102.65	104.00	79.71	79.58	82.58	83.51
2	93.58	94.57	93.27	92.83	94.81	95.75	94.68	94.53	97.65	99.39	97.82	97.74	100.72	102.58	100.64	100.56	42.30	43.27	42.41	42.35
3	90.97	93.58	91.60	93.68	91.61	94.23	92.95	94.30	95.05	96.54	95.79	96.62	98.15	99.74	98.90	99.79	87.37	88.66	87.82	88.44
4	92.80	95.78	93.35	95.64	94.68	96.36	94.79	96.20	96.91	98.39	97.27	98.34	99.66	100.60	100.26	100.72	93.26	94.38	93.83	94.62
5	97.31	100.17	96.28	99.19	98.62	101.09	98.01	100.79	100.88	103.33	100.85	103.36	103.71	106.64	103.63	106.52	83.13	85.11	83.83	85.71
6	94.84	95.07	94.74	94.92	95.60	95.51	95.40	95.38	97.57	97.71	97.49	97.65	99.85	100.53	100.04	100.59	94.14	94.71	94.49	94.68
7	93.73	94.87	93.80	94.65	95.05	96.23	95.40	96.13	98.44	100.19	99.05	100.22	101.71	103.62	102.29	103.65	84.81	86.24	85.22	86.07
8	84.32	94.34	85.78	93.92	86.21	94.96	88.17	95.13	96.75	99.71	96.79	99.65	99.39	102.40	99.67	102.38	53.91	54.37	52.67	52.82
9	97.90	99.87	97.76	99.69	98.73	100.87	98.64	100.79	101.54	103.85	101.84	103.86	103.71	106.01	103.90	106.35	77.60	78.99	81.01	82.38
10	96.79	96.13	97.50	96.72	97.18	96.90	97.82	97.20	99.17	99.10	99.84	99.30	101.58	101.81	102.59	102.05	97.68	98.25	97.61	97.49
11	93.26	95.20	93.40	95.13	93.77	95.79	93.95	95.78	96.49	98.46	96.37	98.48	99.44	102.30	99.45	102.21	96.08	98.59	91.72	98.61
12	92.58	94.62	92.60	94.95	93.88	95.50	93.70	95.55	96.80	98.57	96.60	98.62	100.59	102.42	100.84	102.51	62.22	63.53	62.64	63.91
13	92.08	95.27	92.91	95.55	93.11	96.00	93.92	96.16	97.30	99.13	97.25	99.13	100.04	101.69	100.10	101.83	94.44	96.45	94.72	96.71
14	96.23	97.58	95.94	97.68	99.18	100.55	98.92	100.63	104.75	106.41	104.51	106.39	108.52	109.97	108.39	110.01	105.97	107.24	104.88	106.46
15	97.09	97.19	96.94	96.98	98.86	98.67	98.66	98.52	102.14	102.46	102.31	102.62	105.00	105.82	105.83	106.59	97.11	98.27	97.60	98.48
16	90.33	94.11	91.27	94.05	92.10	94.94	93.05	95.00	96.89	98.31	97.03	98.23	99.46	101.18	99.79	101.08	74.83	76.07	76.19	77.11
17	96.24	97.26	95.46	96.95	97.32	98.48	96.79	98.34	100.30	101.94	100.45	101.89	102.73	104.19	102.98	104.31	66.66	66.98	70.49	70.36
18	92.00	95.51	92.46	95.47	92.93	96.47	93.70	96.49	96.44	99.12	96.68	99.13	98.84	101.60	99.11	101.70	69.63	71.39	69.17	70.85
19	90.97	93.75	91.79	93.61	91.86	94.48	93.02	94.33	96.16	97.27	96.06	97.20	98.63	100.22	99.01	100.24	95.92	97.44	95.99	97.23
20	93.35	95.84	94.16	96.04	94.54	96.60	95.44	97.35	97.85	99.29	98.33	100.00	101.51	103.50	102.05	104.52	41.11	42.14	40.30	40.98
21	96.87	98.58	97.27	98.73	98.23	99.78	98.38	99.84	100.83	102.35	100.80	102.36	103.29	104.54	103.27	104.54	84.25	84.87	76.96	77.30
22	94.29	95.52	94.91	95.56	95.21	96.11	95.59	96.12	97.66	99.11	98.13	99.04	99.95	101.78	100.57	101.77	77.01	78.32	77.54	78.21
23	96.32	96.62	96.57	96.17	97.82	97.87	98.13	97.68	100.81	102.09	100.97	101.95	103.02	104.28	103.44	104.32	72.73	73.56	71.24	71.90
24	94.98	97.03	94.70	97.12	95.52	97.86	95.22	97.84	98.01	100.48	97.75	100.33	100.65	103.09	100.66	102.93	97.87	100.48	97.74	100.25
25	96.34	97.45	96.79	97.72	97.97	99.51	98.34	99.64	100.60	102.77	101.01	102.79	102.90	104.80	103.21	104.82	91.75	93.67	90.34	91.59
26	96.60	98.99	96.51	99.05	98.34	100.54	98.30	100.62	101.12	103.08	101.14	103.04	104.12	105.87	104.27	106.42	46.28	47.03	44.90	45.43
27	95.95	97.12	95.87	96.89	96.70	97.95	96.52	97.88	98.37	99.85	98.05	99.79	101.34	101.71	100.27	101.69	74.22	75.69	73.24	75.00
28	96.78	97.63	96.54	97.59	97.91	99.05	97.81	99.08	101.38	103.42	101.58	103.44	103.92	105.94	104.04	106.08	81.48	82.86	80.53	81.72
29	99.37	100.88	99.85	100.91	100.04	101.65	100.51	101.64	101.31	103.17	101.73	103.23	103.97	105.62	104.26	105.82	11.10	11.09	8.68	8.56
30	100.95	103.05	102.36	103.82	101.61	103.76	103.00	104.50	104.16	106.60	105.03	106.67	105.16	107.96	106.04	107.93	18.22	18.69	18.15	18.30

2. Average individual bulk density (VMAT)

Pt. no.	PTV (%)																Brain stem (%)			
	$D_{98\%}$				$D_{95\%}$				$D_{50\%}$				$D_{2\%}$				D_{1cc}			
	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W
1	98.69	97.88	98.82	99.69	99.99	99.30	100.18	101.10	102.66	102.47	102.79	104.18	105.08	104.77	105.15	106.54	94.84	94.4832	97.17	96.93
2	97.33	98.56	96.92	96.49	98.40	99.61	98.22	98.04	100.99	102.59	100.95	100.90	104.22	105.45	104.05	104.01	40.41	41.2415	42.51	40.07
3	92.32	95.34	93.11	95.45	93.63	96.21	95.08	96.29	97.72	98.96	98.71	98.96	100.92	102.34	102.03	102.43	93.85	95.1232	94.65	95.11
4	94.41	97.88	95.31	97.80	96.61	98.61	96.88	98.52	99.62	101.28	99.91	101.22	102.58	104.11	103.12	104.13	98.20	99.9584	98.68	100.07
5	97.12	99.49	96.00	98.57	98.94	101.06	98.46	100.78	102.31	104.73	102.15	104.71	105.59	109.27	105.57	109.18	90.21	91.9478	89.17	91.13
6	96.27	96.85	96.69	96.92	97.48	97.61	97.64	97.62	99.54	99.76	99.70	99.76	102.13	102.75	102.55	102.65	97.57	97.6826	98.30	97.72
7	93.87	94.85	93.99	94.87	96.51	97.64	96.88	97.71	102.42	104.21	103.01	104.15	106.39	107.74	106.18	107.58	82.69	83.9339	82.84	83.57
8	85.47	96.94	87.29	97.29	87.18	97.46	89.42	97.69	96.30	99.72	96.66	99.70	98.41	101.61	98.81	101.56	56.85	58.3875	56.33	57.54
9	99.25	101.20	98.91	100.72	100.51	102.58	100.51	102.46	103.12	105.62	103.40	105.67	105.93	108.54	106.09	108.88	79.35	80.8051	82.17	83.51
10	96.76	96.08	96.89	96.22	97.07	96.60	97.16	96.62	98.72	98.60	98.94	98.57	101.22	101.57	101.81	101.19	97.07	96.6234	96.90	95.95
11	97.33	98.61	97.12	98.55	98.17	99.46	97.97	99.45	100.52	102.11	100.37	102.07	104.48	107.20	104.40	107.17	99.28	102.199	95.27	102.16
12	95.24	97.81	95.37	98.04	96.77	98.93	96.83	99.00	100.44	102.41	100.48	102.44	103.68	105.51	103.93	105.64	79.45	80.9695	79.66	80.96
13	94.02	97.49	94.80	97.61	95.74	98.65	96.35	98.74	99.82	101.68	99.81	101.68	103.18	104.95	103.22	104.98	99.37	101.293	99.55	101.20
14	94.06	94.98	93.66	94.93	96.21	97.22	95.87	97.22	105.65	107.27	105.42	107.26	109.36	111.21	109.26	111.22	107.69	109.467	107.24	109.52
15	97.52	98.35	97.54	98.08	99.77	100.48	99.81	100.33	103.57	104.52	103.63	104.41	106.07	107.31	106.28	107.21	99.94	100.885	100.26	100.69
16	91.55	94.42	92.20	94.35	93.24	95.27	94.16	95.39	98.91	99.33	98.93	99.43	101.92	103.22	102.24	103.44	88.93	89.8238	85.52	90.61
17	98.15	99.04	97.79	98.78	99.77	100.67	99.55	100.48	102.48	103.90	102.44	103.86	105.00	106.48	105.16	106.58	71.46	72.3068	73.08	73.70
18	91.81	94.91	92.18	95.03	93.58	96.68	93.94	96.74	98.48	101.35	98.84	101.34	101.69	104.17	101.86	104.12	75.35	77.2403	74.70	76.39
19	93.05	95.65	94.09	95.62	94.41	96.34	95.60	96.25	98.89	99.77	98.94	99.72	101.39	102.80	101.54	102.80	98.48	99.6724	98.74	99.51
20	93.54	95.58	93.20	94.49	95.80	97.75	96.03	97.46	101.19	102.35	101.39	102.77	104.46	105.24	104.91	105.83	45.14	45.3763	44.58	45.48
21	95.99	97.51	96.41	97.68	98.31	99.65	98.57	99.76	102.76	104.29	102.73	104.30	105.96	107.69	106.00	107.75	88.39	89.0037	83.90	84.27
22	95.82	97.66	96.29	97.57	97.19	98.38	97.48	98.31	99.58	100.82	99.90	100.75	102.06	103.62	102.39	103.59	86.24	87.5142	86.11	86.89
23	95.59	96.43	95.51	95.61	98.31	98.99	98.43	98.47	102.73	103.84	102.67	103.70	105.90	106.79	106.21	106.87	77.33	78.3529	75.68	76.58
24	97.33	99.84	96.93	99.60	97.84	100.52	97.55	100.34	99.98	102.56	99.86	102.43	102.66	105.28	102.47	105.26	100.45	103.386	100.57	103.22
25	98.25	99.70	98.78	99.76	99.67	101.09	99.98	101.12	102.06	104.12	102.42	104.13	104.43	106.53	104.78	106.61	98.86	100.821	98.54	100.08
26	99.41	100.78	99.02	100.62	100.86	102.46	100.50	102.30	103.23	105.17	103.00	105.05	106.71	108.95	106.65	109.27	46.94	47.5104	44.23	44.59
27	95.48	97.22	95.35	97.29	96.39	98.14	96.14	98.19	98.41	100.24	98.07	100.10	101.52	101.97	100.51	101.92	76.14	78.0586	75.63	77.60
28	98.39	99.35	98.50	99.42	99.97	101.13	100.03	101.08	102.64	104.57	102.77	104.56	105.18	107.86	105.32	107.98	91.96	93.3029	91.19	92.28
29	99.16	100.52	99.55	100.46	100.33	102.00	100.72	102.00	102.00	103.96	102.44	104.02	105.48	106.85	105.76	107.02	14.56	14.5879	11.78	11.69
30	100.41	102.80	101.69	103.37	101.02	103.45	102.22	103.90	102.47	105.02	103.43	105.10	103.78	106.24	104.68	106.32	29.63	30.2341	30.23	30.55

3. Average mean bulk density (IMRT)

Pt. no.	PTV (%)																Brain stem (%)			
	$D_{98\%}$				$D_{95\%}$				$D_{50\%}$				$D_{2\%}$				D_{1cc}			
	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W
1	96.34	94.85	95.96	97.49	97.48	96.48	97.24	98.75	100.70	100.62	100.41	102.16	102.53	102.53	102.36	104.00	79.71	79.58	82.27	83.51
2	93.58	94.57	93.63	92.83	94.81	95.75	95.00	94.53	97.65	99.39	98.08	97.74	100.72	102.58	100.90	100.56	42.30	43.27	42.50	42.35
3	90.97	93.58	91.25	93.68	91.61	94.23	92.58	94.30	95.05	96.54	95.48	96.62	98.15	99.74	98.68	99.79	87.37	88.66	87.48	88.44
4	92.80	95.78	93.67	95.64	94.68	96.36	94.89	96.20	96.91	98.39	97.24	98.34	99.66	100.60	100.18	100.72	93.26	94.38	93.77	94.62
5	97.31	100.17	96.57	99.19	98.62	101.09	98.44	100.79	100.88	103.33	101.22	103.36	103.71	106.64	103.99	106.52	83.13	85.11	84.23	85.71
6	94.84	95.07	94.70	94.92	95.60	95.51	95.33	95.38	97.57	97.71	97.44	97.65	99.85	100.53	99.99	100.59	94.14	94.71	94.41	94.68
7	93.73	94.87	93.22	94.65	95.05	96.23	94.96	96.13	98.44	100.19	98.76	100.22	101.71	103.62	102.12	103.65	84.81	86.24	84.93	86.07
8	84.32	94.34	86.18	93.92	86.21	94.96	88.60	95.13	96.75	99.71	97.10	99.65	99.39	102.40	99.84	102.38	53.91	54.37	52.72	52.82
9	97.90	99.87	98.00	99.69	98.73	100.87	98.86	100.79	101.54	103.85	102.02	103.86	103.71	106.01	104.06	106.35	77.60	78.99	81.15	82.38
10	96.79	96.13	97.24	96.72	97.18	96.90	97.56	97.20	99.17	99.10	99.53	99.30	101.58	101.81	102.33	102.05	97.68	98.25	97.20	97.49
11	93.26	95.20	93.58	95.13	93.77	95.79	94.11	95.78	96.49	98.46	96.55	98.48	99.44	102.30	99.59	102.21	96.08	98.59	96.33	98.61
12	92.58	94.62	92.78	94.95	93.88	95.50	93.82	95.55	96.80	98.57	96.66	98.62	100.59	102.42	100.89	102.51	62.22	63.53	62.65	63.91
13	92.08	95.27	92.84	95.55	93.11	96.00	93.85	96.16	97.30	99.13	97.21	99.13	100.04	101.69	100.03	101.83	94.44	96.45	94.69	96.71
14	96.23	97.58	96.07	97.68	99.18	100.55	99.03	100.63	104.75	106.41	104.63	106.39	108.52	109.97	108.46	110.01	105.97	107.24	105.00	106.46
15	97.09	97.19	96.89	96.98	98.86	98.67	98.60	98.52	102.14	102.46	102.28	102.62	105.00	105.82	105.81	106.59	97.11	98.27	97.53	98.48
16	90.33	94.11	91.24	94.05	92.10	94.94	93.02	95.00	96.89	98.31	96.95	98.23	99.46	101.18	99.74	101.08	74.83	76.07	76.16	77.11
17	96.24	97.26	95.60	96.95	97.32	98.48	96.93	98.34	100.30	101.94	100.56	101.89	102.73	104.19	103.07	104.31	66.66	66.98	70.57	70.36
18	92.00	95.51	92.99	95.47	92.93	96.47	94.22	96.49	96.44	99.12	97.17	99.13	98.84	101.60	99.51	101.70	69.63	71.39	69.48	70.85
19	90.97	93.75	91.91	93.61	91.86	94.48	93.04	94.33	96.16	97.27	95.98	97.20	98.63	100.22	98.98	100.24	95.92	97.44	95.95	97.23
20	93.35	95.84	93.50	96.04	94.54	96.60	94.72	97.35	97.85	99.29	97.72	100.00	101.51	103.50	101.59	104.52	41.11	42.14	39.96	40.98
21	96.87	98.58	97.05	98.73	98.23	99.78	98.19	99.84	100.83	102.35	100.61	102.36	103.29	104.54	103.16	104.54	84.25	84.87	76.90	77.30
22	94.29	95.52	94.51	95.56	95.21	96.11	95.21	96.12	97.66	99.11	97.77	99.04	99.95	101.78	100.16	101.77	77.01	78.32	77.29	78.21
23	96.32	96.62	96.52	96.17	97.82	97.87	98.08	97.68	100.81	102.09	100.89	101.95	103.02	104.28	103.40	104.32	72.73	73.56	71.17	71.90
24	94.98	97.03	94.65	97.12	95.52	97.86	95.18	97.84	98.01	100.48	97.70	100.33	100.65	103.09	100.63	102.93	97.87	100.48	97.72	100.25
25	96.34	97.45	96.74	97.72	97.97	99.51	98.30	99.64	100.60	102.77	100.95	102.79	102.90	104.80	103.15	104.82	91.75	93.67	90.29	91.59
26	96.60	98.99	96.72	99.05	98.34	100.54	98.52	100.62	101.12	103.08	101.26	103.04	104.12	105.87	104.27	106.42	46.28	47.03	44.98	45.43
27	95.95	97.12	96.42	96.89	96.70	97.95	97.13	97.88	98.37	99.85	98.59	99.79	101.34	101.71	100.74	101.69	74.22	75.69	73.65	75.00
28	96.78	97.63	97.01	97.59	97.91	99.05	98.18	99.08	101.38	103.42	101.80	103.44	103.92	105.94	104.29	106.08	81.48	82.86	80.73	81.72
29	99.37	100.88	99.76	100.91	100.04	101.65	100.39	101.64	101.31	103.17	101.57	103.23	103.97	105.62	104.13	105.82	11.10	11.09	8.72	8.56
30	100.95	103.05	102.23	103.82	101.61	103.76	102.87	104.50	104.16	106.60	104.91	106.67	105.16	107.96	105.92	107.93	18.22	18.69	18.13	18.30

4. Average mean bulk density (VMAT)

Pt. no.	PTV (%)																Brain stem (%)			
	$D_{98\%}$				$D_{95\%}$				$D_{50\%}$				$D_{2\%}$				D_{1cc}			
	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W
1	98.69	97.88	98.40	99.69	99.99	99.30	99.79	101.10	102.66	102.47	102.37	104.18	105.08	104.77	104.73	106.54	94.84	94.48	96.80	96.93
2	97.33	98.56	97.20	96.49	98.40	99.61	98.48	98.04	100.99	102.59	101.21	100.90	104.22	105.45	104.26	104.01	40.41	41.24	40.24	40.07
3	92.32	95.34	92.90	95.45	93.63	96.21	94.83	96.29	97.72	98.96	98.37	98.96	100.92	102.34	101.63	102.43	93.85	95.12	94.36	95.11
4	94.41	97.88	95.62	97.80	96.61	98.61	96.98	98.52	99.62	101.28	99.88	101.22	102.58	104.11	103.06	104.13	98.20	99.96	98.63	100.07
5	97.12	99.49	96.25	98.57	98.94	101.06	98.79	100.78	102.31	104.73	102.52	104.71	105.59	109.27	106.06	109.18	90.21	91.95	89.55	91.13
6	96.27	96.85	96.67	96.92	97.48	97.61	97.59	97.62	99.54	99.76	99.64	99.76	102.13	102.75	102.48	102.65	97.57	97.68	98.21	97.72
7	93.87	94.85	93.62	94.87	96.51	97.64	96.53	97.71	102.42	104.21	102.72	104.15	106.39	107.74	106.28	107.58	82.69	83.93	82.62	83.57
8	85.47	96.94	87.63	97.29	87.18	97.46	89.78	97.69	96.30	99.72	96.88	99.70	98.41	101.61	98.99	101.56	56.85	58.39	56.44	57.54
9	99.25	101.20	99.14	100.72	100.51	102.58	100.73	102.46	103.12	105.62	103.62	105.67	105.93	108.54	106.34	108.88	79.35	80.81	82.31	83.51
10	96.76	96.08	96.61	96.22	97.07	96.60	96.87	96.62	98.72	98.60	98.64	98.57	101.22	101.57	101.57	101.19	97.07	96.62	96.51	95.95
11	97.33	98.61	97.25	98.55	98.17	99.46	98.10	99.45	100.52	102.11	100.50	102.07	104.48	107.20	104.55	107.17	99.28	102.20	99.43	102.16
12	95.24	97.81	95.54	98.04	96.77	98.93	96.96	99.00	100.44	102.41	100.55	102.44	103.68	105.51	103.97	105.64	79.45	80.97	79.73	80.96
13	94.02	97.49	94.74	97.61	95.74	98.65	96.29	98.74	99.82	101.68	99.76	101.68	103.18	104.95	103.18	104.98	99.37	101.29	99.50	101.20
14	94.06	94.98	93.75	94.93	96.21	97.22	95.96	97.22	105.65	107.27	105.55	107.26	109.36	111.21	109.35	111.22	107.69	109.47	107.45	109.52
15	97.52	98.35	97.49	98.08	99.77	100.48	99.74	100.33	103.57	104.52	103.56	104.41	106.07	107.31	106.23	107.21	99.94	100.89	100.15	100.69
16	91.55	94.42	92.22	94.35	93.24	95.27	94.15	95.39	98.91	99.33	98.85	99.43	101.92	103.22	102.16	103.44	88.93	89.82	89.66	90.61
17	98.15	99.04	97.89	98.78	99.77	100.67	99.65	100.48	102.48	103.90	102.54	103.86	105.00	106.48	105.26	106.58	71.46	72.31	73.14	73.70
18	91.81	94.91	92.66	95.03	93.58	96.68	94.43	96.74	98.48	101.35	99.31	101.34	101.69	104.17	102.42	104.12	75.35	77.24	75.01	76.39
19	93.05	95.65	94.19	95.62	94.41	96.34	95.61	96.25	98.89	99.77	98.86	99.72	101.39	102.80	101.48	102.80	98.48	99.67	98.68	99.51
20	93.54	95.58	92.84	94.49	95.80	97.75	95.63	97.46	101.19	102.35	100.96	102.77	104.46	105.24	104.70	105.83	45.14	45.38	44.32	45.48
21	95.99	97.51	96.24	97.68	98.31	99.65	98.40	99.76	102.76	104.29	102.54	104.30	105.96	107.69	105.82	107.75	88.39	89.00	83.82	84.27
22	95.82	97.66	95.92	97.57	97.19	98.38	97.08	98.31	99.58	100.82	99.51	100.75	102.06	103.62	101.98	103.59	86.24	87.51	85.83	86.89
23	95.59	96.43	95.47	95.61	98.31	98.99	98.39	98.47	102.73	103.84	102.59	103.70	105.90	106.79	106.16	106.87	77.33	78.35	75.68	76.58
24	97.33	99.84	96.88	99.60	97.84	100.52	97.50	100.34	99.98	102.56	99.83	102.43	102.66	105.28	102.45	105.26	100.45	103.39	100.54	103.22
25	98.25	99.70	98.72	99.76	99.67	101.09	99.93	101.12	102.06	104.12	102.36	104.13	104.43	106.53	104.73	106.61	98.86	100.82	98.48	100.08
26	99.41	100.78	99.15	100.62	100.86	102.46	100.62	102.30	103.23	105.17	103.14	105.05	106.71	108.95	106.76	109.27	46.94	47.51	44.35	44.59
27	95.48	97.22	95.85	97.29	96.39	98.14	96.67	98.19	98.41	100.24	98.61	100.10	101.52	101.97	100.99	101.92	76.14	78.06	75.98	77.60
28	98.39	99.35	98.79	99.42	99.97	101.13	100.28	101.08	102.64	104.57	103.03	104.56	105.18	107.86	105.64	107.98	91.96	93.30	91.43	92.28
29	99.16	100.52	99.43	100.46	100.33	102.00	100.55	102.00	102.00	103.96	102.28	104.02	105.48	106.85	105.65	107.02	14.56	14.59	11.80	11.69
30	100.41	102.80	101.57	103.37	101.02	103.45	102.10	103.90	102.47	105.02	103.31	105.10	103.78	106.24	104.53	106.32	29.63	30.23	30.19	30.55

5. ICRU bulk density (IMRT)

Pt. no.	PTV (%)																Brain stem (%)			
	$D_{98\%}$				$D_{95\%}$				$D_{50\%}$				$D_{2\%}$				D_{1cc}			
	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W
1	96.34	94.85	95.44	97.49	97.48	96.48	96.71	98.75	100.70	100.62	100.02	102.16	102.53	102.53	102.01	104.00	79.71	79.58	81.75	83.51
2	93.58	94.57	92.97	92.83	94.81	95.75	94.36	94.53	97.65	99.39	97.37	97.74	100.72	102.58	100.29	100.56	42.30	43.27	42.16	42.35
3	90.97	93.58	90.32	93.68	91.61	94.23	91.69	94.30	95.05	96.54	94.78	96.62	98.15	99.74	98.02	99.79	87.37	88.66	87.01	88.44
4	92.80	95.78	92.52	95.64	94.68	96.36	94.16	96.20	96.91	98.39	96.70	98.34	99.66	100.60	99.80	100.72	93.26	94.38	93.37	94.62
5	97.31	100.17	95.83	99.19	98.62	101.09	97.80	100.79	100.88	103.33	100.68	103.36	103.71	106.64	103.64	106.52	83.13	85.11	83.43	85.71
6	94.84	95.07	94.37	94.92	95.60	95.51	95.06	95.38	97.57	97.71	97.12	97.65	99.85	100.53	99.65	100.59	94.14	94.71	94.17	94.68
7	93.73	94.87	92.46	94.65	95.05	96.23	94.37	96.13	98.44	100.19	98.14	100.22	101.71	103.62	101.33	103.65	84.81	86.24	84.43	86.07
8	84.32	94.34	85.35	93.92	86.21	94.96	87.29	95.13	96.75	99.71	96.10	99.65	99.39	102.40	98.85	102.38	53.91	54.37	52.46	52.82
9	97.90	99.87	97.33	99.69	98.73	100.87	98.20	100.79	101.54	103.85	101.48	103.86	103.71	106.01	103.69	106.35	77.60	78.99	80.53	82.38
10	96.79	96.13	96.78	96.72	97.18	96.90	97.07	97.20	99.17	99.10	99.01	99.30	101.58	101.81	101.84	102.05	97.68	98.25	96.93	97.49
11	93.26	95.20	92.68	95.13	93.77	95.79	93.24	95.78	96.49	98.46	95.82	98.48	99.44	102.30	98.82	102.21	96.08	98.59	95.57	98.61
12	92.58	94.62	91.97	94.95	93.88	95.50	93.19	95.55	96.80	98.57	96.06	98.62	100.59	102.42	100.08	102.51	62.22	63.53	62.21	63.91
13	92.08	95.27	91.91	95.55	93.11	96.00	93.04	96.16	97.30	99.13	96.53	99.13	100.04	101.69	99.38	101.83	94.44	96.45	90.16	96.71
14	96.23	97.58	95.83	97.68	99.18	100.55	98.79	100.63	104.75	106.41	104.46	106.39	108.52	109.97	108.27	110.01	105.97	107.24	104.76	106.46
15	97.09	97.19	96.80	96.98	98.86	98.67	98.51	98.52	102.14	102.46	102.19	102.62	105.00	105.82	105.48	106.59	97.11	98.27	97.20	98.48
16	90.33	94.11	90.49	94.05	92.10	94.94	92.20	95.00	96.89	98.31	96.23	98.23	99.46	101.18	98.94	101.08	74.83	76.07	75.54	77.11
17	96.24	97.26	95.18	96.95	97.32	98.48	96.45	98.34	100.30	101.94	99.95	101.89	102.73	104.19	102.60	104.31	66.66	66.98	70.20	70.36
18	92.00	95.51	92.15	95.47	92.93	96.47	93.39	96.49	96.44	99.12	96.37	99.13	98.84	101.60	98.80	101.70	69.63	71.39	68.99	70.85
19	90.97	93.75	90.92	93.61	91.86	94.48	92.25	94.33	96.16	97.27	95.47	97.20	98.63	100.22	98.15	100.24	95.92	97.44	95.24	97.23
20	93.35	95.84	92.80	96.04	94.54	96.60	94.08	97.35	97.85	99.29	97.25	100.00	101.51	103.50	101.09	104.52	41.11	42.14	39.74	40.98
21	96.87	98.58	96.47	98.73	98.23	99.78	97.67	99.84	100.83	102.35	100.23	102.36	103.29	104.54	102.89	104.54	84.25	84.87	76.37	77.30
22	94.29	95.52	93.74	95.56	95.21	96.11	94.54	96.12	97.66	99.11	97.04	99.04	99.95	101.78	99.40	101.77	77.01	78.32	76.75	78.21
23	96.32	96.62	96.07	96.17	97.82	97.87	97.63	97.68	100.81	102.09	100.37	101.95	103.02	104.28	102.96	104.32	72.73	73.56	70.69	71.90
24	94.98	97.03	94.11	97.12	95.52	97.86	94.64	97.84	98.01	100.48	97.14	100.33	100.65	103.09	100.02	102.93	97.87	100.48	97.05	100.25
25	96.34	97.45	96.11	97.72	97.97	99.51	97.65	99.64	100.60	102.77	100.31	102.79	102.90	104.80	102.68	104.82	91.75	93.67	89.48	91.59
26	96.60	98.99	95.96	99.05	98.34	100.54	97.82	100.62	101.12	103.08	100.81	103.04	104.12	105.87	104.01	106.42	46.28	47.03	44.79	45.43
27	95.95	97.12	95.77	96.89	96.70	97.95	96.42	97.88	98.37	99.85	97.83	99.79	101.34	101.71	100.18	101.69	74.22	75.69	73.17	75.00
28	96.78	97.63	96.38	97.59	97.91	99.05	97.52	99.08	101.38	103.42	101.24	103.44	103.92	105.94	103.85	106.08	81.48	82.86	80.16	81.72
29	99.37	100.88	99.19	100.91	100.04	101.65	99.67	101.64	101.31	103.17	100.94	103.23	103.97	105.62	103.68	105.82	11.10	11.09	8.67	8.56
30	100.95	103.05	101.09	103.82	101.61	103.76	101.74	104.50	104.16	106.60	103.68	106.67	105.16	107.96	104.75	107.93	18.22	18.69	17.68	18.30

6. ICRU bulk density (VMAT)

Pt. no.	PTV (%)																Brain stem (%)			
	$D_{98\%}$				$D_{95\%}$				$D_{50\%}$				$D_{2\%}$				D_{1cc}			
	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W
1	98.69	97.88	97.96	99.69	99.99	99.30	99.34	101.10	102.66	102.47	101.92	104.18	105.08	104.77	104.31	106.54	94.84	94.48	96.24	96.93
2	97.33	98.56	96.72	96.49	98.40	99.61	98.03	98.04	100.99	102.59	100.71	100.90	104.22	105.45	103.89	104.01	40.41	41.24	42.36	40.07
3	92.32	95.34	91.71	95.45	93.63	96.21	93.81	96.29	97.72	98.96	97.72	98.96	100.92	102.34	101.06	102.43	93.85	95.12	93.73	95.11
4	94.41	97.88	94.43	97.80	96.61	98.61	96.24	98.52	99.62	101.28	99.32	101.22	102.58	104.11	102.56	104.13	98.20	99.96	98.20	100.07
5	97.12	99.49	95.60	98.57	98.94	101.06	98.20	100.78	102.31	104.73	101.99	104.71	105.59	109.27	105.68	109.18	90.21	91.95	88.87	91.13
6	96.27	96.85	96.39	96.92	97.48	97.61	97.36	97.62	99.54	99.76	99.37	99.76	102.13	102.75	102.18	102.65	97.57	97.68	98.04	97.72
7	93.87	94.85	92.91	94.87	96.51	97.64	95.93	97.71	102.42	104.21	102.07	104.15	106.39	107.74	105.28	107.58	82.69	83.93	82.16	83.57
8	85.47	96.94	86.54	97.29	87.18	97.46	88.20	97.69	96.30	99.72	95.67	99.70	98.41	101.61	97.81	101.56	56.85	58.39	55.83	57.54
9	99.25	101.20	98.56	100.72	100.51	102.58	100.10	102.46	103.12	105.62	102.98	105.67	105.93	108.54	105.84	108.88	79.35	80.81	81.73	83.51
10	96.76	96.08	96.12	96.22	97.07	96.60	96.39	96.62	98.72	98.60	98.13	98.57	101.22	101.57	101.12	101.19	97.07	96.62	96.23	95.95
11	97.33	98.61	96.71	98.55	98.17	99.46	97.57	99.45	100.52	102.11	99.98	102.07	104.48	107.20	104.05	107.17	99.28	102.20	98.73	102.16
12	95.24	97.81	94.74	98.04	96.77	98.93	96.25	99.00	100.44	102.41	99.86	102.44	103.68	105.51	103.27	105.64	79.45	80.97	79.12	80.96
13	94.02	97.49	93.86	97.61	95.74	98.65	95.54	98.74	99.82	101.68	99.06	101.68	103.18	104.95	102.41	104.98	99.37	101.29	97.56	101.20
14	94.06	94.98	93.49	94.93	96.21	97.22	95.72	97.22	105.65	107.27	105.37	107.26	109.36	111.21	109.17	111.22	107.69	109.47	107.27	109.52
15	97.52	98.35	97.27	98.08	99.77	100.48	99.42	100.33	103.57	104.52	103.11	104.41	106.07	107.31	105.79	107.21	99.94	100.89	99.70	100.69
16	91.55	94.42	91.46	94.35	93.24	95.27	93.37	95.39	98.91	99.33	98.26	99.43	101.92	103.22	101.42	103.44	88.93	89.82	84.91	90.61
17	98.15	99.04	97.57	98.78	99.77	100.67	99.33	100.48	102.48	103.90	102.10	103.86	105.00	106.48	104.88	106.58	71.46	72.31	72.81	73.70
18	91.81	94.91	91.87	95.03	93.58	96.68	93.62	96.74	98.48	101.35	98.49	101.34	101.69	104.17	101.84	104.12	75.35	77.24	74.37	76.39
19	93.05	95.65	93.25	95.62	94.41	96.34	94.91	96.25	98.89	99.77	98.31	99.72	101.39	102.80	100.82	102.80	98.48	99.67	98.32	99.51
20	93.54	95.58	92.51	94.49	95.80	97.75	95.30	97.46	101.19	102.35	100.62	102.77	104.46	105.24	104.47	105.83	45.14	45.38	44.14	45.48
21	95.99	97.51	95.59	97.68	98.31	99.65	97.86	99.76	102.76	104.29	102.14	104.30	105.96	107.69	105.45	107.75	88.39	89.00	83.15	84.27
22	95.82	97.66	95.20	97.57	97.19	98.38	96.49	98.31	99.58	100.82	98.92	100.75	102.06	103.62	101.40	103.59	86.24	87.51	85.33	86.89
23	95.59	96.43	95.18	95.61	98.31	98.99	98.08	98.47	102.73	103.84	102.26	103.70	105.90	106.79	105.84	106.87	77.33	78.35	75.27	76.58
24	97.33	99.84	96.32	99.60	97.84	100.52	96.94	100.34	99.98	102.56	99.22	102.43	102.66	105.28	101.85	105.26	100.45	103.39	99.68	103.22
25	98.25	99.70	98.12	99.76	99.67	101.09	99.37	101.12	102.06	104.12	101.75	104.13	104.43	106.53	104.19	106.61	98.86	100.82	97.88	100.08
26	99.41	100.78	98.70	100.62	100.86	102.46	100.23	102.30	103.23	105.17	102.83	105.05	106.71	108.95	106.60	109.27	46.94	47.51	44.11	44.59
27	95.48	97.22	95.20	97.29	96.39	98.14	96.03	98.19	98.41	100.24	97.92	100.10	101.52	101.97	100.35	101.92	76.14	78.06	75.42	77.60
28	98.39	99.35	98.17	99.42	99.97	101.13	99.65	101.08	102.64	104.57	99.65	104.56	105.18	107.86	105.13	107.98	91.96	93.30	90.70	92.28
29	99.16	100.52	98.99	100.46	100.33	102.00	99.93	102.00	102.00	103.96	101.62	104.02	105.48	106.85	105.26	107.02	14.56	14.59	11.73	11.69
30	100.41	102.80	100.57	103.37	101.02	103.45	101.06	103.90	102.47	105.02	102.18	105.10	103.78	106.24	103.39	106.32	29.63	30.23	29.78	30.55

Appendix B: Percent dose difference data

1. Average individual bulk density (IMRT)

Pt. no.	PTV																Brain stem			
	$D_{98\%}$				$D_{95\%}$				$D_{50\%}$				$D_{2\%}$				D_{1cc}			
	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W
1	Ref.	-1.55	0.13	1.19	Ref.	-1.03	0.22	1.30	Ref.	-0.07	0.09	1.46	Ref.	0.00	0.12	1.43	Ref.	-0.16	3.60	4.77
2		1.06	-0.34	-0.81		0.99	-0.14	-0.30		1.78	0.18	0.09		1.84	-0.08	-0.16		2.30	0.26	0.13
3		2.87	0.70	2.98		2.86	1.46	2.94		1.56	0.78	1.65		1.62	0.76	1.67		1.48	0.52	1.23
4		3.21	0.59	3.06		1.78	0.12	1.61		1.52	0.37	1.48		0.95	0.61	1.07		1.21	0.61	1.47
5		2.94	-1.07	1.93		2.51	-0.62	2.20		2.43	-0.03	2.46		2.83	-0.07	2.71		2.38	0.85	3.11
6		0.25	-0.10	0.09		-0.09	-0.21	-0.23		0.14	-0.08	0.08		0.68	0.19	0.73		0.61	0.38	0.57
7		1.22	0.08	0.98		1.24	0.37	1.13		1.78	0.61	1.81		1.87	0.57	1.91		1.69	0.48	1.49
8		11.89	1.74	11.40		10.16	2.27	10.35		3.06	0.04	2.99		3.03	0.28	3.01		0.85	-2.29	-2.03
9		2.01	-0.14	1.83		2.17	-0.10	2.08		2.27	0.29	2.28		2.22	0.18	2.54		1.80	4.40	6.16
10		-0.68	0.73	-0.07		-0.29	0.66	0.02		-0.08	0.67	0.12		0.22	0.99	0.46		0.58	-0.07	-0.19
11		2.07	0.15	2.00		2.15	0.19	2.14		2.04	-0.12	2.07		2.88	0.01	2.79		2.62	-4.53	2.64
12		2.20	0.02	2.56		1.73	-0.18	1.78		1.83	-0.20	1.88		1.82	0.25	1.91		2.12	0.68	2.72
13		3.46	0.90	3.77		3.11	0.87	3.27		1.88	-0.05	1.88		1.65	0.06	1.79		2.12	0.30	2.41
14		1.40	-0.30	1.51		1.38	-0.27	1.46		1.59	-0.23	1.56		1.33	-0.12	1.37		1.20	-1.03	0.46
15		0.10	-0.16	-0.12		-0.19	-0.20	-0.34		0.31	0.17	0.48		0.78	0.79	1.52		1.20	0.50	1.41
16		4.18	1.04	4.11		3.09	1.04	3.16		1.47	0.15	1.39		1.72	0.33	1.63		1.66	1.82	3.04
17		1.06	-0.81	0.74		1.19	-0.54	1.05		1.63	0.15	1.59		1.42	0.25	1.53		0.47	5.74	5.54
18		3.81	0.50	3.77		3.81	0.83	3.83		2.77	0.25	2.78		2.79	0.27	2.89		2.53	-0.67	1.75
19		3.06	0.91	2.90		2.86	1.26	2.69		1.16	-0.10	1.09		1.61	0.39	1.63		1.59	0.07	1.37
20		2.67	0.87	2.89		2.18	0.95	2.97		1.48	0.49	2.20		1.96	0.53	2.97		2.50	-1.98	-0.31
21		1.77	0.42	1.92		1.58	0.15	1.64		1.51	-0.02	1.52		1.21	-0.02	1.21		0.73	-8.66	-8.25
22		1.31	0.66	1.35		0.95	0.40	0.96		1.49	0.49	1.42		1.83	0.62	1.82		1.70	0.69	1.56
23		0.31	0.26	-0.16		0.05	0.32	-0.14		1.28	0.16	1.13		1.22	0.40	1.26		1.14	-2.05	-1.15
24		2.16	-0.30	2.25		2.45	-0.31	2.42		2.52	-0.27	2.37		2.43	0.01	2.27		2.66	-0.13	2.43
25		1.15	0.47	1.43		1.57	0.38	1.71		2.16	0.41	2.18		1.85	0.31	1.86		2.09	-1.53	-0.17
26		2.48	-0.09	2.54		2.23	-0.04	2.32		1.93	0.01	1.90		1.68	0.14	2.21		1.63	-2.99	-1.83
27		1.22	-0.08	0.98		1.30	-0.18	1.22		1.51	-0.32	1.45		0.36	-1.06	0.34		1.98	-1.32	1.05
28		0.88	-0.25	0.84		1.17	-0.11	1.20		2.02	0.20	2.04		1.94	0.12	2.08		1.69	-1.17	0.29
29		1.52	0.49	1.56		1.61	0.47	1.60		1.84	0.41	1.90		1.59	0.27	1.78		-0.10	-21.77	-22.90
30		2.08	1.40	2.84		2.12	1.37	2.84		2.34	0.83	2.40		2.66	0.84	2.64		2.56	-0.40	0.43

2. Average individual bulk density (VMAT)

Pt. no.	PTV																Brain stem			
	$D_{98\%}$				$D_{95\%}$				$D_{50\%}$				$D_{2\%}$				D_{1cc}			
	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W
1		-0.82	0.13	1.01		-0.69	0.19	1.11		-0.19	0.12	1.48		-0.29	0.07	1.39		-0.38	2.46	2.21
2		1.26	-0.42	-0.87		1.23	-0.19	-0.37		1.59	-0.04	-0.09		1.18	-0.16	-0.20		2.06	5.21	-0.84
3		3.27	0.85	3.39		2.75	1.54	2.83		1.27	1.01	1.26		1.40	1.09	1.49		1.36	0.85	1.34
4		3.68	0.95	3.58		2.07	0.27	1.98		1.67	0.30	1.61		1.49	0.52	1.51		1.79	0.49	1.91
5		2.44	-1.15	1.49		2.15	-0.48	1.86		2.37	-0.15	2.35		3.49	-0.02	3.40		1.93	-1.14	1.02
6		0.61	0.44	0.68		0.14	0.16	0.14		0.22	0.15	0.21		0.60	0.41	0.51		0.11	0.74	0.15
7		1.05	0.13	1.07		1.16	0.38	1.24		1.75	0.58	1.69		1.27	-0.20	1.12		1.51	0.19	1.07
8		13.42	2.13	13.83		11.79	2.57	12.05		3.54	0.37	3.53		3.25	0.41	3.20		2.70	-0.92	1.22
9		1.96	-0.33	1.49		2.07	0.00	1.94		2.42	0.27	2.47		2.46	0.15	2.78		1.84	3.55	5.24
10		-0.71	0.13	-0.56		-0.49	0.10	-0.46		-0.12	0.23	-0.16		0.34	0.58	-0.03		-0.46	-0.18	-1.16
11		1.31	-0.21	1.26		1.31	-0.21	1.30		1.58	-0.15	1.55		2.60	-0.08	2.57		2.94	-4.04	2.90
12		2.70	0.13	2.93		2.23	0.06	2.30		1.95	0.03	1.99		1.77	0.24	1.89		1.91	0.27	1.89
13		3.70	0.83	3.83		3.04	0.63	3.13		1.86	-0.01	1.86		1.72	0.04	1.74		1.93	0.18	1.84
14		0.98	-0.43	0.92		1.05	-0.35	1.05		1.53	-0.22	1.52		1.69	-0.09	1.70		1.65	-0.42	1.70
15	Ref.	0.86	0.02	0.58	Ref.	0.71	0.04	0.56	Ref.	0.91	0.06	0.80	Ref.	1.18	0.20	1.08	Ref.	0.95	0.32	0.76
16		3.14	0.71	3.06		2.18	0.98	2.30		0.43	0.02	0.53		1.28	0.31	1.50		1.00	-3.84	1.88
17		0.91	-0.36	0.64		0.90	-0.22	0.71		1.39	-0.04	1.35		1.40	0.15	1.51		1.19	2.27	3.14
18		3.37	0.40	3.50		3.31	0.38	3.38		2.91	0.37	2.90		2.43	0.16	2.39		2.50	-0.87	1.38
19		2.79	1.12	2.76		2.05	1.26	1.95		0.89	0.05	0.83		1.39	0.15	1.39		1.21	0.27	1.05
20		2.19	-0.36	1.02		2.04	0.24	1.73		1.15	0.20	1.56		0.75	0.44	1.32		0.53	-1.22	0.76
21		1.58	0.44	1.76		1.36	0.26	1.47		1.48	-0.03	1.49		1.64	0.04	1.69		0.69	-5.09	-4.66
22		1.92	0.49	1.82		1.22	0.30	1.15		1.25	0.32	1.18		1.53	0.32	1.50		1.48	-0.15	0.75
23		0.88	-0.08	0.02		0.69	0.13	0.16		1.08	-0.06	0.94		0.83	0.28	0.91		1.33	-2.13	-0.96
24		2.58	-0.41	2.34		2.73	-0.30	2.56		2.58	-0.11	2.46		2.56	-0.18	2.54		2.93	0.12	2.76
25		1.48	0.54	1.54		1.43	0.31	1.46		2.02	0.36	2.03		2.01	0.34	2.09		1.98	-0.33	1.23
26		1.38	-0.39	1.22		1.60	-0.36	1.44		1.87	-0.23	1.76		2.10	-0.06	2.40		1.22	-5.77	-5.00
27		1.81	-0.15	1.89		1.81	-0.26	1.86		1.85	-0.34	1.72		0.44	-0.99	0.40		2.52	-0.67	1.92
28		0.97	0.11	1.04		1.16	0.06	1.12		1.88	0.13	1.87		2.55	0.13	2.66		1.46	-0.83	0.35
29		1.37	0.39	1.31		1.67	0.39	1.66		1.92	0.43	1.98		1.30	0.26	1.46		0.17	-19.10	-19.70
30		2.39	1.28	2.95		2.41	1.19	2.85		2.48	0.93	2.56		2.37	0.87	2.44		2.04	2.04	3.10

3. Average mean bulk density (IMRT)

Pt. no.	PTV																Brain stem			
	$D_{98\%}$				$D_{95\%}$				$D_{50\%}$				$D_{2\%}$				D_{1cc}			
	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W
1	Ref.	-1.55	-0.39	1.19	Ref.	-1.03	-0.24	1.30	Ref.	-0.07	-0.29	1.46	Ref.	0.00	-0.17	1.43	Ref.	-0.16	3.22	4.77
2		1.06	0.05	-0.81		0.99	0.20	-0.30		1.78	0.44	0.09		1.84	0.17	-0.16		2.30	0.47	0.13
3		2.87	0.31	2.98		2.86	1.06	2.94		1.56	0.45	1.65		1.62	0.54	1.67		1.48	0.13	1.23
4		3.21	0.93	3.06		1.78	0.22	1.61		1.52	0.34	1.48		0.95	0.53	1.07		1.21	0.55	1.47
5		2.94	-0.76	1.93		2.51	-0.19	2.20		2.43	0.34	2.46		2.83	0.27	2.71		2.38	1.32	3.11
6		0.25	-0.14	0.09		-0.09	-0.28	-0.23		0.14	-0.14	0.08		0.68	0.13	0.73		0.61	0.29	0.57
7		1.22	-0.54	0.98		1.24	-0.10	1.13		1.78	0.33	1.81		1.87	0.40	1.91		1.69	0.15	1.49
8		11.89	2.21	11.40		10.16	2.77	10.35		3.06	0.36	2.99		3.03	0.45	3.01		0.85	-2.20	-2.03
9		2.01	0.10	1.83		2.17	0.13	2.08		2.27	0.47	2.28		2.22	0.34	2.54		1.80	4.58	6.16
10		-0.68	0.46	-0.07		-0.29	0.38	0.02		-0.08	0.36	0.12		0.22	0.74	0.46		0.58	-0.49	-0.19
11		2.07	0.34	2.00		2.15	0.36	2.14		2.04	0.06	2.07		2.88	0.16	2.79		2.62	0.27	2.64
12		2.20	0.22	2.56		1.73	-0.06	1.78		1.83	-0.14	1.88		1.82	0.30	1.91		2.12	0.70	2.72
13		3.46	0.83	3.77		3.11	0.80	3.27		1.88	-0.09	1.88		1.65	-0.01	1.79		2.12	0.27	2.41
14		1.40	-0.17	1.51		1.38	-0.15	1.46		1.59	-0.11	1.56		1.33	-0.06	1.37		1.20	-0.92	0.46
15		0.10	-0.21	-0.12		-0.19	-0.26	-0.34		0.31	0.14	0.48		0.78	0.77	1.52		1.20	0.43	1.41
16		4.18	1.01	4.11		3.09	1.00	3.16		1.47	0.07	1.39		1.72	0.27	1.63		1.66	1.77	3.04
17		1.06	-0.66	0.74		1.19	-0.40	1.05		1.63	0.26	1.59		1.42	0.33	1.53		0.47	5.87	5.54
18		3.81	1.08	3.77		3.81	1.38	3.83		2.77	0.75	2.78		2.79	0.68	2.89		2.53	-0.21	1.75
19		3.06	1.04	2.90		2.86	1.29	2.69		1.16	-0.19	1.09		1.61	0.35	1.63		1.59	0.03	1.37
20		2.67	0.16	2.89		2.18	0.19	2.97		1.48	-0.13	2.20		1.96	0.07	2.97		2.50	-2.81	-0.31
21		1.77	0.19	1.92		1.58	-0.04	1.64		1.51	-0.21	1.52		1.21	-0.13	1.21		0.73	-8.73	-8.25
22		1.31	0.24	1.35		0.95	0.01	0.96		1.49	0.11	1.42		1.83	0.21	1.82		1.70	0.36	1.56
23		0.31	0.20	-0.16		0.05	0.27	-0.14		1.28	0.09	1.13		1.22	0.36	1.26		1.14	-2.15	-1.15
24		2.16	-0.34	2.25		2.45	-0.36	2.42		2.52	-0.32	2.37		2.43	-0.02	2.27		2.66	-0.16	2.43
25		1.15	0.42	1.43		1.57	0.33	1.71		2.16	0.35	2.18		1.85	0.25	1.86		2.09	-1.59	-0.17
26		2.48	0.13	2.54		2.23	0.18	2.32		1.93	0.14	1.90		1.68	0.14	2.21		1.63	-2.79	-1.83
27		1.22	0.49	0.98		1.30	0.45	1.22		1.51	0.23	1.45		0.36	-0.59	0.34		1.98	-0.77	1.05
28		0.88	0.24	0.84		1.17	0.28	1.20		2.02	0.41	2.04		1.94	0.36	2.08		1.69	-0.92	0.29
29		1.52	0.40	1.56		1.61	0.35	1.60		1.84	0.25	1.90		1.59	0.15	1.78		-0.10	-21.45	-22.90
30		2.08	1.27	2.84		2.12	1.24	2.84		2.34	0.72	2.40		2.66	0.73	2.64		2.56	-0.48	0.43

4. Average mean bulk density (VMAT)

Pt. no.	PTV																Brain stem			
	$D_{98\%}$				$D_{95\%}$				$D_{50\%}$				$D_{2\%}$				D_{1cc}			
	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W
1		-0.82	-0.29	1.01		-0.69	-0.21	1.11		-0.19	-0.28	1.48		-0.29	-0.33	1.39		-0.38	2.07	2.21
2		1.26	-0.13	-0.87		1.23	0.08	-0.37		1.59	0.21	-0.09		1.18	0.04	-0.20		2.06	-0.43	-0.84
3		3.27	0.62	3.39		2.75	1.28	2.83		1.27	0.67	1.26		1.40	0.69	1.49		1.36	0.54	1.34
4		3.68	1.28	3.58		2.07	0.38	1.98		1.67	0.27	1.61		1.49	0.47	1.51		1.79	0.44	1.91
5		2.44	-0.90	1.49		2.15	-0.15	1.86		2.37	0.21	2.35		3.49	0.45	3.40		1.93	-0.72	1.02
6		0.61	0.42	0.68		0.14	0.11	0.14		0.22	0.10	0.21		0.60	0.34	0.51		0.11	0.65	0.15
7		1.05	-0.27	1.07		1.16	0.02	1.24		1.75	0.29	1.69		1.27	-0.11	1.12		1.51	-0.08	1.07
8		13.42	2.53	13.83		11.79	2.98	12.05		3.54	0.59	3.53		3.25	0.59	3.20		2.70	-0.73	1.22
9		1.96	-0.10	1.49		2.07	0.22	1.94		2.42	0.48	2.47		2.46	0.38	2.78		1.84	3.74	5.24
10		-0.71	-0.16	-0.56		-0.49	-0.20	-0.46		-0.12	-0.08	-0.16		0.34	0.34	-0.03		-0.46	-0.58	-1.16
11		1.31	-0.08	1.26		1.31	-0.08	1.30		1.58	-0.02	1.55		2.60	0.06	2.57		2.94	0.15	2.90
12		2.70	0.32	2.93		2.23	0.19	2.30		1.95	0.11	1.99		1.77	0.28	1.89		1.91	0.35	1.89
13		3.70	0.77	3.83		3.04	0.57	3.13		1.86	-0.06	1.86		1.72	0.00	1.74		1.93	0.13	1.84
14		0.98	-0.33	0.92		1.05	-0.26	1.05		1.53	-0.10	1.52		1.69	-0.01	1.70		1.65	-0.22	1.70
15	Ref.	0.86	-0.03	0.58	Ref.	0.71	-0.03	0.56	Ref.	0.91	-0.02	0.80	Ref.	1.18	0.15	1.08	Ref.	0.95	0.22	0.76
16		3.14	0.73	3.06		2.18	0.97	2.30		0.43	-0.06	0.53		1.28	0.24	1.50		1.00	0.82	1.88
17		0.91	-0.27	0.64		0.90	-0.12	0.71		1.39	0.06	1.35		1.40	0.24	1.51		1.19	2.35	3.14
18		3.37	0.92	3.50		3.31	0.90	3.38		2.91	0.84	2.90		2.43	0.72	2.39		2.50	-0.46	1.38
19		2.79	1.23	2.76		2.05	1.27	1.95		0.89	-0.04	0.83		1.39	0.09	1.39		1.21	0.21	1.05
20		2.19	-0.74	1.02		2.04	-0.18	1.73		1.15	-0.23	1.56		0.75	0.23	1.32		0.53	-1.81	0.76
21		1.58	0.26	1.76		1.36	0.09	1.47		1.48	-0.22	1.49		1.64	-0.13	1.69		0.69	-5.17	-4.66
22		1.92	0.10	1.82		1.22	-0.12	1.15		1.25	-0.07	1.18		1.53	-0.09	1.50		1.48	-0.48	0.75
23		0.88	-0.12	0.02		0.69	0.08	0.16		1.08	-0.14	0.94		0.83	0.24	0.91		1.33	-2.13	-0.96
24		2.58	-0.46	2.34		2.73	-0.35	2.56		2.58	-0.15	2.46		2.56	-0.20	2.54		2.93	0.09	2.76
25		1.48	0.48	1.54		1.43	0.26	1.46		2.02	0.30	2.03		2.01	0.28	2.09		1.98	-0.39	1.23
26		1.38	-0.26	1.22		1.60	-0.23	1.44		1.87	-0.09	1.76		2.10	0.05	2.40		1.22	-5.52	-5.00
27		1.81	0.38	1.89		1.81	0.28	1.86		1.85	0.20	1.72		0.44	-0.52	0.40		2.52	-0.21	1.92
28		0.97	0.40	1.04		1.16	0.32	1.12		1.88	0.38	1.87		2.55	0.44	2.66		1.46	-0.58	0.35
29		1.37	0.27	1.31		1.67	0.22	1.66		1.92	0.28	1.98		1.30	0.16	1.46		0.17	-18.96	-19.70
30		2.39	1.16	2.95		2.41	1.07	2.85		2.48	0.82	2.56		2.37	0.73	2.44		2.04	1.90	3.10

5. ICRU bulk density (IMRT)

Pt. no.	PTV																Brain stem			
	$D_{98\%}$				$D_{95\%}$				$D_{50\%}$				$D_{2\%}$				D_{1cc}			
	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W
1		-1.55	-0.94	1.19		-1.03	-0.79	1.30		-0.07	-0.67	1.46		0.00	-0.51	1.43		-0.16	2.56	4.77
2		1.06	-0.65	-0.81		0.99	-0.48	-0.30		1.78	-0.29	0.09		1.84	-0.43	-0.16		2.30	-0.32	0.13
3		2.87	-0.72	2.98		2.86	0.09	2.94		1.56	-0.29	1.65		1.62	-0.13	1.67		1.48	-0.42	1.23
4		3.21	-0.30	3.06		1.78	-0.55	1.61		1.52	-0.22	1.48		0.95	0.15	1.07		1.21	0.13	1.47
5		2.94	-1.52	1.93		2.51	-0.83	2.20		2.43	-0.20	2.46		2.83	-0.06	2.71		2.38	0.36	3.11
6		0.25	-0.49	0.09		-0.09	-0.57	-0.23		0.14	-0.46	0.08		0.68	-0.20	0.73		0.61	0.03	0.57
7		1.22	-1.35	0.98		1.24	-0.71	1.13		1.78	-0.31	1.81		1.87	-0.38	1.91		1.69	-0.44	1.49
8		11.89	1.23	11.40		10.16	1.25	10.35		3.06	-0.68	2.99		3.03	-0.54	3.01		0.85	-2.68	-2.03
9		2.01	-0.58	1.83		2.17	-0.53	2.08		2.27	-0.07	2.28		2.22	-0.03	2.54		1.80	3.78	6.16
10		-0.68	-0.01	-0.07		-0.29	-0.11	0.02		-0.08	-0.17	0.12		0.22	0.25	0.46		0.58	-0.77	-0.19
11		2.07	-0.63	2.00		2.15	-0.57	2.14		2.04	-0.69	2.07		2.88	-0.62	2.79		2.62	-0.53	2.64
12		2.20	-0.66	2.56		1.73	-0.74	1.78		1.83	-0.76	1.88		1.82	-0.51	1.91		2.12	-0.01	2.72
13		3.46	-0.18	3.77		3.11	-0.07	3.27		1.88	-0.79	1.88		1.65	-0.66	1.79		2.12	-4.54	2.41
14		1.40	-0.42	1.51		1.38	-0.40	1.46		1.59	-0.28	1.56		1.33	-0.23	1.37		1.20	-1.14	0.46
15	Ref.	0.10	-0.30	-0.12	Ref.	-0.19	-0.35	-0.34	Ref.	0.31	0.05	0.48	Ref.	0.78	0.46	1.52	Ref.	1.20	0.10	1.41
16		4.18	0.18	4.11		3.09	0.11	3.16		1.47	-0.68	1.39		1.72	-0.53	1.63		1.66	0.96	3.04
17		1.06	-1.10	0.74		1.19	-0.89	1.05		1.63	-0.35	1.59		1.42	-0.13	1.53		0.47	5.31	5.54
18		3.81	0.16	3.77		3.81	0.50	3.83		2.77	-0.08	2.78		2.79	-0.04	2.89		2.53	-0.93	1.75
19		3.06	-0.05	2.90		2.86	0.42	2.69		1.16	-0.71	1.09		1.61	-0.49	1.63		1.59	-0.70	1.37
20		2.67	-0.58	2.89		2.18	-0.49	2.97		1.48	-0.61	2.20		1.96	-0.42	2.97		2.50	-3.33	-0.31
21		1.77	-0.41	1.92		1.58	-0.57	1.64		1.51	-0.59	1.52		1.21	-0.39	1.21		0.73	-9.36	-8.25
22		1.31	-0.58	1.35		0.95	-0.70	0.96		1.49	-0.63	1.42		1.83	-0.55	1.82		1.70	-0.34	1.56
23		0.31	-0.26	-0.16		0.05	-0.19	-0.14		1.28	-0.44	1.13		1.22	-0.06	1.26		1.14	-2.81	-1.15
24		2.16	-0.91	2.25		2.45	-0.93	2.42		2.52	-0.89	2.37		2.43	-0.62	2.27		2.66	-0.84	2.43
25		1.15	-0.24	1.43		1.57	-0.33	1.71		2.16	-0.29	2.18		1.85	-0.21	1.86		2.09	-2.47	-0.17
26		2.48	-0.66	2.54		2.23	-0.52	2.32		1.93	-0.31	1.90		1.68	-0.11	2.21		1.63	-3.21	-1.83
27		1.22	-0.19	0.98		1.30	-0.28	1.22		1.51	-0.54	1.45		0.36	-1.15	0.34		1.98	-1.41	1.05
28		0.88	-0.41	0.84		1.17	-0.40	1.20		2.02	-0.14	2.04		1.94	-0.06	2.08		1.69	-1.62	0.29
29		1.52	-0.18	1.56		1.61	-0.37	1.60		1.84	-0.37	1.90		1.59	-0.28	1.78		-0.10	-21.87	-22.90
30		2.08	0.14	2.84		2.12	0.12	2.84		2.34	-0.46	2.40		2.66	-0.39	2.64		2.56	-2.97	0.43

6. ICRU bulk density (VMAT)

Pt. no.	PTV																Brain stem			
	$D_{98\%}$				$D_{95\%}$				$D_{50\%}$				$D_{2\%}$				D_{1cc}			
	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W	CT_F	CT_W	MR_B	MR_W
1		-0.82	-0.74	1.01		-0.69	-0.65	1.11		-0.19	-0.72	1.48		-0.29	-0.74	1.39		-0.38	1.47	2.21
2		1.26	-0.63	-0.87		1.23	-0.38	-0.37		1.59	-0.28	-0.09		1.18	-0.32	-0.20		2.06	4.83	-0.84
3		3.27	-0.66	3.39		2.75	0.19	2.83		1.27	0.00	1.26		1.40	0.13	1.49		1.36	-0.13	1.34
4		3.68	0.02	3.58		2.07	-0.39	1.98		1.67	-0.30	1.61		1.49	-0.02	1.51		1.79	0.00	1.91
5		2.44	-1.57	1.49		2.15	-0.75	1.86		2.37	-0.31	2.35		3.49	0.09	3.40		1.93	-1.48	1.02
6		0.61	0.13	0.68		0.14	-0.12	0.14		0.22	-0.17	0.21		0.60	0.05	0.51		0.11	0.48	0.15
7		1.05	-1.02	1.07		1.16	-0.61	1.24		1.75	-0.34	1.69		1.27	-1.05	1.12		1.51	-0.64	1.07
8		13.42	1.25	13.83		11.79	1.16	12.05		3.54	-0.66	3.53		3.25	-0.61	3.20		2.70	-1.80	1.22
9		1.96	-0.70	1.49		2.07	-0.40	1.94		2.42	-0.14	2.47		2.46	-0.09	2.78		1.84	3.01	5.24
10		-0.71	-0.66	-0.56		-0.49	-0.70	-0.46		-0.12	-0.59	-0.16		0.34	-0.10	-0.03		-0.46	-0.87	-1.16
11		1.31	-0.63	1.26		1.31	-0.62	1.30		1.58	-0.54	1.55		2.60	-0.42	2.57		2.94	-0.55	2.90
12		2.70	-0.53	2.93		2.23	-0.53	2.30		1.95	-0.58	1.99		1.77	-0.40	1.89		1.91	-0.41	1.89
13		3.70	-0.16	3.83		3.04	-0.21	3.13		1.86	-0.77	1.86		1.72	-0.74	1.74		1.93	-1.83	1.84
14		0.98	-0.60	0.92		1.05	-0.51	1.05		1.53	-0.27	1.52		1.69	-0.18	1.70		1.65	-0.38	1.70
15	Ref.	0.86	-0.25	0.58	Ref.	0.71	-0.35	0.56	Ref.	0.91	-0.44	0.80	Ref.	1.18	-0.26	1.08	Ref.	0.95	-0.24	0.76
16		3.14	-0.10	3.06		2.18	0.13	2.30		0.43	-0.65	0.53		1.28	-0.49	1.50		1.00	-4.52	1.88
17		0.91	-0.59	0.64		0.90	-0.44	0.71		1.39	-0.36	1.35		1.40	-0.12	1.51		1.19	1.89	3.14
18		3.37	0.06	3.50		3.31	0.04	3.38		2.91	0.00	2.90		2.43	0.15	2.39		2.50	-1.30	1.38
19		2.79	0.21	2.76		2.05	0.53	1.95		0.89	-0.59	0.83		1.39	-0.57	1.39		1.21	-0.16	1.05
20		2.19	-1.09	1.02		2.04	-0.52	1.73		1.15	-0.56	1.56		0.75	0.01	1.32		0.53	-2.21	0.76
21		1.58	-0.41	1.76		1.36	-0.46	1.47		1.48	-0.60	1.49		1.64	-0.48	1.69		0.69	-5.93	-4.66
22		1.92	-0.65	1.82		1.22	-0.72	1.15		1.25	-0.65	1.18		1.53	-0.65	1.50		1.48	-1.05	0.75
23		0.88	-0.42	0.02		0.69	-0.23	0.16		1.08	-0.46	0.94		0.83	-0.06	0.91		1.33	-2.66	-0.96
24		2.58	-1.04	2.34		2.73	-0.92	2.56		2.58	-0.76	2.46		2.56	-0.79	2.54		2.93	-0.76	2.76
25		1.48	-0.14	1.54		1.43	-0.30	1.46		2.02	-0.30	2.03		2.01	-0.23	2.09		1.98	-1.00	1.23
26		1.38	-0.71	1.22		1.60	-0.62	1.44		1.87	-0.40	1.76		2.10	-0.10	2.40		1.22	-6.02	-5.00
27		1.81	-0.29	1.89		1.81	-0.38	1.86		1.85	-0.50	1.72		0.44	-1.16	0.40		2.52	-0.94	1.92
28		0.97	-0.22	1.04		1.16	-0.31	1.12		1.88	-2.91	1.87		2.55	-0.06	2.66		1.46	-1.37	0.35
29		1.37	-0.17	1.31		1.67	-0.40	1.66		1.92	-0.38	1.98		1.30	-0.21	1.46		0.17	-19.46	-19.70
30		2.39	0.16	2.95		2.41	0.04	2.85		2.48	-0.29	2.56		2.37	-0.38	2.44		2.04	0.50	3.10

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