EVALUATION OF TWO QUALITY CONTROL SOFTWARES IN GENERATING THE DOSE VOLUME HISTOGRAMS FOR VOLUMETRIC MODULATED ARC RADIOTHERAPY PLAN IN HEAD REGION

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ABSTRACT

This study was aimed to evaluate the dose volume histogram (DVHs) between COMPASS and 3DVH software for 3D patient-specific QA in VMAT technique used for head region. The MatriXX characteristics were studied before the clinical use. The DVHs of COMPASS and 3DVH software were evaluated for basic and advanced clinical application. The homogeneous phantom with four fields box technique plan was employed in the basic clinical application. For the advanced clinical application, 15 VMAT treatment plans targeting the head region were investigated. The treatment plans were transferred to MatriXX and ArcCHECK for measurement and to generated the DVHs in COMPASS and 3DVH software, respectively. The DVHs and percent gamma pass were compared with calculations from the Eclipse treatment planning system (TPS) according to dose specified in ICRU 83 for PTV and OARs. The study of the MatriXX characteristics illustrated the data provided were suitable for using in the clinic. With regard to the basic clinical application in homogeneous phantom with four fields box technique, COMPASS and 3DVH software showed comparable dose outcomes between the measurement and calculation from TPS for $D_{98\%,}$ $D_{95\%,}$ $D_{50\%,}$ $D_{2\%}$ and D_{mean} in PTV. For the advanced clinical application in 15 VMAT plans, the mean percent dose difference from TPS for the COMPASS of $D_{98\%,}$ $D_{95\%,}$ $D_{50\%,}$ $D_{2\%}$ and D_{mean} in PTV were -4.10±3.88%, 2.21±3.13%, 1.26±2.35%, 3.25±2.32% and 0.96±2.19%, respectively. The mean percent dose showed a difference of $D_{98\%,}$ $D_{95\%,}$ $D_{50\%,}$ $D_{2\%}$ and D_{mean} in PTV for the 3DVH were -8.34±4.32%, -7.90±4.02%, -4.06±2.45%, -0.19±2.27% and -4.23±2.12%, respectively. The TPS mean percent dose difference in OARs of both QA softwares showed a large variation with the highest difference of 11% in COMPASS software and 6.66% in 3DVH software. The percent of gamma pass (3%/3mm) of COMPASS, 3DVH and ArcCHECK were 99.19± 0.49, 94.98±3.49 and 98.87±0.84, respectively. The difference of percent pass in 3DVH was lower than ArcCHECK because of 3DVH software estimated 3D dose using PDP files while ArcCHECK displayed planar dose distribution. A weak correlation between percent gamma pass and dose in patient were observed. So, the pre-treatment verifications with DVHs analysis are recommended. The COMPASS and 3DVH software illustrated that both of QA software can be used in 3D pre-treatment verification.

KEY WORDS: VMAT / DVH / MATRIXX / COMPASS / 3DVH

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การประเมินความสัมพันธ์ของปริมาณรังสีและปริมาตร จากสองซอฟต์แวร์ ในแผนการรักษาเทคนิคการฉายรังสีแบบปรับความเข้มหมุนรอบตัวผู้ป่วยบริเวณศีรษะ

EVALUATION OF TWO QUALITY CONTROL SOFTWARES IN GENERATING THE DOSE VOLUME HISTOGRAMS FOR VOLUMETRIC MODULATED ARC RADIOTHERAPY PLAN IN HEAD REGION

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คณะกรรมการที่ปรึกษาวิทยานิพนธ์: พวงเพ็ญ ตั้งบุญดวงจิตร, Ph.D., ศิวลี สุริยาปี, M.Eng.

บทคัดย่อ

งานวิจัยครั้งนี้มีจุดประสงค์เพื่อศึกษาปริมาณรังสีและปริมาตร (DVHs) ของ COMPASS และ 3DVH ซอฟต์แวร์ ในการประกันคุณภาพของการฉายรังสีเทคนิคปรับความเข้มหมุนรอบตัวผู้ป่วย (VMAT) เครื่องวัดรังสี MatriXX ซึ่งใช้ข้อมูลสำหรับคำนวณใน COMPASS ถูกนำมาตรวจสอบคุณสมบัติก่อนนำมาใช้งานทางคลินิก การประเมิน DVHs ของ COMPASS และ 3DVH ได้ทำทั้งในคลินิคพื้นฐาน และคลินิคขั้นสูง ในการประเมินสำหรับคลินิคพื้นฐานใช้เทคนิคการฉายรังสีแบบสี่ทิศทางในแฟนทอมแผ่นที่เสมือนเนื้อเยื่อ และสำหรับการทดสอบทางคลินิกขั้นสูงใช้ 15 แผนการรักษาด้วยเทคนิค VMAT บริเวณศีรษะ โดยแผนการรักษาได้ส่งไปยังระบบการวัดของเครื่องวัด MatriXX และ ArcCHECK และใช้เป็นข้อมูลในการสร้าง DVHs ของ COMPASS และ 3DVH ซอฟต์แวร์ กราฟของ DVHs และ ค่าร้อยละการผ่านดัชนีแกมมาได้นำมาเปรียบเทียบกับปริมาณรังสีที่คำนวณในระบบการวางแผนการรักษา (TPS) ด้วยค่าการรายงานปริมาณรังสีจาก ICRU 83 สำหรับก้อนมะเร็ง (PTV) และ อวัยวะปกติข้างเคียง (OARs) การศึกษาคุณสมบัติของ MatriXX พบว่ามีคุณสมบัติเหมาะสมต่อการนำมาใช้งานทางคลินิก ผลการทดสอบพื้นฐานทางคลินิกพบว่า COMPASS และ 3DVH ซอฟต์แวร์ มี DVHs ของ PTV ตรงกันกับ TPS ด้วยการรายงานปริมาณรังสี $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ and D_{mean} และการทดสอบทางคลินิกขั้นสูงใน 15 แผนการรักษาพบว่าความแตกต่างของ DVHs เมื่อเปรียบเทียบกับ TPS ของ PTV ใน COMPASS เท่ากับ -4.10±3.88%, -2.21±3.13%, 1.26±2.35%, 3.25±2.32% และ 0.96±2.19% สำหรับ 3DVH ซอฟต์แวร์ เท่ากับ -8.34±4.32%, -7.90±4.02%, -4.06±2.45%, -0.19±2.27% และ -4.23±2.12% ตามลำดับ อวัยวะปกติใกล้เคียงพบว่ามีช่วงของความแตกต่างค่อนข้างกว้างเมื่อเปรียบเทียบกับ TPS ด้วยความแตกต่างสูงสุดของ COMPASS เท่ากับ 11% และ 3DVH เท่ากับ 6.66% การรายงานค่าร้อยละการผ่านดัชนีแกมมาของ COMPASS เท่ากับ 99.19 ± 0.49 3DVH มีค่าเท่ากับ 94.98 ± 3.49 และ ArcCHECK เท่ากับ 98.87±0.84 ความแตกต่างของค่าร้อยละการผ่านดัชนีแกมมาใน 3DVH พบว่ามีค่าต่ำกว่า ArcCHECK เนื่องจาก 3DVH ทำการประเมินปริมาณรังสีเป็นแบบ 3 มิติด้วยการใช้ไฟล์ PDP ขณะที่ ArcCHECK แสดงการประเมินด้วยการกระจายของปริมาณรังสีในระนาบ นอกจากนี้ยังพบว่าร้อยละการผ่านดัชนีแกมมาไม่สัมพันธ์กับปริมาณรังสีในผู้ป่วย ดังนั้นจึงควรตรวจสอบแผนการรักษาด้วยการวิเคราะห์ผลแบบ DVHs จากการศึกษาครั้งนี้สามารถนำ COMPASS และ 3DVH ซอฟต์แวร์ในการตรวจสอบแผนการฉายรังสีลักษณะของการประเมินปริมาณรังสีแบบ 3 มิติในทางคลินิกได้

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LIST OF ABBREVIATIONS

Abbreviation	Term
α	Alpha
%	Percentage
γ	Gamma
2D	Two dimensional
3D	Three dimensional
3D-CRT	Three dimensional conformal radiation therapy
AAA	Analytical anisotropic algorithm
cc	Cubic centimeter
cGy	Centi Gray
cm	Centimeter
cm^2	Square centimeter
$D_{2\%}$	The near maximum dose delivered to 2% of the target volume
$D_{50\%}$	The dose delivered to 50% of the target volume
$D_{95\%}$	The goal dose that dose delivered to 95% of the target volume
$D_{98\%}$	The near minimum dose that dose delivered to 98% of the target volume
D_{mean}	The mean dose
DTA	Distance to agreement
DVHs	Dose volume histograms
HI	Homogeneity Index

LIST OF ABBREVIATIONS (cont.)

Abbreviation	Term
IC	Ionization chamber
ICRU	The International Commission on Radiation Unit
IMRT	Intensity modulated radiotherapy
MeV	Mega electron volt
MLC	Multileaf collimator
ms	Millisecond
MU	Monitor unit
MV	Megavolt
OARs	Organ at risks
PDP	Plan dose perturbation
QA	Quality assurance
s	Second
TPS	Treatment planning system
VMAT	Volumetric modulated arc radiotherapy

CHAPTER I
INTRODUCTION

1.1 Background and Rationale

Radiotherapy is the procedure to treat cancer using radiation. It is used to treat cancer in several ways as a cure or as an adjuvant. Radiation treatment is considered a local treatment because only cells in and around the cancer are affected. It cannot cure cancer that has already spread to distant parts of the body because most forms of radiation therapy do not reach all parts of the body.

The images are employed during the treatment planning stage to determine; location, size of tumor and appropriate beam direction. Nowadays, we use radiological images to view the patient data in 3D or volume. Examples of which include; Computed tomography (CT), Magnetic resonance imaging **(**MRI**)** or Positron emission tomography **(**PET**).** The goals of the treatment process are; improving radiation dose accuracy and reducing side effects of radiation to normal tissue.

In addition, radiotherapy treatment techniques were developed, such as; 3 Dimensional Conformal Radiation Therapy (3DCRT), Intensity Modulated Radiotherapy (IMRT) and Volumetric Modulated Arc Radiotherapy (VMAT). The development of radiotherapy techniques contribute to the complexity in calculating the radiation dose and verification in treatment planning such as VMAT. VMAT is a technique that was developed from the IMRT technique and delivers radiation by rotating the gantry with the radiation continuously on [1]. Parameters in VMAT technique allow for variation of the MLC movement, dose rate and gantry rotation speed. VMAT planning is much more complicated than 3DCRT or IMRT. Therefore, patient specific QA is very important to make sure that the modulate dose is accurate. The treatment plan of VMAT is shown in Figure 1.1.

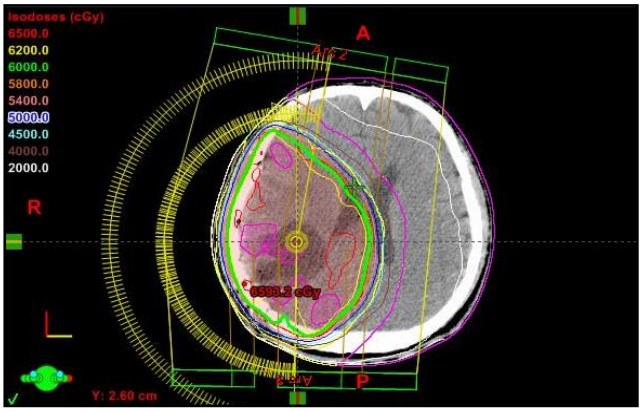


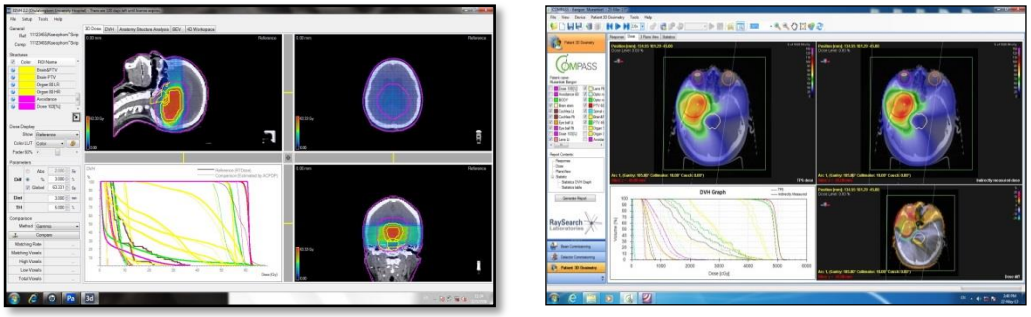
Figure 1.1 VMAT technique planning.

Patient specific QA is the process of dose accuracy check before patient treatment by comparison between calculated radiation dose in the treatment planning system and radiation dose from measuring. This is performed in phantom to prevent errors and to increase confidence that patients will receive the prescribed treatment dose correctly [2].

Nowadays, the most common treatment technique in the radiation oncology division at King Chulalongkorn Memorial Hospital is a VMAT. Patient specific QA for VMAT normally uses the 3D diode array (ArcCHECK: Sun Nuclear, USA). The ArcCHECK consists of 1386 diode detectors these are arranged in a spiral pattern with a distance between detectors of 1 cm [3]. The reporting of verification treatment plan illustrated a planar dose distribution in criteria of 95% gamma pass ($\gamma \leq 1$). Using a 2D planar dose distribution, it was found that the limitation in dose distribution did not relate to the patient dose. It did not show areas of hot and cold doses, it did not detect the precise locations of discrepancies and it did not predict the clinical impact on the patient in terms of changes in Dose Volume Histograms (DVHs).

Currently, the treatment plan can be verified by commercial QA tools in 3D dose or DVHs. In our clinic, the two commercial QA tools are; the 3DVH software (Sun Nuclear, USA) and the COMPASS software (IBA, Germany). For the 3DVH software (Sun Nuclear, USA), fluences from ArcCHECK detector and PDP algorithm are used to estimate dose [4]. The COMPASS software (IBA, Germany), fluences from MatriXX detector and collapse cone convolution/superposition algorithm are

used to generate dose [5]. The advantages of 3D dose verification are the displayed dose in term of DVHs change of patients, and the dose discrepancies can be determined before treatment process. Both of commercial QA tools are shown in Figure 1.2.



a)

b)

Figure 1.2 Commercial QA tools a) 3DVH software (Sun Nuclear, USA) and b) COMPASS software (IBA, Germany).

DVHs can be analyzed by dose definition of $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ and D_{mean} in PTV, D_{mean} in OARs and homogeneity index (HI) from ICRU 83 report [6]. In addition, both commercial QA tools can evaluate the dose distribution in term of gamma pass. In this study gamma pass ($\gamma \leq 1$) with 3%/3mm used to evaluate.

The 2D QA verification has limitations as it does not deal with patient dose, thus, it is unable to assess organ specific doses prior to actual treatment. Also, modern commercial QA tools can analyze in DVHs but there remains a lack of research in VMAT treatment planning. Both of these issues shall be addressed in this study. The purpose of this work is to observe DVH and dose report according to ICRU 83 definition in VMAT techniques of head region in both COMPASS and 3DVH softwares.

CHAPTER III
LITERATURE REVIEWS

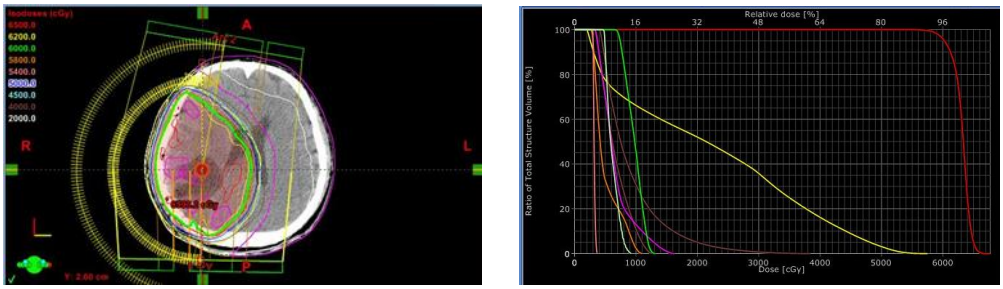
3.1 Review

3.1.1 VMAT [1]

The radiation dose in VMAT was delivered 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: the MLC aperture shape, the fluence output rate ("dose rate") and the gantry rotation speed. It is undisputed that VMAT can deliver highly conformal dose distributions similar to those created by other forms of IMRT.

VMAT can take advantage of the above mentioned for four available 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. The first and fourth of these are of course linked. 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. Unlike the technologies for optimizing "conventional" IMRT techniques, this planning technology is not yet considered mature and completed.

VMAT can generate equivalently conformal dose distributions with fewer monitor units (MUs), i.e., in a faster time. To have that is clearly advantageous (shorter treatments, better for patients in discomfort, less susceptibility to intra-fraction motion, possibly less induced secondary cancers and quicker overall treatment slots). The VMAT treatment technique is shown in Figure 3.1.



a) b)

Figure 3.1 Treatment plan of VMAT technique a) Isodose distribution and b) DVHs.

3.1.2. Treatment planning [7]

The computerized TPS are used in external beam radiotherapy to generate beam shape and dose distributions with the intent to maximize tumor control and minimize normal tissue complications. Patient anatomy and tumor targets can be represented as 3D models. The medical physicist is responsible for the overall integrity of the computerized TPS to accurately and reliably produce dose distributions and associated calculations for external beam radiotherapy. The simultaneous development of CT, along with the advent of readily accessible computing power, led to the development of CT based computerized treatment planning, providing the ability to view dose distributions directly superimposed upon a patient's axial anatomy. The entire treatment planning process involves many steps, beginning from beam data acquisition and entry into the computerized TPS, through patient data acquisition, to treatment plan generation and the final transfer of data to the treatment machine.

3.1.2.1 Inverse treatment planning [8]

Traditional forward based treatment planning is based on a trial and error approach by experienced professionals. The inverse planning makes using of dose optimization techniques to satisfy. The user specified criteria for the dose to the target and critical structures. Dose optimization is possible by making use of DVH based on CT, MRI or other digital imaging techniques. These optimized plans make using the required dose to the target organ while respecting dose constraint criteria for critical organs.

In VMAT, the objective function is a function of the beam let weights. The number of beam let for a given case varies from a few hundred to several thousands. 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 and 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. These variables and parameters constitute an additional multi-dimensional space, which is coupled to the beam profiles in complicated fashion.

3.1.3 Treatment planning verification [9]

The goal of radiation therapy is to achieve the greatest possible local and regional tumor control. To minimize the variability of tissue response, the ICRU has recommended that the uncertainty in dose delivery be maintained below approximately 5%. During radiation delivery for VMAT techniques, the MLC leaves are moving so the dosimetric verification of VMAT before treatment is necessary due to the complexity of delivery beams. To ensure that the intensity map pattern matches that intended by the treatment planning system and the MUs specified by the treatment planning system will in fact deliver the intended dose.

3.1.3.1 VMAT planning verification [10]

Dosimetric accuracy requirements have been developed for ‘‘conventional’’ treatments. Dose distributions are analyzed based on dose gradients. Low dose gradient regions are required to meet the acceptance criteria placed on dose difference, and high dose gradient regions are required to meet the acceptance criteria placed on distance to agreement (DTA). Tolerance levels for photon beam calculations are 3% and 3 mm, respectively.

Currently, the commercial VMAT QA tools can verify treatment planning in 3D dose distribution representation in DVHs comparison such as 3DVH and COMPASS software.

3.1.4 Commercial VMAT QA tools

3.1.4.1 ArcCHECK [3]

ArcCHECK (Sun Nuclear Corp., Melbourne, Florida, USA) is a detector array designed specifically for rotational delivery. ArcCHECK utilizes a unique cylindrical detector geometry that is nearly isotropic regardless of gantry angle. In addition, ArcCHECK utilizes Sun Nuclear SunPoint® diode detectors and appropriate detectors for routine, patient specific QA. ArcCHECK detector is shown in Figure 3.2.

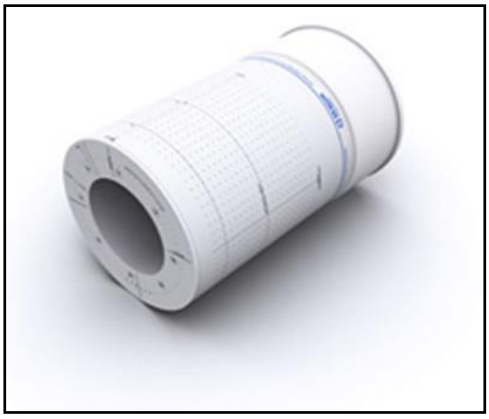


Figure 3.2 ArcCHECK detector (Sun Nuclear Corp., Melbourne, Florida, USA).

ArcCHECK phantoms are ideally shaped like a patient. The cylindrical design of ArcCHECK intentionally emulates patient geometry to better match reality. Specification of ArcCHECK is shown in Table 3.1.

ArcCHECK QA plans are in three dimensions which are generated to ArcCHECK phantom. The DICOM RT Dose and RT plan are imported to measurement device. The dose grid corresponding to detector locations is extracted for comparison to measurement. Verification treatment planning of ArcCHECK is shown in Figure 3.3.

Table 3.1 ArcCHECK specifications

Type	Specification
Sensor	Sunpoint Diode Detector
Number of sensor	1386 , Arrange in spiral pattern
ewDetector Volume	0.000019 cm^3
Distance between detectors	1cm
Physical detector depth	2.9 cm
Array diameter	21 cm
Array height	21 cm
Cavity diameter	15 cm
Phantom material	PMMA (Acrylic)

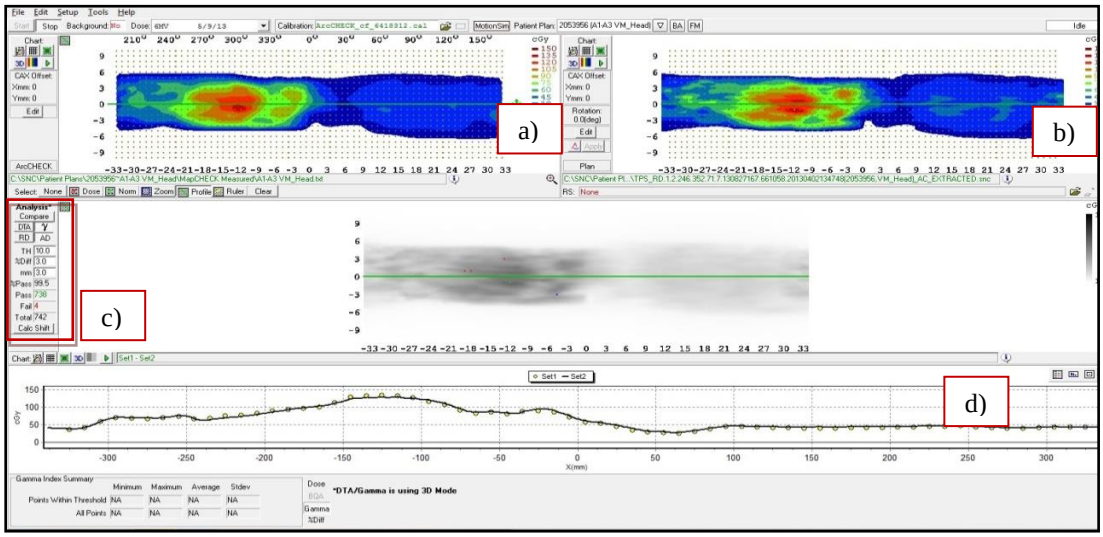


Figure 3.3 VMAT treatment verification planning of ArcCHECK; a) Measured, b) Planned, c) Gamma index comparison and d) Profiles comparison.

3.1.4.2 3DVH software [4, 11]

The 3DVH (Sun Nuclear Corp., Melbourne, Florida, USA) utilizes the Planned Dose Perturbation (PDP) algorithm to accurately estimate dose to patient and patient DVH using conventional planar VMAT QA data as inputs. The presence of significant tissue heterogeneities and their effect on PDP accuracy is a consideration given that input dose planes which a single depth in a homogeneous QA phantom. CT image sets are not required for the PDP calculation. Remapping of CT based tissue heterogeneities is not required for 3DVH because 3D dose voxel modification can be accomplished with great accuracy by knowing the patient geometry (surface, internal regions of interest), and the beam geometries relative to the patient model. Depth dependence is built into PDP (in addition to other variables, such as the effects of beam energy, linac, and MLC model).

The goal of PDP is not to correct for heterogeneities if the TPS has not, because a properly commissioned modern TPS dose algorithm will account for this. TPS errors (e.g. beam modeling, failure in a specific patient plan, etc.) or delivery errors (e.g. MLC errors, file corruption, output errors, etc.) that are measured in conventional VMAT QA, are used by PDP to estimate the impact to the patient dose/DVH. The inherent heterogeneity corrections by the TPS will be preserved and the dose voxels will be modified. 3DVHs work flow is shown in Figure 3.4.

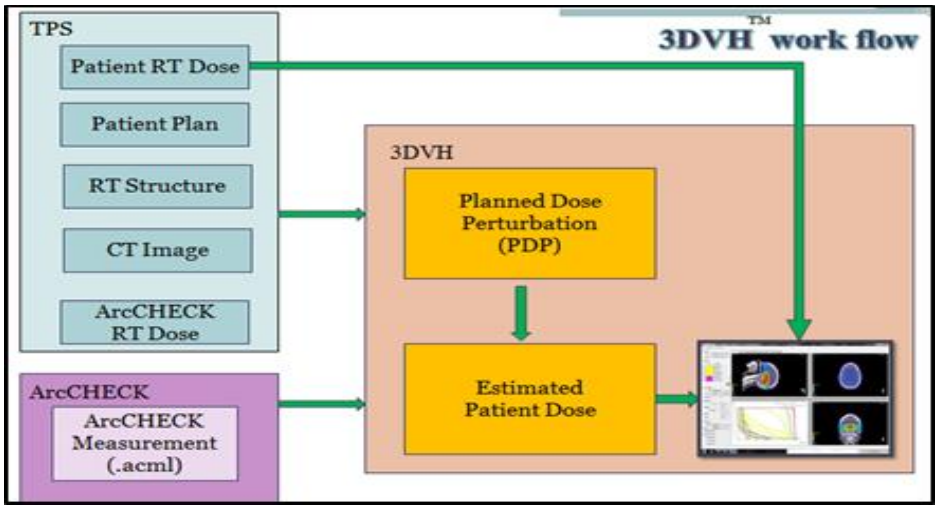


Figure 3.4 3DVH work flow.

3DVH software can generate 3D local (per structure) and global (per patient) such as gamma pass, DVH curves and dose statistic. Software input include: DICOMRT Plan, RT Dose, RT structure and planning CT dataset. The software output is shown in Figure 3.5.

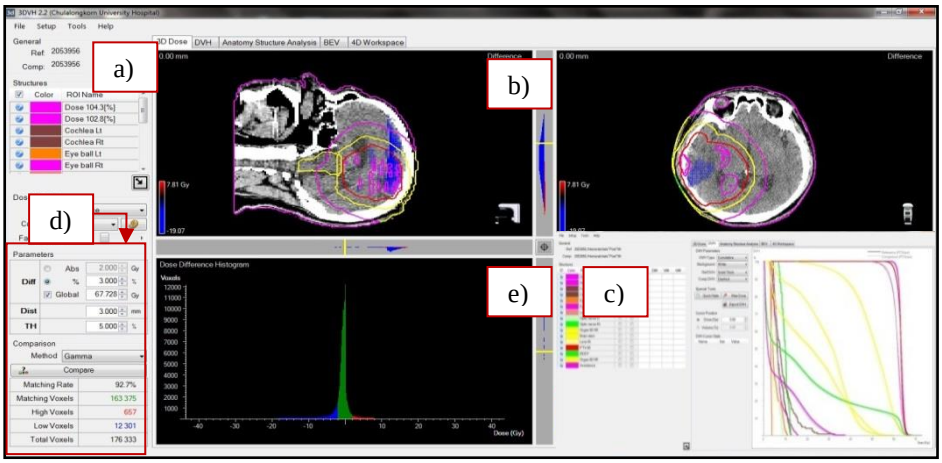


Figure 3.5 3DVH software output; a) Structures, b) Dose difference in structure, c) DVHs comparison, d) 3D gamma index comparison and e) Dose difference histogram.

3.1.4.3 MatriXX detector [12, 13]

The MatriXX detectors (IBA Dosimetry GmbH, Schwarzenbruck, Germany) have 1020 ionization chambers distributed in an active area of 24.4 × 24.4 cm², no dead time during the data acquisition due to unique electrometer solution, proven long term stability, and accuracy up to 2400 MU/min which is shown in Figure 3.6.

The MatriXX detector can be used in combination with the OmniPro-I´mRT or COMPASS software for verifying treatment plan. Specification of MatriXX is shown in Table 3.2.

Table 3.2 Specification of MatriXX detector

Type	Specification
Sensor	Vented parallel plate ion chamber
Number of sensor	1020 , Arrange in 32x32 cm^2
Chamber diameter	4.5 mm
Chamber height	5 mm
Chamber Volume	0.08 cm^3
Distance between detectors	7.62 mm
Nominal sensitivity	2.4 nC/Gy
Maximum dose rate	12 Gy/min
Minimum dose rate	0.02 Gy/min
Absorber material on top	3 mm ABS Tecaran (density 1.06 g/cm^3)
Effective point of measurement	Peff = 3 mm below surface

Figure 3.6 MatriXX detector (IBA Dosimetry GmbH, Schwarzenbruck, Germany).

3.1.4.4 COMPASS software [5, 14]

The COMPASS QA system (IBA Dosimetry GmbH, Schwarzenbruck, Germany) consists of COMPASSR software which can be used for pure dose computation or together with a 2D array sensor (MatriXX with the gantry angle sensor) for a measurement based dose reconstruction.

COMPASS is a system for clinically relevant 3D treatment verification and patient dose analysis. The COMPASS reconstructs dose from measured fluence, compares the patient plan with measurements and provides 3D dose deposition information inside the patient's anatomy. Plan evaluation is achieved either by visual means (evaluating dose differences/gamma relative to TPS inside patient CT) or on a structure by structure. The overall work flow of COMPASS dose reconstruction is shown in Figure 3.7.

COMPASS software performs a full three dimensional collapsed cone convolution/superposition dose reconstruction based on a dose engine. The patient's DICOM information from the TPS is imported into COMPASS. Afterwards, patient specific measurements are collected and dose is computed inside the patient's anatomy as opposed to that which is calculated inside a phantom by other QA systems. COMPASS can also compute dose independently and function as an independent secondary TPS verification without the need for detector based measurements. COMPASS employs a TPS class dose engine in order to provide not only accurate but anatomically localized QA dose information. The software output is shown in Figure 3.8.

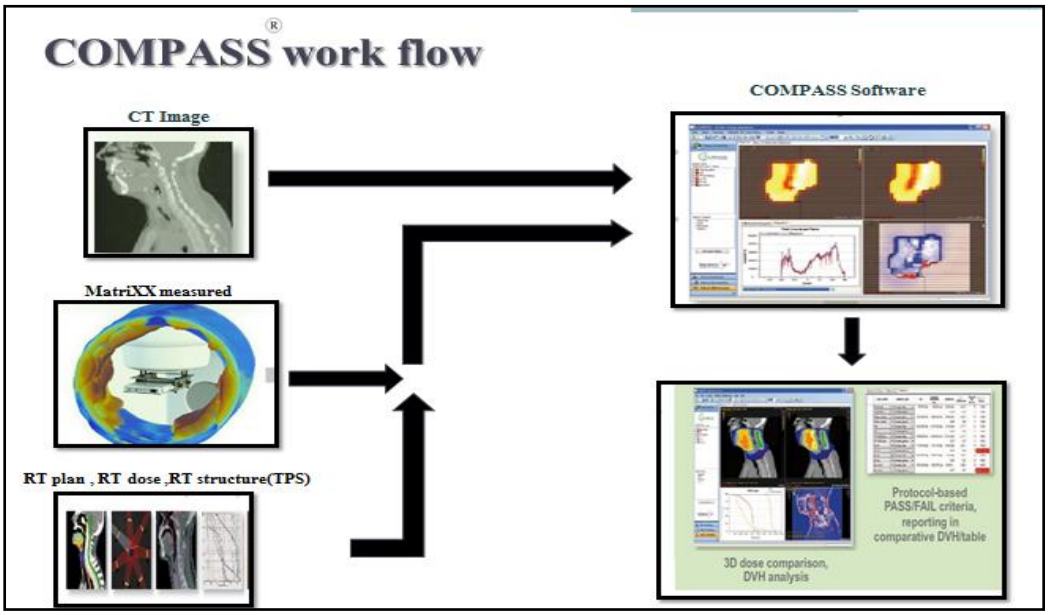


Figure 3.7 COMPASS reconstruction work flow.

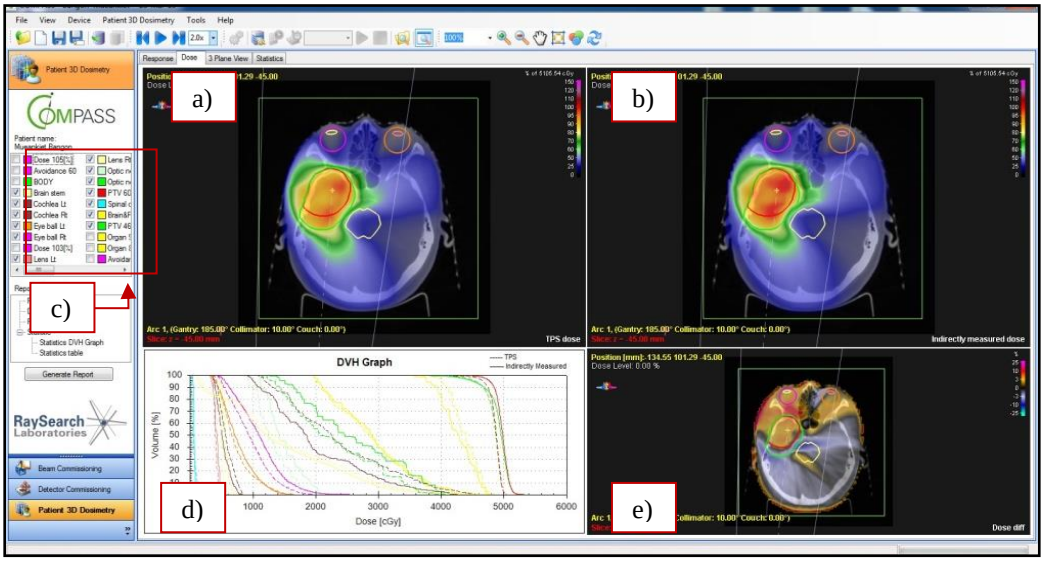


Figure 3.8 COMPASS software output; a) TPS dose, b) Indirectly measured dose, c) Structure, d) DVHs comparison and e) Dose difference.

3.1.5 Reporting dose in modern radiotherapy [6, 15]

Reporting dose recommendations in practical use in radiotherapy are based on absorbed dose and volume information obtained from DVHs which a level 2 and level 3 of ICRU83 dose report. 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 or other absorbed dose heterogeneities, which are often difficult to assess rapidly.

Cumulative DVHs are histograms of the volume elements that receive at least a given absorbed dose, and they are usually expressed as either the absolute volume or the volume relative to the total structure volume, receiving at least a given absorbed dose, each point on the line of a relative cumulative DVH is described by equation 3.1

$$\mathrm{DVH}_{\mathrm{rel\,cum}}(\mathrm{D}) = 1 - \frac{1}{\mathrm{V}}\int_0^{\mathrm{D_{max}}} \frac{\mathrm{dV(D)}}{\mathrm{dD}}\,\mathrm{dD} \qquad 3.1$$

Where; V is a volume of the structure. Dmax is the maximum dose in the structure. The differential DVH is defined by dV(D)/dD which is the increment of volume per absorbed dose at absorbed dose, D.

All commercial treatment planning systems now report cumulative DVHs for the specified volumes which a variety of metrics for reporting can be obtained. The main reason for the use of dose volume reporting in VMAT is that the coverage of the PTV by a specific absorbed dose can be explicitly determined from a DVH, and be better controlled through optimized planning. The use of dose volume reporting instead of reporting the absorbed dose at the ICRU Reference Point is predicated on the use of an adequate dose calculation system. Recently, dose calculation algorithms, such as the convolution/superposition method, have been adopted and provide accurate absorbed dose calculations because they function well in inhomogeneous tissues. The reporting dose of level 2 can be performed from DVHs, the doses at difference volumes which are shown in Figure 3.9.

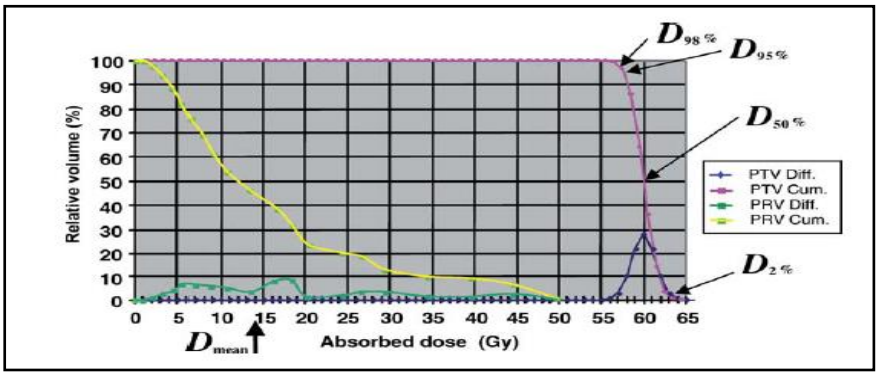


Figure 3.9 The dose specification of ICRU83 report in term of $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ and D_{mean}.

The doses specification of ICRU83 describe as follows;

$D_{98\%}$ or near minimum dose is the dose to 98% of PTV volume, which should be received more than 93% of prescription dose.

$D_{95\%}$ or goal dose is the dose to 95% of PTV volume, which should be received at prescription dose.

$D_{50\%}$ or median dose is the dose to 50% of PTV volume.

$D_{2\%}$ or near maximum dose is the dose 2% of PTV volume, which should not be received more than 110% of prescription dose.

D_{mean} is the mean dose of organ volume.

The Level 3 reporting describes techniques and concepts that sufficiently established to recommend their use in routine practice, such as dose homogeneity and dose conformity. For this study, the level 3 reporting were used in term of dose homogeneity.

Dose homogeneity or homogeneity index is an independent specification of the quality of the absorbed dose distribution. Homogeneity index characterizes the uniformity of the absorbed dose distribution within the target volume. The smaller value of homogeneity index value corresponds to more homogenous irradiation of target volume. For the homogeneity index value of 0 ("zero") corresponds to absolute homogeneity of dose within target. The homogeneity index can calculate from equation 3.2

$$HI = \frac{D_{2\%} - D_{98\%}}{\text{Median dose}} \qquad 3.2$$

3.2 Literature review

The researches related to this study are the characteristic study of VMAT QA tools (ArcCHECK and MatriXX detector) and the study in performance of 3DVH and COMPASS software in term of 3D dose verification. These published papers are presented as follows:

Kananan U. et al. [16] evaluated the performance of 2D planar and 3D cylindrical diode arrays for patient specific QA in IMRT and VMAT. MapCHECK and ArcCHECK were studied for their properties before clinical use. The clinical performance was demonstrated with IMRT and VMAT plans, the measured results were compared with the calculation from Eclipse treatment planning. The gamma index of 3% /3mm with 10% threshold dose were the criteria of agreement between measured and calculated.

MapCHECK and ArcCHECK showed linearly dose response and demonstrated a short term reproducibility within ±0.02% and long term reproducibility within ±1% for MapCHECK and ±2% for ArcCHECK. The repeatability rate effect was within ±0.25% and the dose rate response was within ±1% for both detectors. The field size dependence was close to ionization chamber response. The variation in energy response was within ±4% for MapCHECK and ±2% for ArcCHECK. The beam profile of open and 30° of hard and enhance dynamic wedge showed good agreement with calculated dose. Both detectors illustrated the excellent passing rates for all 15 IMRT and VMAT plans. For IMRT, The average of the % pass of MapCHECK was 97.31 with the mean gamma of 0.45 while the average of the % pass of ArcCHECK was 97.21 with the mean gamma of 0.46. For VMAT, The average of the % pass of MapCHECK was 98.55 with the mean gamma of 0.37, while the average of the % pass of ArcCHECK was 97.04 with the mean gamma of 0.43.Both detectors have excellent performance for IMRT and VMAT verification, however, the characteristics of the devices should be studied before clinical used.

Herzen J. et al. [17] presented the results of a dosimetric evaluation of a 2D ionization chamber array with the objective of its implementation for quality assurance in clinical routine. The effective depth of measurement under the surface of

the detector was determined. The dose and energy dependence, the behavior of the device during its initial phase and its time stability as well as the lateral response of a single chamber of the detector in cross plane and diagonal directions were analyzed.

The results showed, that the detector's response was dose linearity with correlation coefficient of showed the comparable reading linear R^2 and energy independent in the ranging from 4 to 15 MV photon beams. During the start up phase, the detector needs a pre-irradiation of approximately 10 Gy to reach a stable signal. The response functions of a single ionization chamber of the array were measured in the cross plane and diagonal directions. This characteristic was taken into account for the verification of IMRT fields that the planned data were corrected. The comparisons of the profiles for two different dose distributions were in a good agreement when the corrections were applied. From these investigations it can be concluded that the detector is a suitable device for quality assurance and 2D dose verifications.

Li J. et al. [18] compared commercial 2D array to use in the quality assurance of patient specific IMRT treatment plans: one was a diode based array (MapCHECK) and the other was an ion chamber based array (MatriXX). The dependence of the response of detectors on field size, dose rate, and radiation energy was measured and compared with reference measurements using a Farmer type ionization chamber. The linearity of the detector response, short term and long term reproducibility, statistical uncertainty as a function of delivered dose, and the validity of the array calibration were also examined to understand the stability and uncertainty of the systems. No field size or SSD dependence was observed within the range of the field sizes and SSDs used in the study at both 6 MV and 18MV photon energies. Both detector arrays showed negligible errors (<1%) when measuring doses of more than ~8 cGy, but exhibited errors of ~3% when measuring doses on the order of 1 cGy. While the MapCHECK showed a stable short-term reproducibility to within measurement error, the MatriXX showed a slow but continuous increase in readings during the initial one hour period (about 0.8%). The MapCHECK also showed a slightly better array sensitivity correction with all the detectors having less than 1% discrepancy and more than 90% of the detectors within 0.5% variation, whereas about 60% of the MatriXX detectors showed a less than 0.5% variation and ~8% exhibited a larger than

1% discrepancy. MatriXX detectors also displayed a volume averaging effect consistent with its detector size of ~ 4.5 mm in diameter. Excellent passing rates were obtained for both detector arrays when compared with the planar dose distributions from the treatment planning system for three 6 MV IMRT fields and three 18 MV IMRT fields after the volume averaging effect of the MatriXX was taken into account.

Heming Z.et al. [19] explored the usefulness of the gamma pass metric for per patient, pretreatment dose QA and to validate a DVH based method and its accuracy and correlation. Specifically, correlations between: (1) gamma pass for three 3D dosimeter detector geometries vs. clinically relevant patient DVH-based metrics, (2) Gamma pass of whole patient dose grids vs. DVH based metrics, (3) gamma pass filtered by region of interest (ROI) vs. DVH based metrics and (4) the capability of a novel software algorithm that estimates corrected patient dose DVH based on conventional phantom QA data are analyzed.

The ninety six unique "imperfect" step and shoot IMRT plans were generated by applying four different types of errors on 24 clinical Head&Neck patients. The 3D patient doses as well as the dose to a cylindrical QA phantom were then recalculated using an error-free beam model to serve as a simulated measurement for comparison. Resulting deviations to the planned vs. simulated measured DVH based metrics were generated, as were gamma pass for a variety of difference/distance criteria covering: dose in phantom comparisons and dose in patient comparisons, with the in-patient results calculated both over the whole grid and per ROI volume. Finally, patient dose and DVH were predicted using the conventional per-beam planar data as input into a commercial "planned dose perturbation" (PDP) algorithm, and the results of these predicted DVH based metrics were compared to the known values.

The results show that: A range of weak to moderate correlations were found between clinically relevant patient DVH metrics ($CTVD_{95}$, parotid D_{mean}, spinal cord D1cc, and larynx Dmean) and both 3D detector and 3D patient gamma pass (3%/3 mm, 2%/2 mm) for dose in phantom along with dose inpatient for both whole patient volume and filtered per ROI. There was considerable scatter in the gamma pass vs DVH based metric curves. However, for the same input data, the PDP estimates were in agreement with actual patient DVH results.

Gamma pass, even if calculated based on patient dose grids, has generally weak correlation to critical patient DVH errors. However, the PDP algorithm was shown to accurately predict the DVH impact using conventional planar QA results. Using patient DVH based metrics IMRT QA allows per patient dose QA to be based on metrics that are both sensitive and specific.

Boggula R. et al. [20] validated the dosimetric performance of COMPASS, a novel 3D quality assurance system for verification of volumetric modulated arc therapy (VMAT) treatment plans that can correlate the delivered dose to the patient's anatomy, taking into account the tissue inhomogeneity. The accuracy of treatment delivery was assessed by the COMPASS for 12 VMAT patient plans transfered to phantom, and the resulting assessments were evaluated using an ionization chamber and film measurements. Dose volume relationships were evaluated by the COMPASS for three patient treatment plans and these were used to verify the accuracy of treatment planning dose calculations. The results matched well between COMPASS and measurements for the ionization chamber (3%) and film (73–99% for gamma (3%/3mm) <1 and 98–100% for gamma (5%/5mm) <1) for the phantom plans. Differences in dose volume statistics for the average dose to the PTV were within 2.5% for three treatment plans. For the structures located in the low dose region, a maximum difference of <9% was observed. In this implementation, the system could measure the delivered dose with sufficient accuracy and could project the 3D dose distribution directly on the patient's anatomy. Slight deviations were found for large open fields. These could be minimized by improving the COMPASS in built beam model.

CHAPTER IV
MATERIALS AND METHODS

4.1 Materials

4.1.1 Varian Clinac iX linear accelerator

The Varian Clinac iX linear accelerator (Varian Oncology systems, Palo Alto, CA, USA) has dual 6 and 10 MV photon beams and six energy levels of 4, 6, 9, 12, 16 and 20 MeV electron beam. Photon field sizes are ranged from 0.5×0.5 cm^2 to 40×40 cm^2 at the isocenter. The distance from the target to isocenter is 100 cm. Dose rates are ranged from 100 to 600 monitor units per minute. The MLC is 120 leaves that can move as the dynamic movement. Varian Clinac iX linear accelerator is shown in Figure 4.1.

Figure 4.1 Varian Clinac iX linear accelerator (Varian Oncology systems, Palo Alto, CA, USA).

4.1.2. Two dimensional ionization arrays device

The MatriXX (IBA Dosimetry GmbH, Schwarzenbruck, Germany) contains 1020 single air vented plane parallel cylindrical ionization chambers with 0.55 cm height, 0.45 cm chamber diameter, 0.76 cm chamber to chamber distance and 0.07 cm^3 sensitive volumes. Detectors are arranged in a 32×32 cm^2 and no detectors in the corners of the array. Active area is 24.4×24.4 cm^2. Effective point for measurement is 3 mm below surface of the array. The MatriXX is shown in Figure 4.2.

Figure 4.2 MatriXX detectors (IBA Dosimetry GmbH, Schwarzenbruck, Germany).

4.1.3 MatriXX gantry mounting

The MatriXX gantry mounting (IBA Dosimetry GmbH, Schwarzenbruck, Germany) consists of gantry adapter and holder support frame. The gantry adapter in this study has isocenter mounting for 100 cm SDD. The holder support frame has an opening for laser alignment. The surface of the detector area is positioned at 3.0 mm below the MatriXX housing surface so SSD equals 99.7 cm. MatriXX gantry mounting is shown in Figure 4.3.

Figure 4.3 Varian MatriXX gantry mounting for 100 cm SDD (IBA Dosimetry GmbH, Schwarzenbruck, Germany).

4.1.4 Gantry angle sensor

The Gantry angle sensor (IBA Dosimetry GmbH, Schwarzenbruck, Germany) is a tool for VMAT dosimetry in online detection of the gantry angle while irradiating for treatment verification with ± 0.4° accuracy during the first year (± 0.6° for the remaining life time), 3 m cable length, temperature range usage 0°C to +50°C and connection MatriXX service RS 232 port. Gantry angle sensor is shown in Figure 4.4.

Figure 4.4 Gantry angle sensor (IBA Dosimetry GmbH, Schwarzenbruck, Germany).

4.1.5 Omnipro IMRT software

The Omnipro IMRT software (Version 1.7b, IBA Dosimetry GmbH, Schwarzenbruck, Germany) is used to study detector properties. The data is collected from MatriXX signal. Parameters for measuring include; movie measuring mode, not scaling, 500 ms sampling time, 1 number of sample, 0.500 s measuring time, 10,000 numbers of movie images and 20 s of background measuring. The Omnipro IMRT software is shown in Figure 4.5.

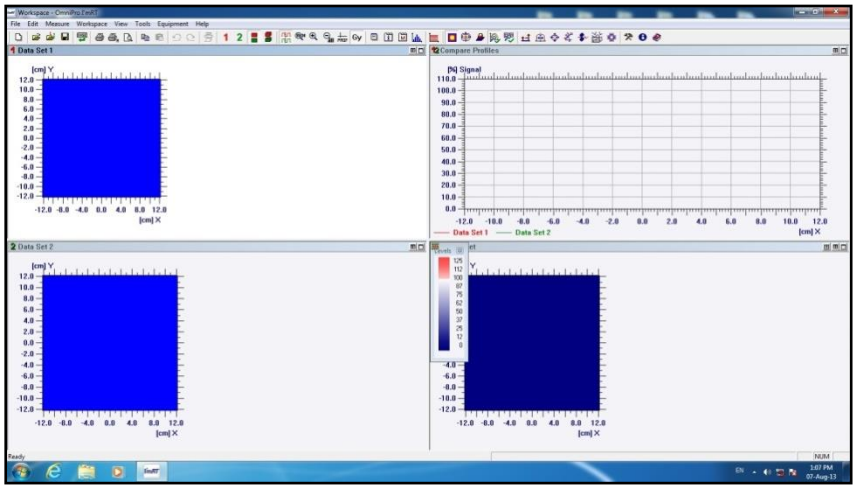


Figure 4.5 Omnipro IMRT software (Version 1.7b, IBA Dosimetry GmbH, Schwarzenbruck, Germany).

4.1.6. COMPASS software

The COMPASS software (Version 2.1.3.0, IBA Dosimetry GmbH, Schwarzenbruck, Germany) can verify the treatment plans in two ways: dose computation based on patient data from TPS (independent secondary TPS verification) and dose reconstruction based on fluence from MatriXX detector measurement. The COMPASS software is shown in Figure 4.6.

Dose computation (independent secondary TPS verification) needs patient DICOM files (RT plan, RT dose, RT structures, and CT images). The COMPASS uses a collapsed cone convolution/superposition algorithm for the dose calculation engine in DVH based comparisons.

The dose reconstruction is a QA systems based on fluence from MatriXX detector measurement. The dose reconstruction needs patient DICOM files (RT plan, RT dose, RT structures, and CT images). The COMPASS has a model that can predict the response in the detector and a response in calculation algorithm. This predicted detector response is compared against the corresponding measured detector response. The differences found from the comparison results are provided as an input to the final dose calculation in DVH based comparisons.

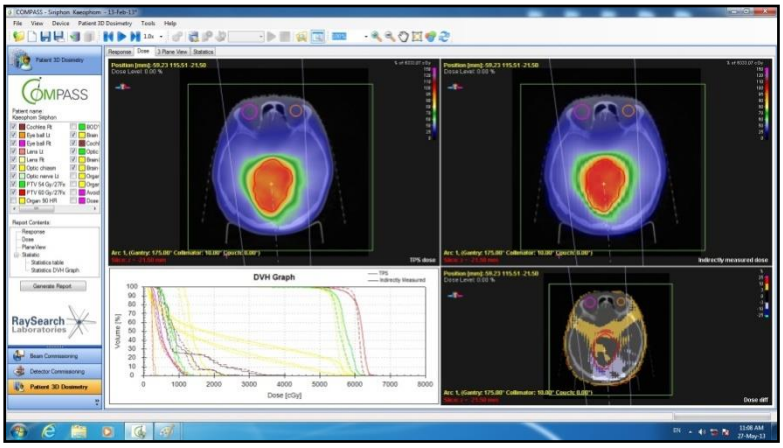


Figure 4.6 The COMPASS Software (Version 2.1.3.0, IBA Dosimetry GmbH, Schwarzenbruck, Germany).

4.1.7 Three dimensional diode arrays device

The ArcCHECK (Sun Nuclear Corp., Melbourne, Florida, USA) is a cylindrical detector geometry with a three dimensional array of 1386 diode detectors in a spiral pattern with 10 mm detector spacing, 21 cm array diameter, 21 cm array height and 2.9 cm physical depth. ArcCHECK detector is shown in Figure 4.7.

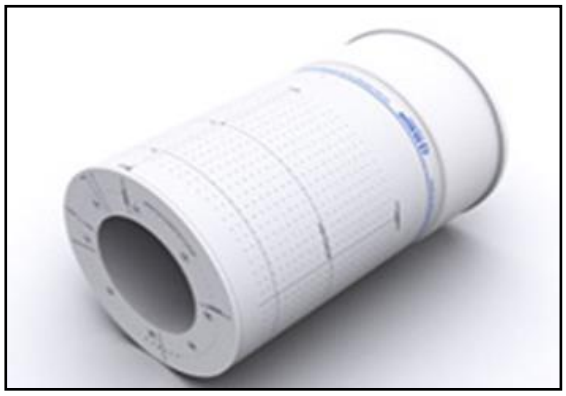


Figure 4.7 The ArcCHECK detector (Sun Nuclear Corp., Melbourne, Florida, USA).

4.1.8 The 3DVH software

The 3DVH software (Version 2.2, Sun Nuclear Corp., Melbourne, Florida, USA) needs patient DICOM files (RT plan, RT dose, RT structures, and CT images) from the TPS. The treatment plan is verified by creating a planned dose perturbation (PDP) file from errors in comparison between patient RT dose and ArcCHECK RT dose. The errors are convulsed in ArcCHECK measurement data. The evaluation base on estimate dose to patient by overlay the resultant using the resultant PDP beams on the patient CT images and show clinical impact using a DVHs analysis tool. The 3DVH software is shown in Figure 4.8.

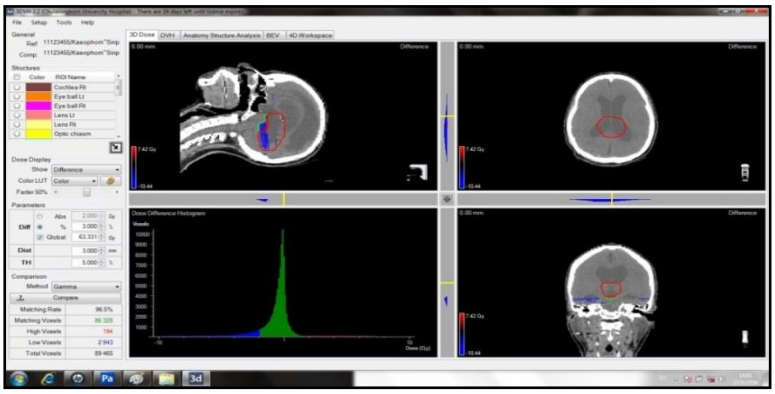


Figure 4.8 The 3DVH software (Version 2.2, Sun Nuclear Corp., Melbourne, Florida, USA).

4.1.9 Solid water phantom

The solid water phantom (RMI 457, CIVCO medical solution, IA, USA) made from epoxy resin based mixture which has the density of 1.03 g/cm^3 and 3.34$\times$ 10^2 electron/g, respectively. The size of the solid water phantom is 30$\times$30 cm^2 with 0.2, 0.5, 2, 4 and 5 cm thicknesses. The solid water phantoms are shown in Figure 4.9.

Figure 4.9 The solid water phantoms (RMI 457, CIVCO medical solution, IA, USA).

4.1.10 Ionization chamber

The CC13 ionization chamber (IBA Dosimetry GmbH, Schwarzenbruck, Germany) is used for clinical in water phantoms or solid water phantoms for output factor measurements. The CC13 ionization chamber is a compact chamber with 0.13 cc volume, 0.044 nC/cGy sensitivity, 5.8 mm active length and 6 mm inner diameter. Venting is accomplished through the waterproofing sheath and the chamber connector. These ion chambers can be safely inserted and used in water. The CC13 ionization chamber is shown in Figure 4.10.

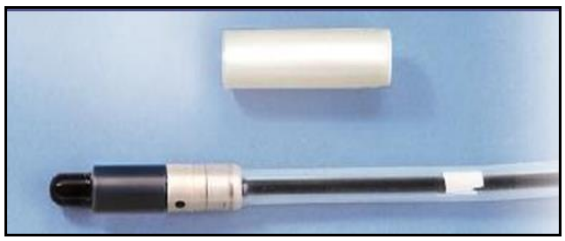


Figure 4.10 The CC13 ionization chamber (IBA Dosimetry GmbH, Schwarzenbruck, Germany).

4.1.11 Electrometer

The DOSE 1 Electrometer (IBA Dosimetry GmbH, Schwarzenbruck, Germany) is a portable, single channel, high precision reference class electrometer that significantly exceeds the recommendations of the IEC 60731 with 500V bias voltage, 15 - 35 ℃ temperature range and 100 – 240 V power supply. The measuring quantities and unit can be displayed in Gy, Sv, R, rad and rem. The electrometer can be used with ionization chambers, semiconductor detectors and diamond probes for measurements of absorbed dose with the two measuring mode in charge mode (ranging from 40 pC to 1.0 pC at 0.1 pC resolution) and current mode (ranging from 40 pA to 1000 nA at 0.1 pA resolution). In combination with radioactive check sources the response stability of the ionization chambers is verified and the cross calibration performed. The DOSE 1 Electrometer is shown in Figure 4.11.

Figure 4.11 The DOSE 1 Electrometer (IBA Dosimetry GmbH, Schwarzenbruck, Germany).

4.1.12 Treatment planning software

The Eclipse treatment planning software (Version 8.9.21, Varian Medical System, Palo Alto, CF, USA) is a comprehensive treatment planning system that simplifies modern radiation therapy planning for all kinds of treatment including 3D conformal, IMRT and VMAT. The conventional technique is planned by forward planning, while IMRT and VMAT are planned by inverse planning using analytical anisotropic algorithm (AAA). The physicists used Eclipse treatment planning software to calculate the dose distribution and verify the best treatment plans for patients. Eclipse treatment planning software version 8.9.21 is shown in Figure 4.12.

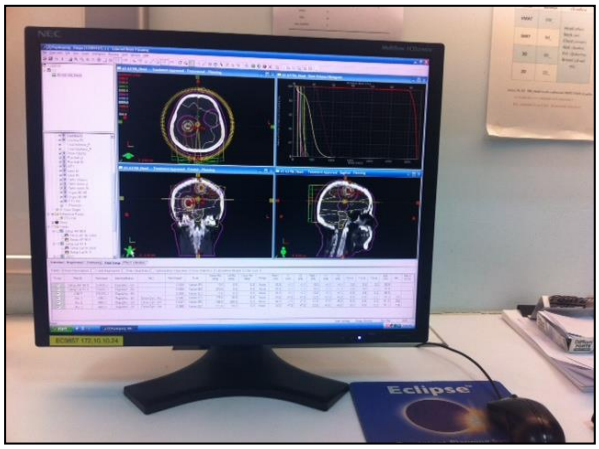


Figure 4.12 The Eclipse treatment planning software (Version 8.9.21 Varian Medical System, Palo Alto, CF, USA).

4.2 Methods

4.2.1 Study of detector properties

The characteristic of the detectors should be studied before using in the clinic. The properties of MatriXX were investigated in this work. The properties of ArcCHECK were already studied since 2011[16].

The setup of detector throughout this study is shown in Figure 4.13. The MatriXX was attached to the gantry with gantry holder. The solid water phantom thickness for buildup of the detector was 4.7 cm. The source to detector distance was set at 100 cm.

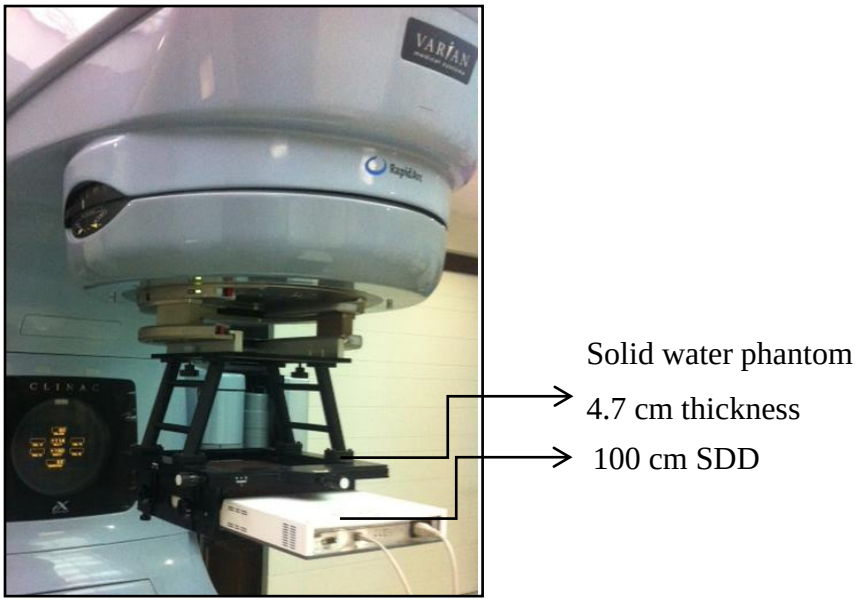


Figure 4.13 MatriXX detector setup

4.2.1.1 Initial phase time dependence

The measurements were performed on the MatriXX detector to study the effect of the device warming up before measurement. The measurement composed of 2 parts. The first part involved measuring before the device was warm up. The second part involved measuring after the device was warmed up for 15 minutes. The dose rate of 400 MU/min at 10×10 cm^2 field size, 100 cm source to detector distance, 100 MU, 6 MV photon beam and 20 times of measurement were acquired. The average signal result of four detectors around central of the MatriXX was taken.

4.2.1.2 Gravitational effect of gantry rotation

The MatriXX detector was attached on the gantry with gantry holder. This study was aimed to see the effect of the gravitation by gantry rotation with the MatriXX detector. The measurements were performed with the following parameters: 400 MU/min dose rate, 10x10 cm^2 field size, 100 cm source to detector distance, 100 MU delivered, 6 MV photon beam and gantry rotation 20° increment. The average signal result of four detectors around central of MatriXX was taken. The 2 Gy pre-irradiation were performed before the measurement was undertaken for all characteristic studies.

4.2.1.3 Dose and energy response

To measure the correlation between dose and energy response, we used different photon beams (6 and 10 MV). The dose was varied from 10 to 2500 cGy (10, 20, 100, 200, 500, 1000, 1500, 2000 and 2500 cGy). The parameters of measurement were: 400 MU/min dose rate, 10×10 cm^2 field size and 100 cm source to detector distance. The average signal result of four detectors around central of the MatriXX was taken. The dose linearity and the energy response were analyzed at the same data measurement.

4.2.1.4 Repetition rate effect

The repetition rate effect of the MatriXX detector were performed by measuring response of 6 and 10 MV photon beams with 100 MU delivered, 10x10 cm^2 field size, 100 cm source to detector distance and repetition rate from 100 to 600 MU/min (100, 200, 300, 400, 500 and 600 MU/min). Average signal result of four detectors around central of MatriXX was taken.

4.2.1.5 Field size effect

The effect of field size for MatriXX detector were performed with 6 and 10 MV photon beams, 100 MU delivered, 10x10 cm^2 field size, 100 cm source to detector distance. The various square field sizes were ranged from 3×3 to 20×20 cm^2 (3×3, 4×4, 6×6, 8×8, 10×10, 12×12, 15×15 and $20 \times 20\ cm^2$). The average signal result of four detectors around central of MatriXX was taken. These results were compared with CC13 ionization chamber measurement in the same condition. The measurement set up of CC13 ionization chamber is shown in Figure 4.14.

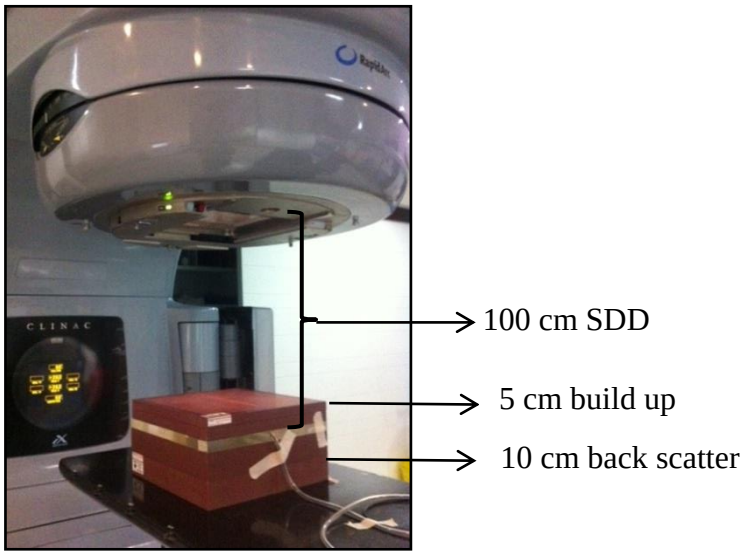


Figure 4.14 The measurement of CC13 for field size effect with 100 SDD, 5 cm build up and 10 cm back scatter.

4.2.1.6 Reproducibility

The studies were undertaken for performance of MatriXX detector over period of time in short and long term reproducibility. The measurement parameters in this study were 400 MU/min dose rate, 100 MU delivered, 10x10 cm^2 field size and 100 cm source to detector distance. The signal was collected after warming up the device and pre-irradiation of 200 cGy. The measurements were undertaken every 5 minutes over 60 minutes in short term reproducibility and every week over 3 months in long term reproducibility.

4.2.1.7 Statistical uncertainty (Function of delivered dose)

Statistical uncertainties were tested on function of delivered dose of MatriXX detector in low dose response. These study were performed with 26×26 cm^2 field size, varied dose ranging from 1 to 300 cGy (1, 2, 5, 10, 50, 100, 200, 300 cGy), 400 MU/min dose rate and 100 cm source to detector distance. The results from measurement were taken from all detectors in MatriXX array. We used the measurement dose with 300 cGy as a base line for calculation. The Percent error

(PE) was calculated according to equation 4.1 and standard deviations of percent error of all detectors in MatriXX were reported.

$$PE_i(D) = \left[R_i(D) x \frac{\bar{R}(D=300)}{\bar{R}(D)} - R_i(D = 300)\right] \div R_i(D = 300) x 100\% \quad 4.1$$

Where:

$PE_i(D)$ is a percent error of each detector (i)

$R_i(D = 300)$ is an detector i received 300 cGy

$R_i(D)$ is a detector i received dose (cGy)

$\bar{R}(D = 300)$ is an average reading of all detectors that received 300 cGy

$\bar{R}(D)$ is an average reading of all detectors that received dose cGy

4.2.2. Basic clinical application

This study was aimed to verify that the DVHs from basic treatment planning in homogeneous phantom plan for four field box technique worked correctly. The structures of homogenous phantom were generated which followed from TRS 430 in dose volume histogram test of compound structure using Boolean logic in TPS. The Boolean logics were used to create compound structure for optimization such as body subtract with PTV, etc. The DVHs comparison was performed in COMPASS independent QA software (dose computation), COMPASS software by MatriXX measurement (dose reconstruction) and 3DVH software. The flow chart of basic clinical application is shown in Figure 4.15

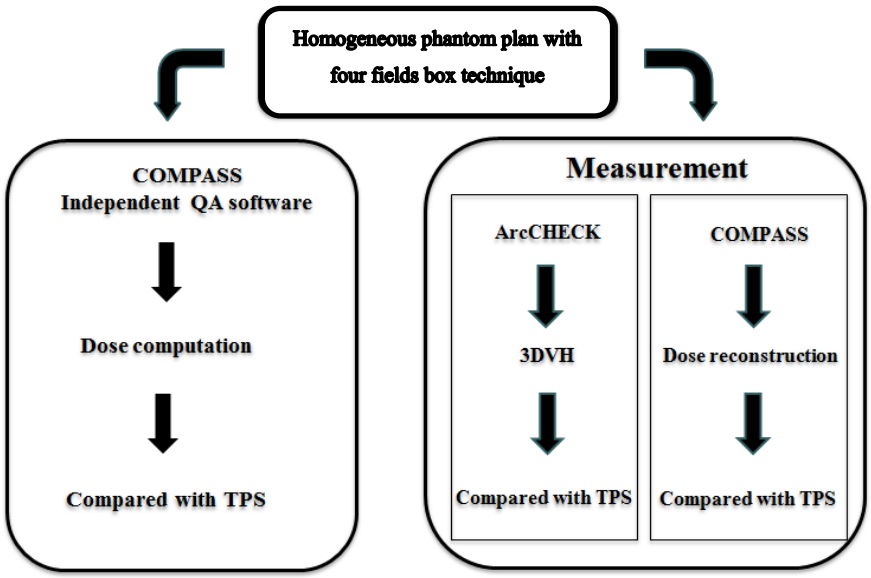
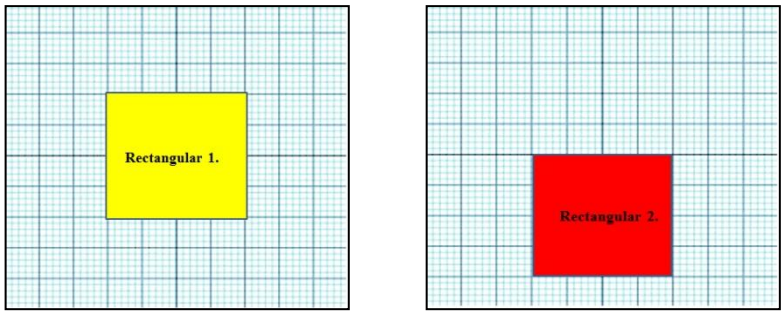


Figure 4.15 Flow chart of basic clinical application study

4.2.2.1 Generating homogeneous phantom plan with four fields box technique

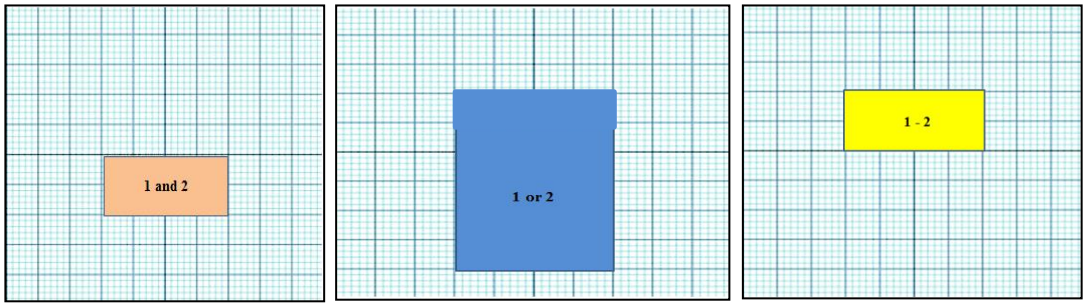
First, the basic structures were created in the solid water phantom with basic 3D structure volumes ($4 \times 4 \times 4$ cm^3) as a rectangular 1 and rectangular 2. This is shown in Figure 4.16.



a) b)

Figure 4.16 Demonstrating of the basic structures in 4x4x4 cm^3 volume size; a) Rectangular 1 and b) Rectangular 2.

Second, the Boolean logics in TPS were used to create the compound structures which consisted of Rectangular 1 and Rectangular 2, Rectangular 1 or Rectangular 2 and Rectangular 1 subtract with Rectangular 2. This is shown in Figure 4.17.



a) b) c)

Figure 4.17 Demonstrating of the basic compound structures by Boolean logic a) 1and 2, b) 1 or 2 and c) 1 subtract 2.

Third, the basic treatment plan was generated in four fields box technique with MLC and TPS dose calculation. The basic treatment plan is shown in Figure 4.18. The planning parameter are as follows;

AP: 0° gantry angle with 8x8 cm^2 field size

PA: 180° gantry angle with 8x8 cm^2 field size

RL: 270° gantry angle with 4x6 cm^2 field size

LL: 90° gantry angle with 4x6 cm^2 field size

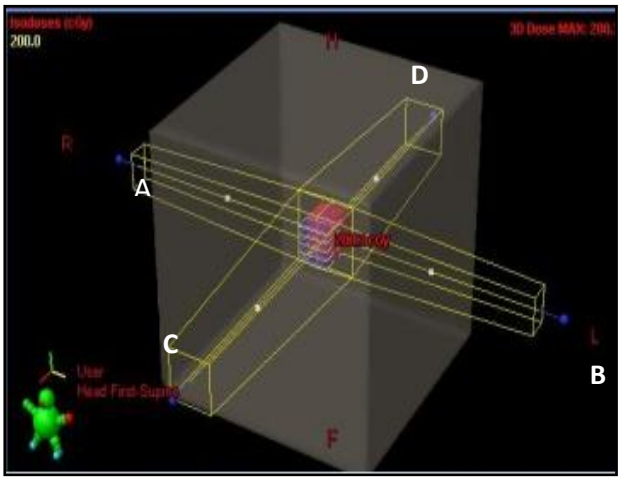


Figure 4.18 Basic treatment plan of homogenous phantom with four fields box technique; A. field RL, B. field LL, C. field AP and D. field PA.

4.2.2.2 DVHs comparison between COMPASS dose computation (independent QA software) and TPS

First, the DICOM files (RT plan, RT dose, RT structures, and CT images) of basic treatment plan in homogeneous phantom were exported to COMPASS software.

Second, the dose computation was selected on the patient 3D dosimetry with computed dose in COMPASS software which is shown in Figure 4.19. The DVHs were created from COMPASS dose computation algorithm.

Finally, the DVHs were compared between COMPASS dose computation and TPS dose calculation.

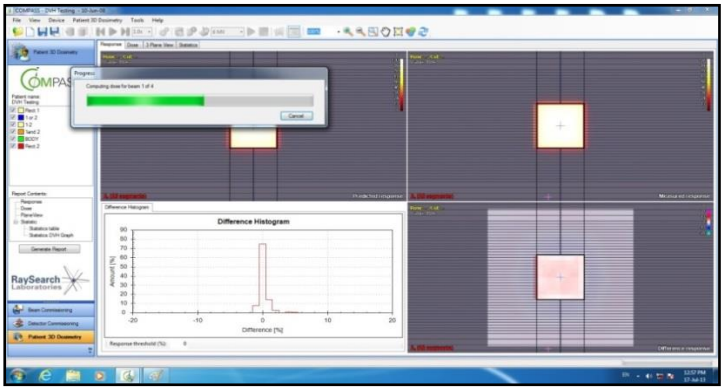


Figure 4.19 COMPASS software in computed dose function.

4.2.2.3 DVHs comparison between COMPASS dose reconstruction (MatriXX measurement) and TPS

First, the DICOM files of basic treatment plan in homogeneous phantom (RT plan, RT dose, RT structures, and CT images) were exported to COMPASS software.

Second, the MatriXX was attached on gantry with gantry holder and the plastic solid water phantoms were placed on the surface of MatriXX detector as a build-up material of 4.7 cm thickness. The gantry rotation was verified with gantry angle sensor. The 100 cm source to detector distance and 15 minutes warming up device before measurement were acquired, also pre-irradiation of 10 Gy was performed according to the manual recommendation. The COMPASS measurement device set up is shown in Figure 4.20.

Third, the calibrated dose of detector was performed before measurement with parameters; 6 MV photon beam, 10x10 cm^2 field size and 100 cGy as a 106 MU dose delivered**.**

Fourth, the fluence from MatriXX measurement was transferred to COMPASS software. The DVHs were generated using COMPASS dose reconstruction algorithm.

Finally, the DVHs were compared between COMPASS dose reconstruction and TPS dose calculation.

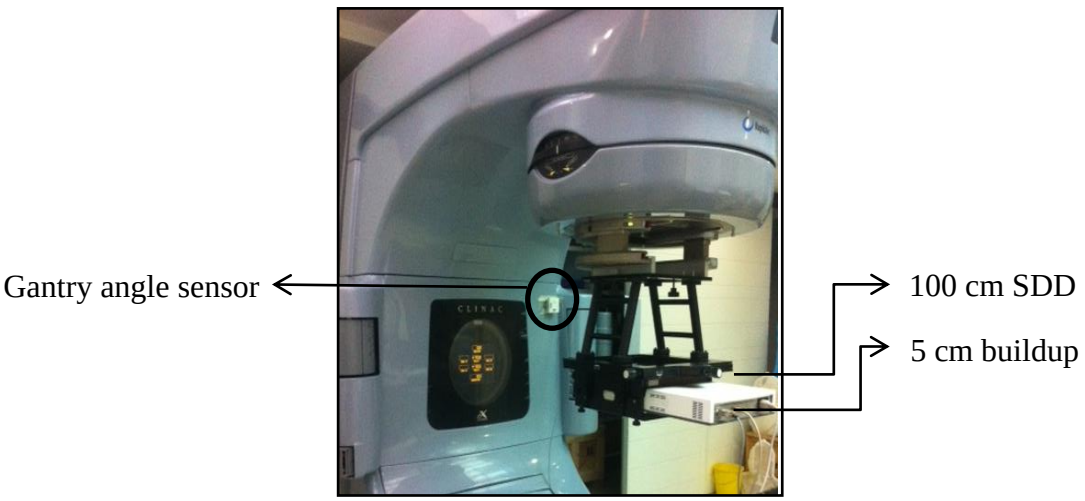


Figure 4.20 MatriXX measurement device setup with gantry angle sensor.

4.2.2.4 DVHs comparison between 3DVH software (ArcCHECK measurement) and TPS

First, the verification plan of basic treatment plan in homogeneous phantom was created and exported to ArcCHECK phantom which is shown in Figure 4.21.

Second, the ArcCHECK measurement devices were placed on treatment couch at 86.65 cm source to surface distance which is shown in Figure 4.22.

Third, the calibrated dose of detector was performed before measurement with parameters; 6 MV photon beam, 10x10 cm^2 field size and 200 cGy as a 163 MU dose delivered**.** The verification plan was exported to ArcCHECK measurement device with the same parameters in beam energy, field size, dose rate, MLC movement and monitor units.

Fourth, the fluence from ArcCHECK measurement was transferred to 3DVHs software.

Finally, the DICOM files (RT plan, RT dose, RT structures, and CT images) of basic treatment plan in homogeneous phantom were imported to 3DVH software. The DVHs were generated and compared with TPS dose calculation.

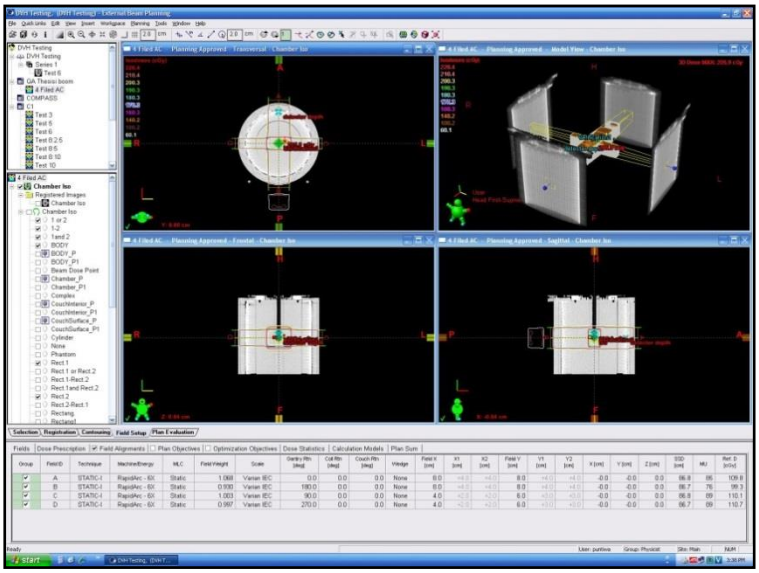


Figure 4.21 Verification plan of homogeneous phantom planning with four field box technique in ArcCHECK phantom.

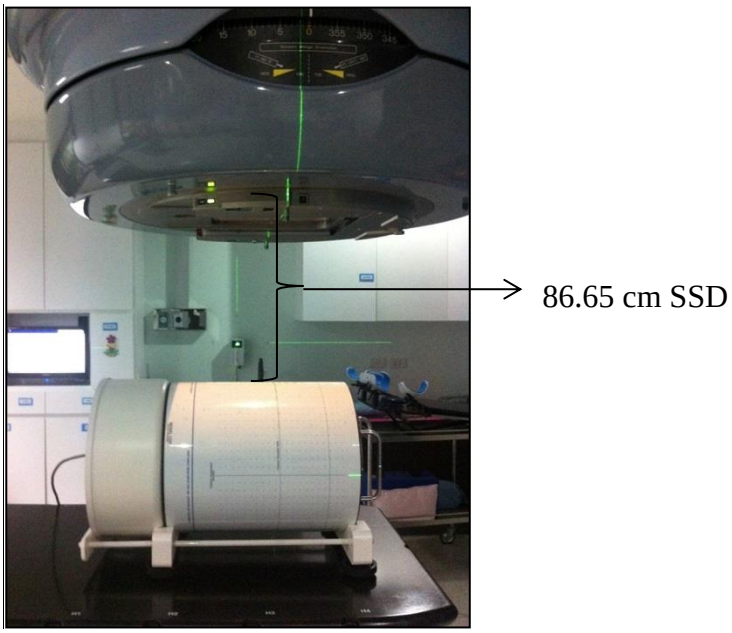


Figure 4.22 ArcCHECK measurement device setup.

4.2.3 Advanced clinical application

The advanced techniques were evaluated by comparing the DVHs from the 3DVH and the COMPASS software. The fifteen plans of VMAT treatment technique (2-3 arcs) in head region at King Chulalongkorn Memorial Hospital during February to May 2013 were selected for this study. The studies were performed by DVHs comparison between measurement in both QA software (3DVH and COMPASS) and TPS dose calculation. The advanced clinical work flow is shown in Figure 4.23.

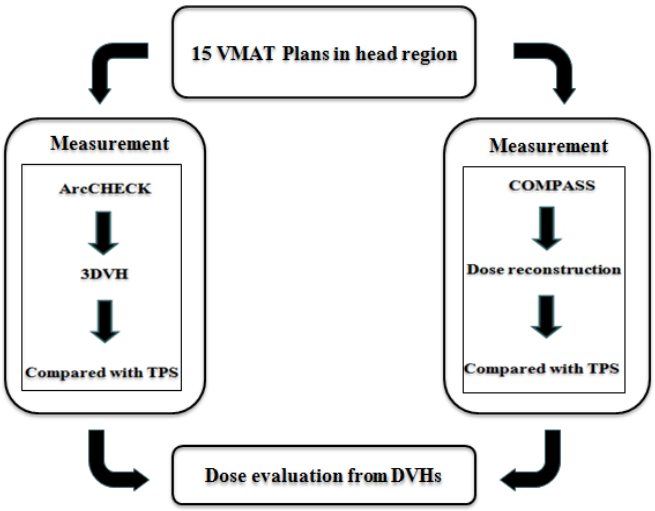


Figure 4.23 Advanced clinical study work flow in DVHs analysis of 3DVH software and COMPASS software.

4.2.3.1 Evaluation of QA software using DVHs analysis in COMPASS dose reconstruction (MatriXX measurement)

First, the fifteen VMAT plans in DICOM files (RT plan, RT dose, RT structures, and CT images) were exported to COMPASS software. This is shown in Figure 4.24.

Second, the MatriXX was attached on gantry with gantry holder. The plastic solid water phantoms were placed on the surface of MatriXX detector as build up material of 4.7 cm thickness. The 100 cm source to detector distance and 15 minute warming up of the device before measurement were acquired together with 10 Gy pre-irradiation.

Third, the gantry rotation was verified with gantry angle sensor. The calibrated doses of detector were performed before measurement with parameters; 6 MV photon beam, 10x10 cm^2 field size and 100 cGy as a 106 MU dose delivered**.**

Fourth, the fluence from MatriXX measurement was transferred to COMPASS software and generated DVHs using COMPASS reconstruction dose algorithm.

Finally, the DVHs were compared between COMPASS dose reconstruction and TPS dose calculation. The 3D gamma pass in COMPASS software

were reported. The output of COMPASS software in function of dose reconstruction is shown in Figure 4.25.

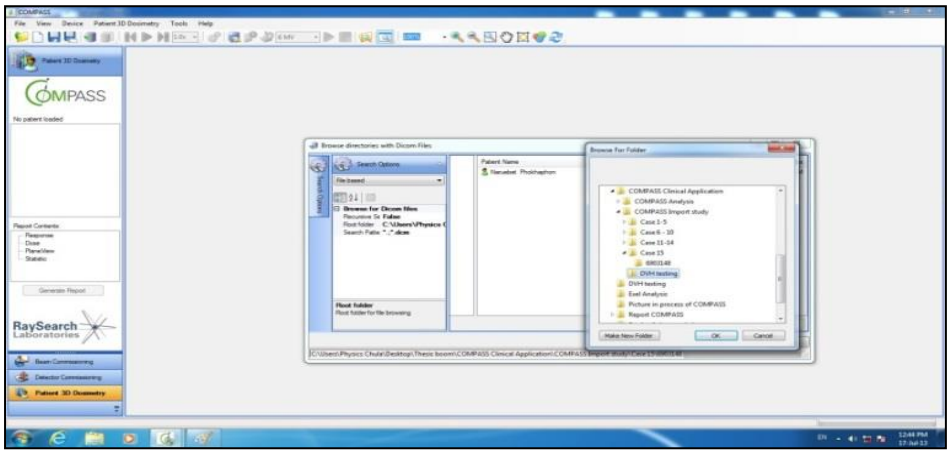


Figure 4.24 The data importing process in COMPASS software.

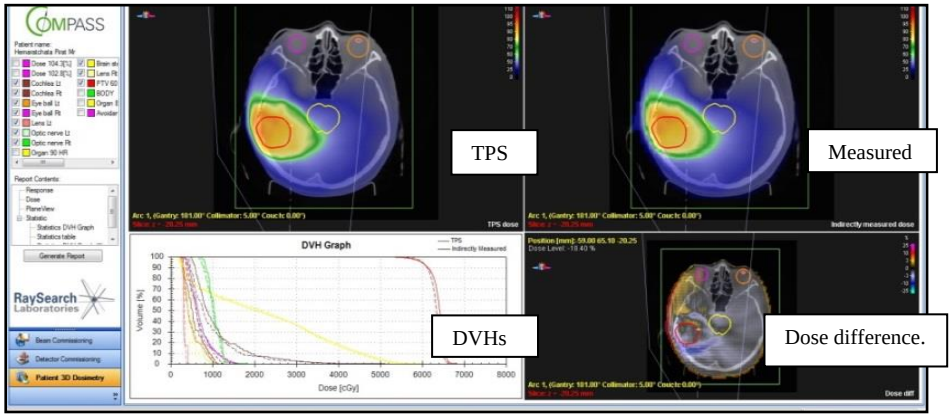


Figure 4.25 The output of COMPASS software in function of dose reconstruction.

4.2.3.2 Evaluation of QA software using DVHs analysis in 3DVH software (ArcCHECK measurement)

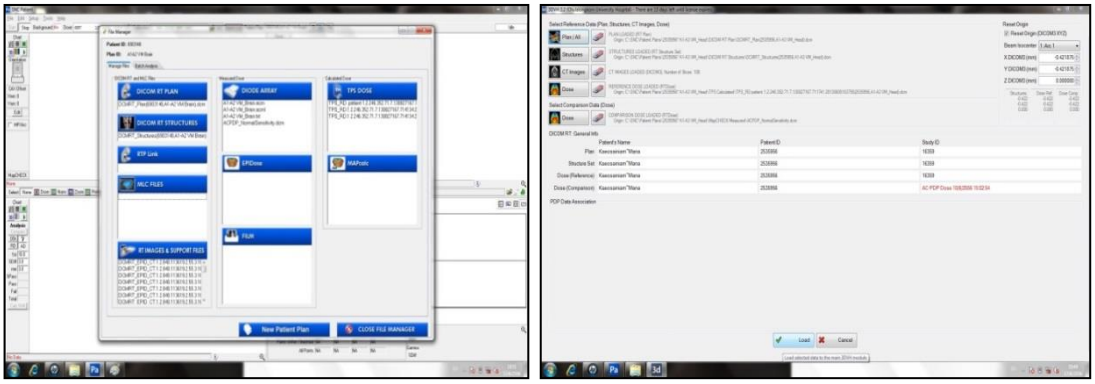
First, the fifteen verification VMAT plans of head region were created in ArcCHECK phantom.

Second, the patient DICOM flies (RT plan, RT dose, RT structures, and CT images) were imported to 3DVH software. This is shown in Figure 4.26.

Third, the ArcCHECK measurement devices were placed on treatment couch at 86.65 cm source to detector distance. The calibrated dose of detector were performed before measurement with parameters; 6 MV photon beam, 10x10 cm^2 field size and 200 cGy as a 163 MU dose delivered.

Fourth, the verification plans were transferred to ArcCHECK measurement device with the same parameters in beam energy, field size, dose rate, MLC movement, monitor units and gantry rotations.

Finally, the DVHs and 3D gamma pass were generated by 3DVH software. The 3D gamma pass of ArcCHECK also were reported. The DVHs were compared between 3DVH software and TPS dose calculation. The output of 3DVH software is shown in Figure 4.27.



a) b)

Figure 4.26 The screen capture of data importing process; a) SNC software and b) 3DVH software.

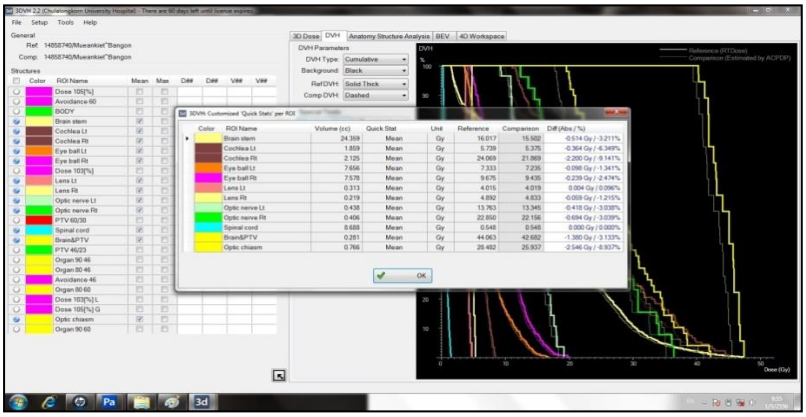


Figure 4.27 The output of 3DVH software.

4.3 Data analysis

The quantitative evaluations in DVHs were employed for comparison. The DVHs in COMPASS and 3DVHs softwares were compared with TPS dose calculation.

The homogeneity index demonstrated the homogeneity of dose in target volume which was calculated according to equation 3.2. The homogeneity index were reported.

The DVHs analysis of PTV were performed by dose specification in term of $D_{98\%,}$ $D_{95\%,}$ $D_{50\%,}$ $D_{2\%}$ and D_{mean}. For the DVHs analysis of OARs, dose specification was defined in term of $D_{mean.}$

The gamma evaluation of 3% dose difference and 3 mm distance to agreement with percent gamma pass more than 95% were used. The agreement between measured and calculated dose were compared between 3DVH software, COMPASS software and ArcCHECK.

4.2 Statistical analysis

The average value, standard deviation (SD), percent difference and p-value were analyzed. All of data were analyzed by statistic in pair sample t-test with 95% confidence level.

4.3 Data Presentation

The data presentations were reported as a scatter scheme and bar chart.

4.4 Ethical Consideration

This study were performed in phantom and used patients data as CT images, however, the ethical was approved by Ethic Committee of Faculty of medicine Ramathibodi hospital.

CHAPTER V
RESULTS

5.1 Study of detector properties

5.1.1 Initial phase and time dependence

The results of initial phase and time dependence of MatriXX detector measured after warming up the device for 15 minutes and no warming up the device, are shown in Table 5.1 and Table 5.2, respectively. The collected MatriXX signal were averaged from four detectors around center of MatriXX array and normalized to average collected signal of all measurement for reporting.

In the condition of warming up the device for 15 minutes before measurement, the deviation of signals was 0.05%. For no warming up of the device before measurement, the deviation of signal was 0.13%. The graph plotted between normalized MatriXX signal and number of measurement is shown in Figure 5.1. The response of the detector in each measurement illustrated more stable for warming up of the device than no warming up.

Table 5.1 Initial phase and time dependence of the MatriXX: The MatriXX were measured after warming up of the device for 15 minutes with 20 times of measurement for 6 MV photon beam.

No.	Collected signal from four central detectors of MatriXX				Ave. collected signal	Normalized to the average signal of all measurements
	1	2	3	4		
1	116850	117260	117260	117260	117157.50	0.9934
2	117600	118000	118000	118000	117900.00	0.9997
3	117660	118030	118030	118030	117937.50	1.0000
4	117670	118080	118080	118080	117977.50	1.0004
5	117600	118020	118020	118020	117915.00	0.9998
6	117660	118030	118400	118030	118030.00	1.0008
7	117600	117950	118300	118300	118037.50	1.0009
8	117420	117800	118180	118180	117895.00	0.9997
9	117420	117800	118180	118180	117895.00	0.9997
10	117720	118080	118080	118080	117990.00	1.0005
11	117670	118080	118080	118080	117977.50	1.0004
12	117720	118080	118080	118080	117990.00	1.0005
13	117390	118170	118170	118170	117975.00	1.0004
14	117800	118180	118180	118180	118085.00	1.0013
15	117420	117800	118180	118180	117895.00	0.9997
16	117660	118030	118030	118030	117937.50	1.0000
17	117780	118170	118170	118170	118072.50	1.0012
18	117660	118030	118400	118030	118030.00	1.0008
19	117660	118030	118030	118030	117937.50	1.0000
20	117660	118030	118400	118030	118030.00	1.0008
Mean = 117933.25, %CV = 0.05%						

Table 5.2 Initial phase and time dependence of the MatriXX: The MatriXX were measured in the condition of no warming up of the device with 20 times of measurement for 6 MV photon beam.

No.	Collected signal from four central detectors of MatriXX				Ave. collected signal	Normalized to the average signal of all measurements
	1	2	3	4		
1	117120	117120	117120	117120	117120.00	0.9951
2	117180	117600	117600	118020	117600.00	0.9992
3	117290	117660	118030	118030	117752.50	1.0005
4	117200	118000	118000	118000	117800.00	1.0009
5	117360	117720	118080	118080	117810.00	1.0009
6	117420	117800	117800	117800	117705.00	1.0000
7	117600	118020	118020	118020	117915.00	1.0018
8	117290	118030	118030	118030	117845.00	1.0012
9	117420	117800	117800	117800	117705.00	1.0000
10	117390	117390	117390	117390	117390.00	0.9974
11	117420	117420	117420	117420	117420.00	0.9976
12	117260	118080	118080	118080	117875.00	1.0015
13	117390	117780	117780	117780	117682.50	0.9999
14	117390	117780	118170	117780	117780.00	1.0007
15	117200	117600	117600	117600	117500.00	0.9983
16	117290	118030	118030	118030	117845.00	1.0012
17	117290	117660	118030	117660	117660.00	0.9997
18	117360	118080	118080	118080	117900.00	1.0017
19	117360	118080	118080	118080	117900.00	1.0017
20	117390	117780	118170	117780	117780.00	1.0007
Mean = 117699.25 , %CV = 0.13%						

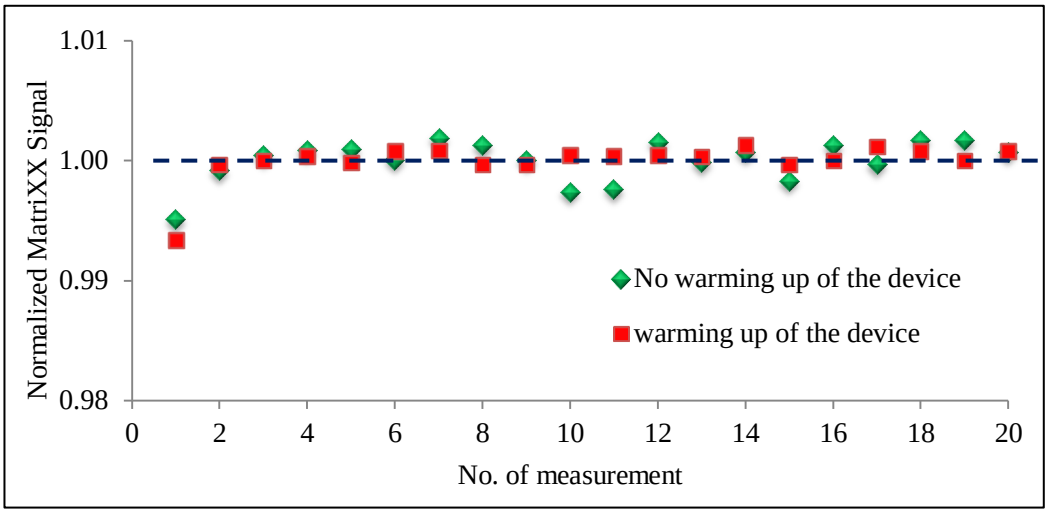


Figure 5.1 Initial phase and time dependence of the MatriXX: The comparison between MatriXX signals from after warming up of the device for 15 minutes (red dot) and no warming up of the device (green dot).

5.1.2 Gravitational effect of gantry rotation

Gravitational effect of gantry rotation of MatriXX was studied by measuring the response of Matrix detector at each gantry rotation of 20° increment for 6 MV photon beam. The collected MatriXX signal were averaged from four detectors around central of MatriXX array and normalized to average collected signal at 0° angle gantry. The results are shown in Table 5.3. The % CV deviation of MatriXX signal when rotated gantry was 0.19%.

The diagram in Figure 5.2 showed the less change of relative dose for gravitational effect of gantry rotation.

Table 5.3 Gravitational effect of gantry rotation in MatriXX detector, the reading was taken at every 20° increment of gantry rotation for 6 MV photon beam.

Gantry angle (Degree)	Collected signal from four central detectors of MatriXX				Ave. collected signal	Normalized to 0 degree
	1	2	3	4		
0	116960	117390	117390	117390	117282.50	1.0000
20	117290	117660	117660	117660	117567.50	1.0024
40	117180	117810	117810	117810	117652.50	1.0032
60	117000	117780	117780	117780	117585.00	1.0026
80	117260	118080	118080	118080	117875.00	1.0051
100	117600	118000	118000	118000	117900.00	1.0053
120	117390	118250	117820	118250	117927.50	1.0055
140	117420	117800	117800	117800	117705.00	1.0036
160	117390	117820	117820	117820	117712.50	1.0037
180	117920	117920	118360	117920	118030.00	1.0064
200	117800	118180	118560	118180	118180.00	1.0077
220	117670	118080	118490	118080	118080.00	1.0068
240	117780	117780	118170	117780	117877.50	1.0051
260	117820	117820	118250	117820	117927.50	1.0055
280	117820	117820	118250	117820	117927.50	1.0055
300	117390	117820	118250	117820	117820.00	1.0046
320	117500	117500	117970	117500	117617.50	1.0029
340	117260	117670	117670	117670	117567.50	1.0024
Mean = 117790.83 , %CV = 0.19%						

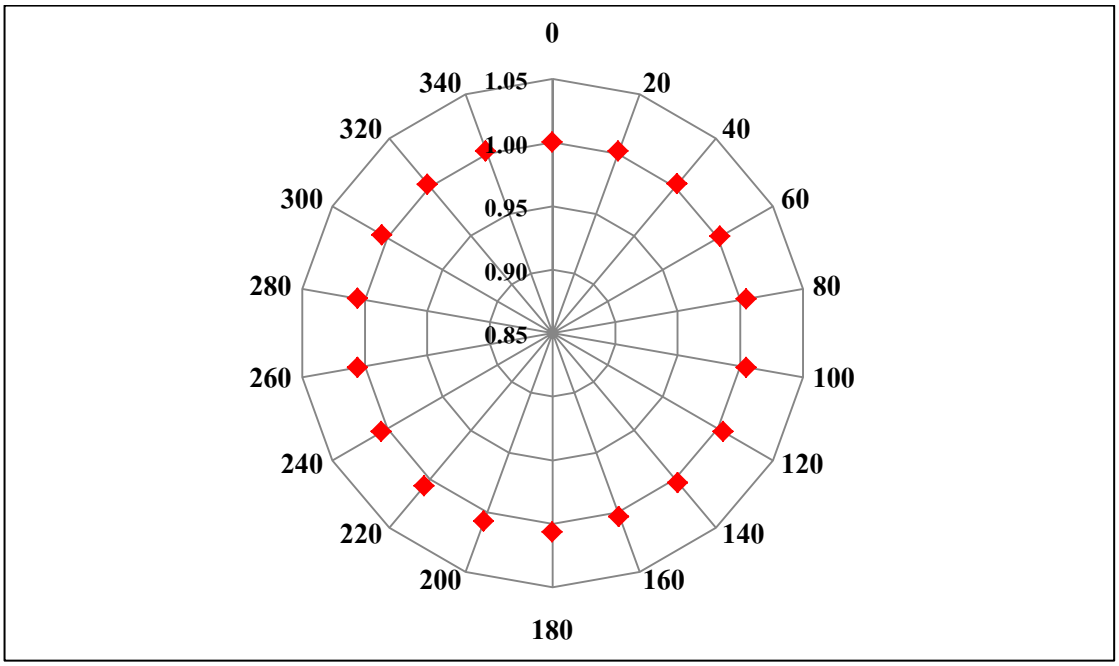


Figure 5.2 Gravitational effect of gantry rotation in MatriXX detector. The circle relative dose were measured by MatriXX detector with gantry holder for 6 MV photon beam.

5.1.3 Linearity and energy response

The results of MatriXX dose linearity and energy response of 6 and 10 MV photon beams over 10 to 2500 cGy delivered dose are shown in Table 5.4 and 5.5, respectively. An average collected signal from four detectors around the center of MatriXX array was reported. The mean ratio of average collected signal of 6 to 10 MV photon beam was 1.01 which is shown in Table 5.6.

The graphs plotted between collected MatriXX signal and delivered dose for 6 and 10 MV photon beams are shown with regression coefficients of 1.00 in Figure 5.3 and 5.4, respectively.

Table 5.4 Dose linearity of the MatriXX with delivered dose from 10 to 2500 cGy for 6 MV photon beam.

Dose(cGy)	Collected signal from four central detectors of MatriXX				Ave. collected signal
	1	2	3	4	
10	13080	13200	13200	13200	13170.00
20	25080	25080	25080	25080	25080.00
50	63180	63440	63440	63440	63375.00
100	126690	126690	127100	127100	126895.00
200	252000	252750	253500	253500	252937.50
500	632060	633750	633750	633750	633327.50
1000	1262220	1265490	1268760	1268760	1266307.50
1500	1893440	1898320	1903200	1903200	1899540.00
2000	2529480	2535900	2535900	2535900	2534295.00
2500	3164040	3172030	3172030	3172030	3170032.50

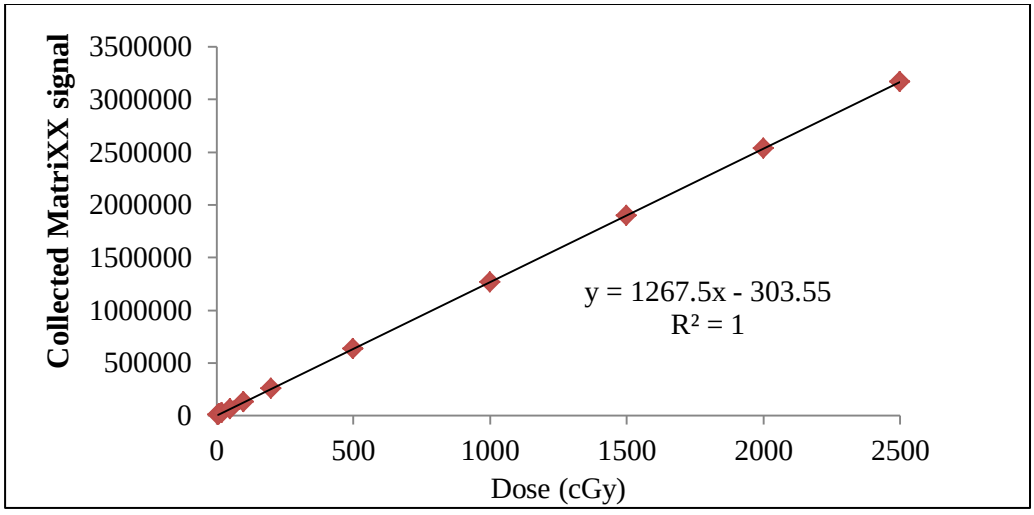


Figure 5.3 MatriXX dose response of 6 MV photon beam as function of delivered dose from 10 to 2500 cGy.

Table 5.5 Dose linearity of the MatriXX with delivered dose from 10 to 2500 cGy for 10 MV photon beam.

Dose (cGy)	Collected signal from four central detectors of MatriXX				Ave. collected signal
	1	2	3	4	
10	13000	13000	13000	13000	13000.00
20	25900	25900	26040	25900	25935.00
50	64530	64800	65070	64800	64800.00
100	127920	128330	128330	128330	128227.50
200	255990	255990	255990	255990	255990.00
500	640560	642130	643700	643700	642522.50
1000	1281280	1284360	1287440	1287440	1285130.00
1500	1922370	1926980	1931590	1931590	1928132.50
2000	2563380	2569440	2575500	2575500	2570955.00
2500	3208920	3208920	3223880	3216400	3214530.00

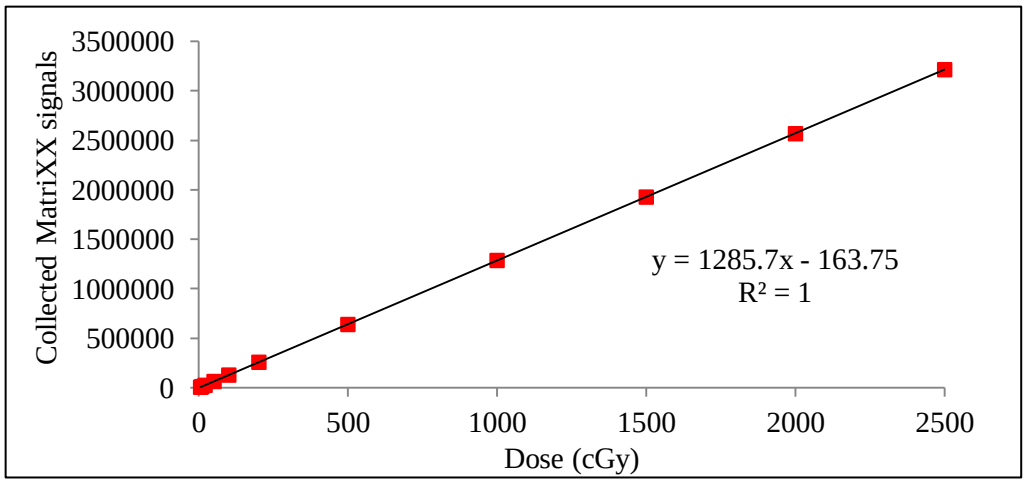


Figure 5.4 MatriXX dose response of 10 MV photon beam as function of delivered dose from 10 to 2500 cGy.

Table 5.6 Ratio of average collected MatriXX signal for 6 to 10 MV photon beam from 10 to 2500 cGy delivered dose.

Dose (cGy)	Average collected of MatriXX signal		6 and 10 MV ratio
	6 MV	10 MV	
10	13170.00	13000.00	0.99
20	25080.00	25935.00	1.03
50	63375.00	64800.00	1.02
100	126895.00	128227.50	1.01
200	252937.50	255990.00	1.01
500	633327.50	642522.50	1.01
1000	1266307.50	1285130.00	1.01
1500	1899540.00	1928132.50	1.02
2000	2534295.00	2570955.00	1.01
2500	3170032.50	3214530.00	1.01
	Mean ratio		1.01±0.01

5.1.4 Repetition rate effect

Repetition rate effect of MatriXX detector was studied with the ranging repetition rate from 100 to 600 MU/min for 6 and 10 MV photon beams. The average signal result of the four detectors around central of MatriXX array were taken and normalized to 400 MU/min for reporting. The results in this study are shown in Table 5.7 and 5.8. The graph plotted between normalized MatriXX signal and repetition rate (MU/min) is shown in Figure 5.5. Green and red dot represent to normalized MatriXX signal of 6 and 10 MV photon beams, respectively. Percent deviation of MatriXX signal in repetition rate effect for 6 and 10 MV photon beams was 0.32% and 0.25%, respectively.

Table 5.7 Repetition rate effect of MatriXX detector with ranging of repetition rate from 100 to 600 MU/min for 6 MV photon beam.

MU/min	Collected signal from four central detectors of MatriXX				Ave. collected signal	Normalized to 400 MU/min
	1	2	3	4		
100	118300	119600	119600	118300	118950.00	1.010
200	117800	118560	118560	118560	118370.00	1.005
300	117500	118000	118000	118000	117875.00	1.001
400	117390	117780	118170	117780	117780.00	1.000
500	117180	117800	117800	117800	117645.00	0.999
600	117160	117740	117740	117740	117595.00	0.998
Mean = 118035.83, %CV = 0.32%						

Table 5.8 Repetition rate effect of MatriXX detector with ranging repetition rate from 100 to 600 MU/min for 10 MV photon beam.

MU/min	Collected signal from four central detectors of MatriXX				Ave. collected signal	Normalized to 400 MU/min
	1	2	3	4		
100	126900	128310	128310	128310	127957.50	1.006
200	127280	127280	128020	127280	127465.00	1.002
300	127050	127050	127600	127050	127187.50	1.000
400	126920	126920	127680	127300	127205.00	1.000
500	126690	127100	127510	127510	127202.50	1.000
600	126790	127100	127410	127100	127100.00	0.999
Mean = 127352.92, %CV = 0.25%						

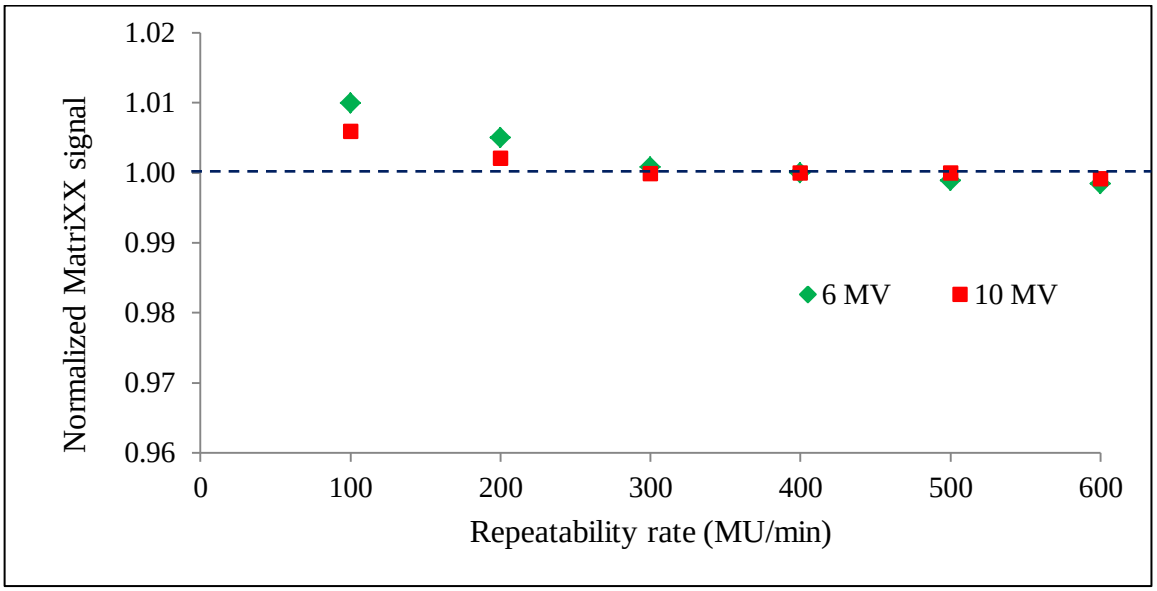


Figure 5.5 The repetition rate effect of MatriXX detector for 6 (green dot) and 10 MV (red dot) photon beams.

5.1.5 Field size effect

The field size effect of MatriXX detector was studied with the varied square field size from 3×3 to 20×20 cm^2 field sizes for 6 and 10 MV photon beams. The collected MatriXX signal were averaged from four detectors around center of MatriXX array and normalized signal to 10×10 cm^2 field size to be a relative output factor. The results from MatriXX measurement were compared to the results from CC13 ionization chamber with the same parameters. Percent difference of MatriXX detector and CC13 ionization chamber were calculated and reported.

The field size effect of MatriXX detector and CC13 Ionization chamber for 6 and 10 MV photon beams are shown in Table 5.9 and 5.10, respectively. The graph plotted between the relative output factor and the side square of field (cm) of MatriXX detector and CC13 Ionization chamber are shown in Figure 5.6 and 5.7 for 6 and 10 MV photon beam, respectively. The percent differences between MatriXX detector and CC13 ionization chamber were less than 1%.

Table 5.9 Field size effect of MatriXX detector with varied square field sizes from 3×3 to 20×20 cm^2 for 6 MV photon beam.

Field size (cm^2)	MatriXX detector		CC13 Ionization chamber		%Diff.
	Ave. collected signal (signal)	Normalized signal to 10×10 cm^2	Ave. collected signal (nC)	Normalized signal to 10×10 cm^2	
3x3	101065	0.875	3.11	0.874	0.08
4x4	104500	0.904	3.22	0.903	0.19
6x6	109680	0.949	3.37	0.945	0.43
8x8	113145	0.979	3.48	0.977	0.21
10x10	115560	1.000	3.56	1.000	-0.00
12x12	117845	1.020	3.63	1.020	-0.02
15x15	119985	1.038	3.71	1.042	-0.31
20x20	122700	1.062	3.80	1.067	-0.46

%Diff = ((MatriXX - CC13) / CC13)*100

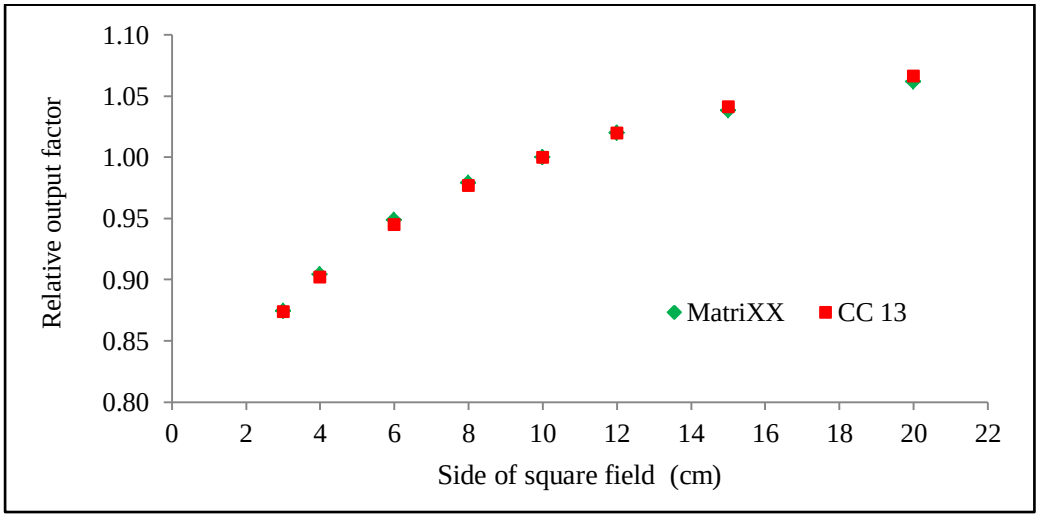


Figure 5.6 Relative output factor of MatriXX (green dot) and CC13 ionization chamber (red dot) for 6 MV photon beam.

Table 5.10 Field size effect of MatriXX detector with varied square field sizes from 3×3 to 20×20 cm^2 for 10 MV photon beam.

Field size (cm^2)	MatriXX detector		Ionization chamber CC13		%Diff.
	Ave. collected signal (signal)	Normalized signal to 10x10 cm^2	Avg. collected signal (nC)	Normalized signal to 10x10 cm^2	
3×3	108720.00	0.873	3.38	0.881	-0.77
4×4	113520.00	0.912	3.50	0.914	-0.28
6×6	118500.00	0.952	3.65	0.953	-0.15
8×8	121950.00	0.980	3.75	0.979	0.01
10×10	124500.00	1.000	3.83	1.000	-0.00
12×12	126635.00	1.017	3.89	1.016	0.10
15×15	128407.50	1.031	3.96	1.034	-0.28
20×20	130700.00	1.050	4.04	1.055	-0.48

% Diff. = ((MatriXX - CC13) / CC13)*100

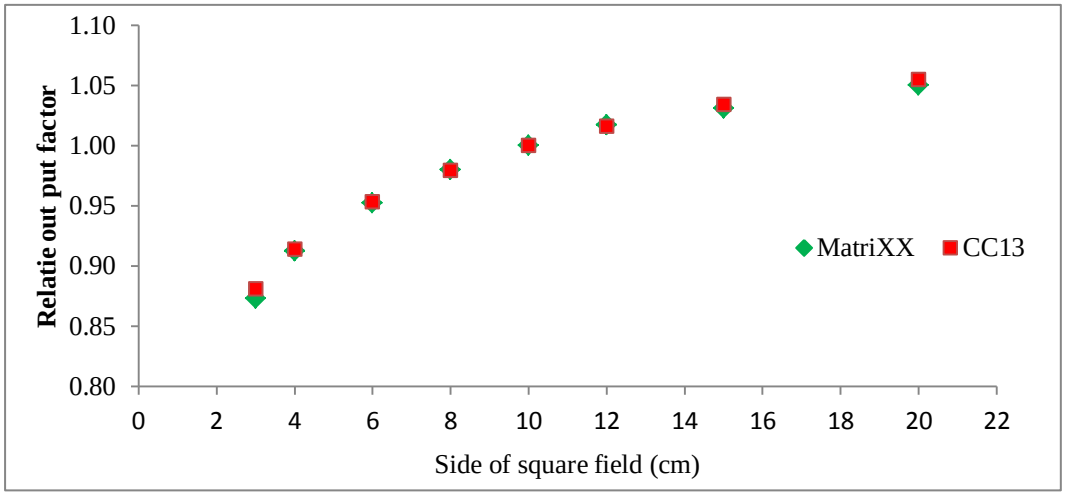


Figure 5.7 Relative output factor of MatriXX (green dot) and CC13 ionization chamber (red dot) for 10 MV photon beam.

5.1.6 Reproducibility

The reproducibility of MatriXX detector was studied in short and long term as a period of time for measurement. The collected MatriXX signal were normalized to average signal of all measurement. The results are shown in Table 5.11 and 5.12 for short and long term reproducibility, respectively. The percent deviation of MatriXX signal for short term reproducibity was 0.11%. The long term reproducibility was 0.54%. The graph plotted between normalized MatriXX signal and time (minute) is shown in Figure 5.8 for short term reproducibility. For long term reproducibility, the graph plotted between normalized MatriXX signal and time (week) is shown in Figure 5.9.

Table 5.11 The short term reproducibility of MatriXX detector. Data were collected from measurement in every 5 minutes over 60 minutes for 6 MV photon beam.

Time (min)	Collected signal from four central of MatriXX				Ave. collected signal	The value normalized to average signal of all measurement
	1	2	3	4		
0	119320	119700	119700	119700	119605.00	1.002
5	119130	119130	119700	119130	119272.50	0.999
10	119110	119540	119540	119540	119432.50	1.000
15	119310	119720	119720	119720	119617.50	1.002
20	119280	119280	119700	119700	119490.00	1.001
25	119000	119500	119500	119500	119375.00	1.000
30	119040	119520	119520	119520	119400.00	1.000
35	118800	119400	119400	119400	119250.00	0.999
40	119040	119680	119680	119680	119520.00	1.001
45	118800	119340	119340	119340	119205.00	0.998
50	119200	119600	119600	119600	119500.00	1.001
55	119280	119280	119700	119280	119385.00	1.000
60	118860	119280	119700	119700	119385.00	1.000
Mean = 119418.27, %CV = 0.11%						

Table 5.12 The long term reproducibility of MatriXX detector. Data were collected from measurement in every week over 3 months for 6 MV photon beam.

Time (Week)	Collected signal from four central of MatriXX				Ave. collected signal	The value normalized to average signal of all measurement
	1	2	3	4		
1	115181.2	115592.6	115592.6	115063.6	115357.5	0.9938
2	116958.3	117326.0	117326.0	117326.0	117234.1	1.0100
3	115974.0	116443.6	116443.6	116913.1	116443.6	1.0032
4	117245.5	116367.3	116367.3	116367.3	116586.8	1.0044
5	115520.3	115986.1	115986.1	115986.1	115869.7	0.9982
6	115687.4	116112.8	116112.8	116112.8	116006.4	0.9994
7	114990.1	115858.0	115424.1	115858.0	115532.5	0.9954
8	119472.6	120013.2	120013.2	120013.2	119878.1	0.9927
9	115729.7	116278.2	116278.2	116278.2	116141.0	1.0006
10	114775.4	115488.3	115488.3	115488.3	115310.1	0.9935
11	116569.2	116569.2	116569.2	116569.2	116569.2	1.0043
12	116257.3	116666.7	116666.7	116666.7	116564.3	1.0043

Mean = 116069.86, %CV = 0.54%

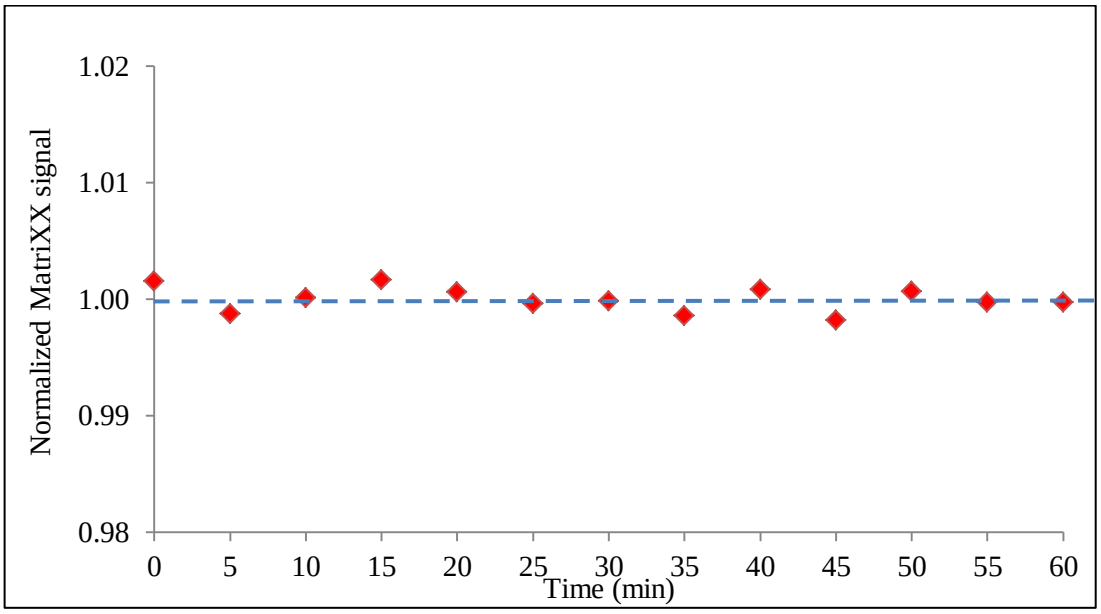


Figure 5.8 Short term reproducibility of MatriXX detector over a period of 60 minutes.

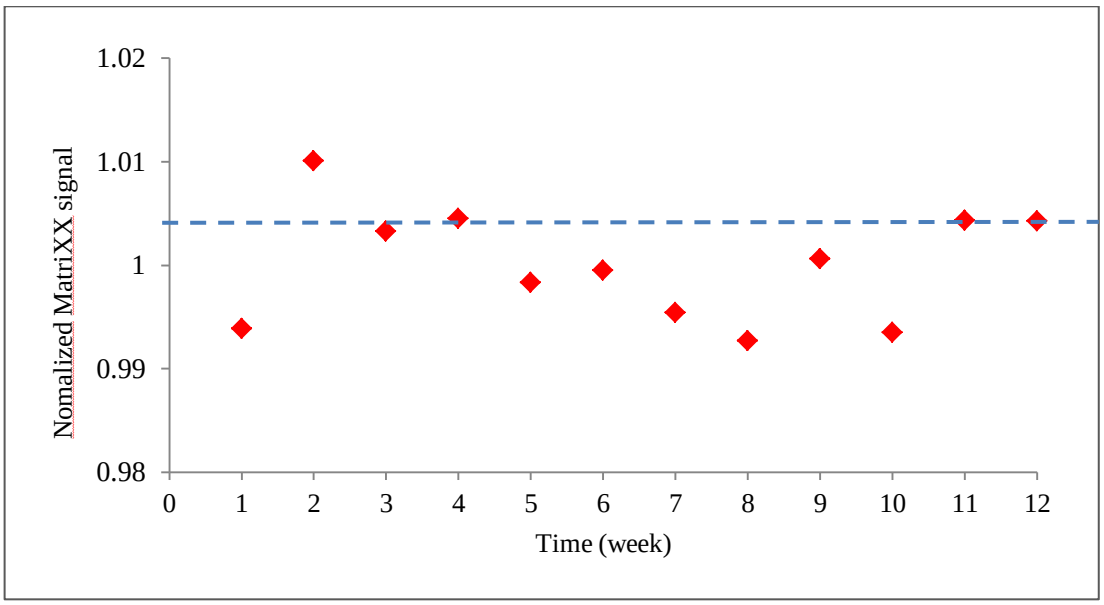


Figure 5.9 Long term reproducibility of MatriXX detector over a period of 3 months.

5.1.7 Statistical uncertainty (Function of delivered dose)

The results of statistical uncertainty study were shown in Table 5.13. All of detectors in MatriXX array were measured with varying delivered dose from 1 to 300 cGy for 6 MV photon beams and the percent error was calculated according to equation 4.1. The standard deviations of percent error were determined and reported. The graph plotted between percent deviation and dose delivered is shown in Figure 5.10.

Table 5.13 The statistical uncertainty (Function of delivered dose) of all detectors in MatriXX array. The deliver dose were varied from 1 to 300 cGy for 6 MV photon beam.

Dose(cGy)	Percent deviation of all detectors (%)
1	1.54
2	0.72
5	1.04
10	0.29
50	0.16
100	0.14
200	0.13
300	0

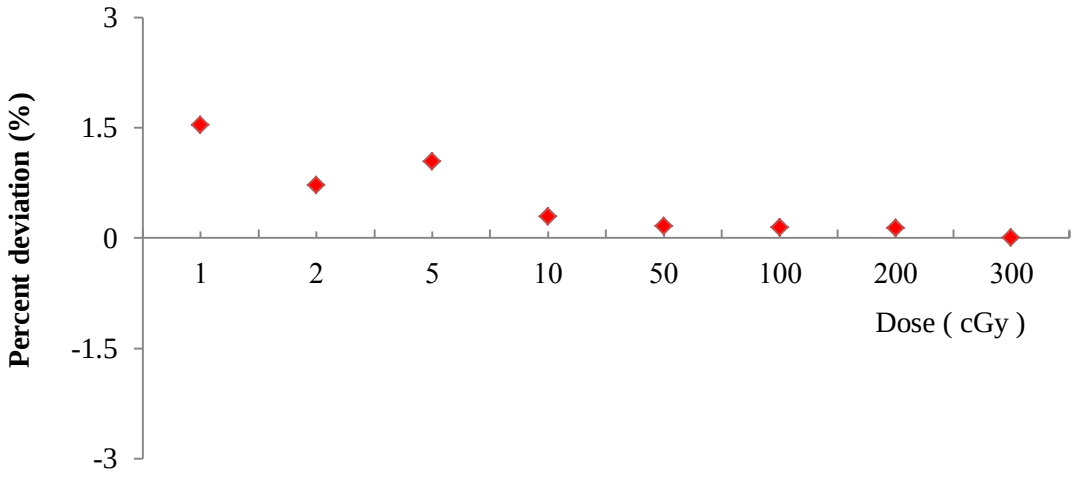


Figure 5.10 The uncertainty for low dose response of all detectors in MatriXX array.

5.2 Basic clinical application

The DVHs of four fields box technique for homogeneous phantom in COMPASS and 3DVH software were compared with the DVHs calculated from TPS. The basic clinical results divided into 3 parts as follows;

5.2.1 DVHs comparison between COMPASS dose computation (independent QA software) and TPS

The DVHs of COMPASS dose computation were compared with TPS. The percent difference of $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ and D_{mean} in 1 and 2 structure (PTV) were 2.25%, 2.14%, 2.06%, 2.25% and 2.12%, respectively. This is shown in Table 5.14. For OARs, the percent difference of D_{mean} in 1 or 2, 1 – 2, Rectangular 1 and Rectangular 2 were 2.28%, 2.34%, 2.21% and 2.26%, respectively. This is shown in Table 5.15. The screen capture of DVHs comparison of COMPASS dose computation is shown in Figure 5.11.

Table 5.14 The comparison of $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ and D_{mean} in PTV between COMPASS dose computation and TPS.

Organs (PTV)	Indices	COMPASS dose computation (cGy)	TPS (cGy)	%Dose diff.
1 and 2	$D_{98\%}$	195.96	191.64	2.25
1 and 2	$D_{95\%}$	197.22	193.09	2.14
1 and 2	$D_{50\%}$	203.24	199.14	2.06
1 and 2	$D_{2\%}$	204.98	200.47	2.25
1 and 2	D_{mean}	202.56	198.36	2.12

%Dose diff. = ((COMPASS - TPS)/TPS)*100

Table 5.15 The comparison of D_{mean} in OARs between COMPASS dose computation and TPS.

Organs (OARs)	Indices	COMPASS dose computation (cGy)	TPS (cGy)	%Dose diff.
1 or 2	D_{mean}	171.07	167.26	2.28
1 - 2	D_{mean}	142.10	138.85	2.34
Rect.1	D_{mean}	172.32	168.59	2.21
Rect.2	D_{mean}	184.81	180.73	2.26

%Dose diff. = ((COMPASS - TPS)/TPS)*100

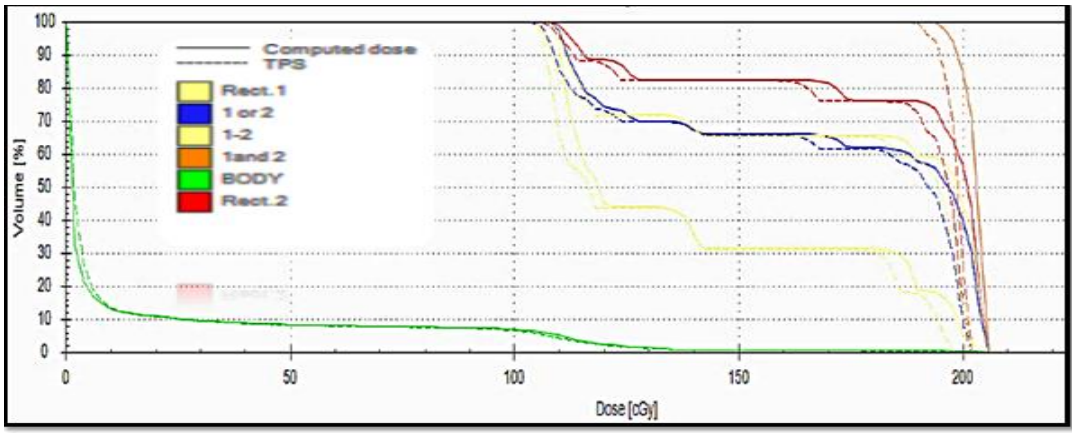


Figure 5.11 The screen capture of DVHs comparison between COMPASS dose computation and TPS.

5.2.2 DVHs comparison between COMPASS dose reconstruction (MatriXX Measurement) and TPS

The DVHs of COMPASS dose reconstruction were compared with TPS. The results showed in Table 5.16 and 5.17 for PTV and OARs, respectively. The percent difference of $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ and D_{mean} in 1 and 2 structure (PTV) were 2.29%, 4.25%, 4.28%, 4.58% and 4.23%, respectively. For OARs, the percent difference of D_{mean} in 1 or 2, 1 – 2, Rectangular 1 and Rectangular 2 were 3.66%, 11.86%, 7.38% and 0.64% respectively. The screen capture of DVHs comparison of COMPASS dose reconstruction is shown in Figure 5.12.

Table 5.16 The dose reporting in $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ and D_{mean} of PTV for COMPASS dose reconstruction and TPS.

Organs (PTV)	Indices	COMPASS dose reconstruction (cGy)	TPS (cGy)	%Dose diff.
1 and 2	$D_{98\%}$	196.02	191.64	2.29
1 and 2	$D_{95\%}$	201.30	193.09	4.25
1 and 2	$D_{50\%}$	207.67	199.14	4.28
1 and 2	$D_{2\%}$	209.66	200.47	4.58
1 and 2	D_{mean}	206.75	198.36	4.23

%Dose diff. = (COMPASS - TPS)/TPS)*100

Table 5.17 The dose reporting in D_{mean} of OARs for COMPASS dose reconstruction and TPS

Organs (OARs)	Indices	COMPASS dose reconstruction (cGy)	TPS (cGy)	%Dose Diff.
1 or 2	D_{mean}	173.39	167.26	3.66
1 - 2	D_{mean}	155.32	138.85	11.86
Rect.1	D_{mean}	181.03	168.59	7.38
Rect.2	D_{mean}	181.88	180.73	0.64

%Dose diff. = (COMPASS - TPS)/TPS)*100

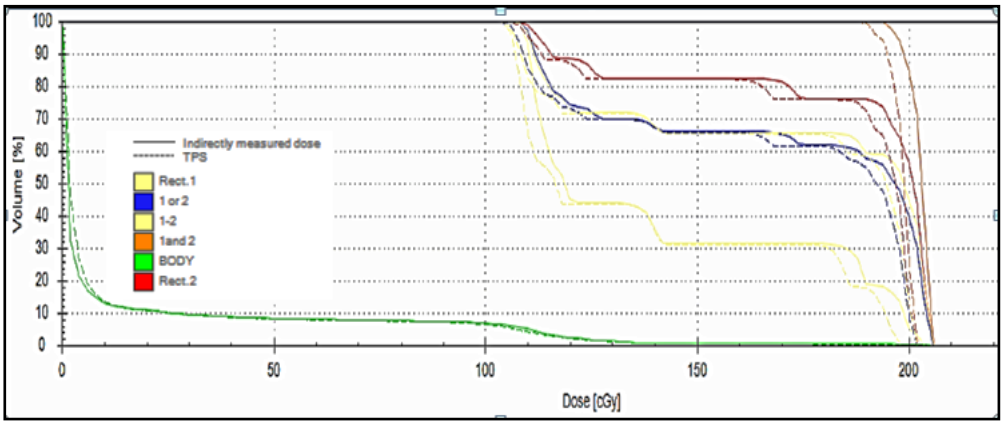


Figure 5.12 The screen capture of DVHs comparison between COMPASS dose reconstruction and TPS.

5.2.3 DVHs comparison between 3DVH software (ArcCHECK Measurement) and TPS

The DVHs of 3DVH software were compared with TPS. The results are shown in Table 5.18 and 5.19 for PTV and OARs, respectively. The percent difference of $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ and D_{mean} in 1 and 2 structure (PTV) were -1.17%, -1.39%, -1.68%, 1.46% and -1.34%, respectively. For OARs, the percent difference of D_{mean} in 1 or 2, 1 – 2, Rectangular 1 and Rectangular 2 were -1.77%, 1.26%, -0.17% and -2.73%, respectively. The screen captures of DVHs comparison of 3DVH software is shown in Figure 5.13.

Table 5.18 The dose reporting in $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ and D_{mean} of PTV for 3DVH software and TPS.

Organs (PTV)	Indices	3DVH (cGy)	TPS (cGy)	%Dose diff.
1 and 2	$D_{98\%}$	189.40	191.64	-1.17
1 and 2	$D_{95\%}$	190.40	193.09	-1.39
1 and 2	$D_{50\%}$	195.80	199.14	-1.68
1 and 2	$D_{2\%}$	203.40	200.47	1.46
1 and 2	D_{mean}	195.70	198.36	-1.34

%Dose difference = (3DVH - TPS)/TPS)*100

Table 5.19 The dose reporting in D_{mean} of OARs 3DVH software and TPS.

Organ (OARs)	Indices	3DVH (cGy)	TPS (cGy)	%Dose diff.
1 or 2	D_{mean}	164.3	167.26	-1.77
1 - 2	D_{mean}	140.6	138.85	1.26
Rect.1	D_{mean}	168.3	168.59	-0.17
Rect.2	D_{mean}	175.8	180.73	-2.73

%Dose diff. = (3DVH - TPS)/TPS)*100

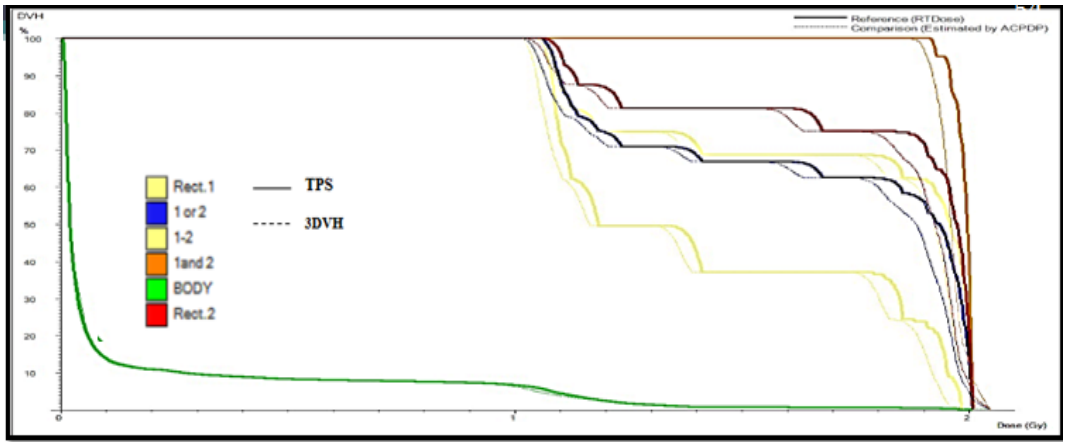


Figure 5.13 The screen capture of DVHs comparison between 3DVH software and TPS.

5.3 Advanced clinical application

The studies for advanced clinical applications were performed by evaluation of the DVHs from 3DVH and COMPASS software in pretreatment verification of fifteen VMAT plan in head region. The example of DVHs comparison from 3DVH and COMPASS software are shown in Figure 5.14 and 5.15, respectively.

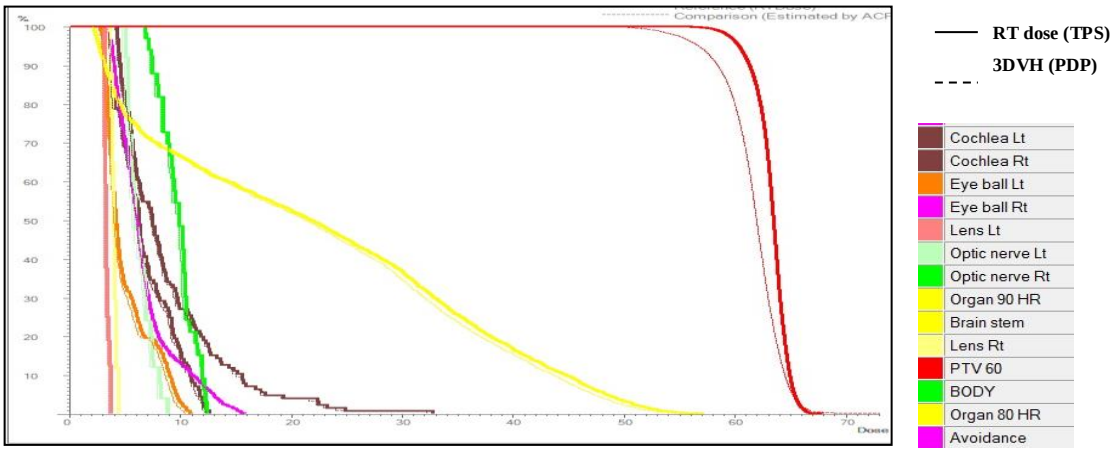


Figure 5.14 The screen capture of DVHs comparison between 3DVH software and TPS (Plan 1).

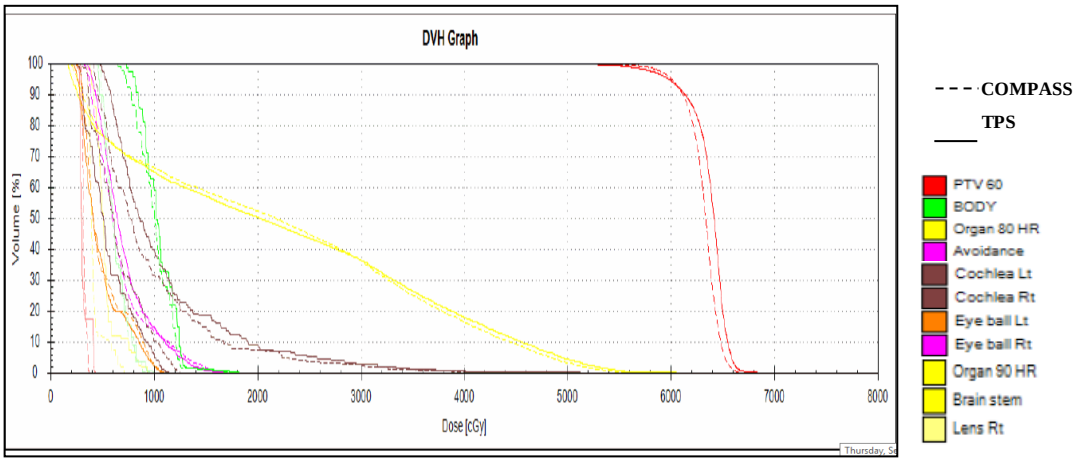


Figure 5.15 The screen capture of DVHs comparison between COMPASS dose reconstruction and TPS (Plan 1).

5.3.1. Evaluation of QA software using DVHs analysis

5.3.1.1 Homogeneity index

The homogeneity index were calculated using equation 3.2. The mean and standard deviation of the homogeneity index in PTV of TPS, COMPASS and 3DVH software were 0.11 ± 0.04, 0.18 ± 0.05 and 0.19 ± 0.05, respectively. This is shown in Table 5.20. Figure 5.16 shows the bar graph of homogeneity index of TPS, COMPASS and 3DVH software.

Table 5.20 The homogeneity index of TPS, COMPASS and 3DVH software.

Plan number	Homogeneity index		
	TPS	COMPASS	3DVH
1	0.09	0.30	0.28
2	0.06	0.16	0.20
3	0.16	0.11	0.14
4	0.12	0.18	0.15
5	0.10	0.13	0.19
6	0.12	0.16	0.16
7	0.06	0.17	0.21
8	0.09	0.20	0.29
9	0.10	0.16	0.21
10	0.18	0.25	0.26
11	0.08	0.11	0.13
12	0.14	0.18	0.16
13	0.09	0.14	0.12
14	0.12	0.22	0.21
15	0.18	0.20	0.20
Mean ± SD	0.11 ± 0.04	0.18 ± 0.05	0.19 ± 0.05

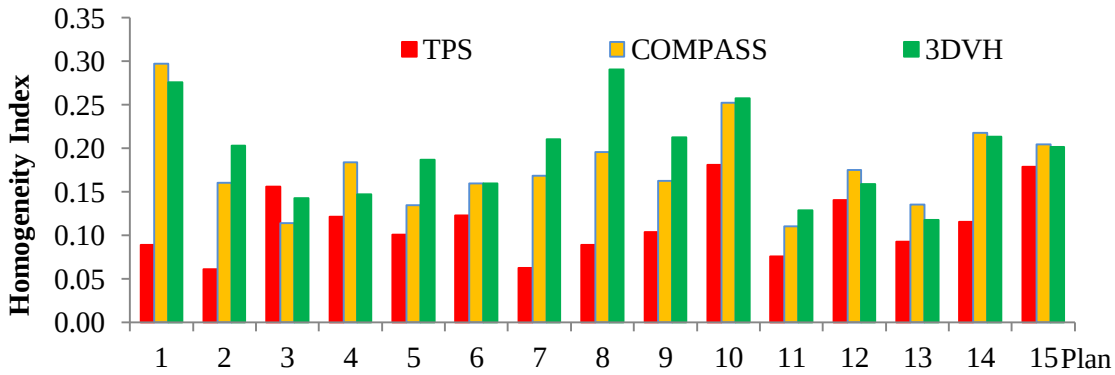


Figure 5.16 The homogeneity index of TPS, COMPASS and 3DVH software of VMAT plan.

5.3.1.2 Dose specification ($D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ and D_{mean})

The results of DVH analysis in fifteen VMAT plans were illustrated in quantitative dose or dose specifications which followed ICRU 83. The dose specifications in term of $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ and D_{mean} of PTV were reported. The OARs were reported using D_{mean}.

The $D_{98\%}$ of fifteen VMAT plans which is shown in Table 5.21 was taken from TPS, COMPASS (dose reconstruction) and 3DVH software. The mean percent differences of $D_{98\%}$ in COMPASS (dose reconstruction) and 3DVH software when compared to TPS were -4.10 ± 3.88% (ranging from -14.42 to 1.93 %) and -8.34 ± 4.82% (ranging from -18.24 to -2.05 %), respectively. This is shown in Table 5.22. Figure 5.17 shows the bar graph of percent differences from TPS of $D_{98\%}$ for COMPASS and 3DVH software.

Table 5.21 The quantitative dose report in term of $D_{98\%}$ for TPS, COMPASS and 3DVH software.

Plan number	Prescribed dose (cGy)	Dose criteria (cGy)	$D_{98\%}$ (cGy)		
			TPS	COMPASS	3DVH
1	3000	2790	2967.18	2539.22	2495.40
2	6000	5580	5861.62	5419.05	5167.20
3	4600	4278	4593.18	4681.81	4409.20
4	1400	1302	1309.81	1271.99	1256.60
5	6000	5580	5763.88	5419.00	5905.21
6	4500	4185	4319.44	4252.30	4230.80
7	5200	4836	5150.35	4812.03	4500.70
8	5400	5022	5300.07	4951.43	4333.30
9	5400	5022	5304.71	5151.99	4668.90
10	3000	2790	2853.60	2712.06	2645.30
11	6000	5580	5861.94	5823.41	5421.70
12	6000	5580	5418.33	5375.05	5240.00
13	6000	5580	5850.05	5745.72	5614.40
14	5200	4836	4997.97	4733.96	4633.50
15	6000	5580	5294.54	5023.88	4939.20

Table 5.22 The percent dose differences of $D_{98\%}$ for COMPASS and 3DVH software compared with TPS.

Plan number	%Dose diff. compared with TPS	
	COMPASS	3DVH
1	-14.42	-15.90
2	-7.55	-11.85
3	1.93	-4.01
4	-2.89	-4.06
5	-2.39	-8.23
6	-1.55	-2.05
7	-6.57	-12.61
8	-6.58	-18.24
9	-2.88	-11.99
10	-4.96	-7.30
11	-0.66	-7.51
12	-0.80	-3.29
13	-1.78	-4.03
14	-5.28	-7.29
15	-5.11	-6.71
Mean ± SD	-4.10±3.88	-8.34±4.82

%Dose diff. = (COMPASS - TPS)/TPS)*100, (3DVH - TPS)/TPS)*100

Figure 5.17 The percent dose differences of $D_{98\%}$ for COMPASS and 3DVH software compared with TPS.

The $D_{95\%}$ of fifteen VMAT plans were reported from TPS, COMPASS (dose reconstruction) and 3DVH software which is shown in Table 5.23. The mean percent differences of $D_{95\%}$ in COMPASS (dose reconstruction) and 3DVH software when compared with TPS were within -2.21 ± 3.13% (ranging from -10.23 to 2.09%) and -7.90 ± 4.02% (ranging from -16.31 to - 2.71%) respectively. This is shown in Table 5.24. Figure 5.18 shows the bar graph of percent differences of $D_{95\%}$ compared with TPS.

Table 5.23 The quantitative dose report in value of $D_{95\%}$ for TPS, COMPASS and 3DVH.

Plan number	Prescribed dose (cGy)	$D_{95\%}$ (cGy)		
		TPS	COMPASS	3DVH
1	3000	3004.90	2697.35	2635.60
2	6000	5936.02	5707.40	5286.60
3	4600	4684.00	4781.69	4478.90
4	1400	1356.67	1339.01	1300.60
5	6000	5982.95	5656.00	6020.45
6	4500	4482.99	4449.32	4361.60
7	5200	5233.81	5023.92	4635.30
8	5400	5397.07	5228.51	4516.80
9	5400	5433.28	5372.82	4789.10
10	3000	2951.53	2906.12	2740.30
11	6000	6001.02	6046.99	5606.60
12	6000	5609.69	5616.39	5443.30
13	6000	5990.88	5959.96	5737.60
14	5200	5133.82	5029.03	4708.00
15	6000	5606.15	5212.61	5090.90

Table 5.24 The percent dose differences of $D_{95\%}$ for COMPASS and 3DVH software compared with TPS.

Plan number	% Dose diff. compared with TPS	
	COMPASS	3DVH
1	-10.23	-12.29
2	-3.85	-10.94
3	2.09	-4.38
4	-1.30	-4.13
5	-0.62	-6.05
6	-0.75	-2.71
7	-4.01	-11.44
8	-3.12	-16.31
9	-1.11	-11.86
10	-1.54	-7.16
11	0.77	-6.57
12	0.12	-2.97
13	-0.52	-4.23
14	-2.04	-8.29
15	-7.02	-9.19
Mean ± SD	-2.21 ± 3.13	-7.90 ± 4.02

%Dose diff. = (COMPASS - TPS)/TPS)*100, (3DVH - TPS)/TPS)*100

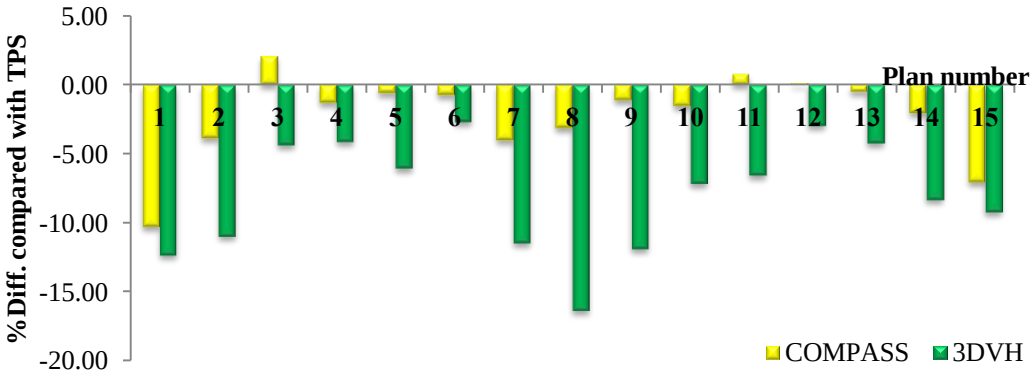


Figure 5.18 The percent dose differences of $D_{95\%}$ for COMPASS and 3DVH software compared with TPS.

The $D_{50\%}$ of fifteen VMAT plans were reported from TPS, COMPASS (dose reconstruction) and 3DVH software which is shown in Table 5.25. The mean percent differences of $D_{50\%}$ in COMPASS (dose reconstruction) and 3DVH software when compared with TPS were within 1.26 ± 2.35% (ranging from -6.98 to 3.07%) and -4.06 ± 2.45% (ranging from -10.09 to -0.67%), respectively. This is shown in Table 5.26. Figure 5.19 shows the bar graph of percent differences of $D_{50\%}$ compared with TPS.

Table 5.25 The quantitative dose report in value of $D_{50\%}$ for TPS, COMPASS and 3DVH software.

Plan number	$D_{50\%}$ (cGy)		
	TPS	COMPASS	3DVH
1	3178.50	3216.89	3102.80
2	6110.88	6211.01	6069.80
3	4879.60	4986.29	4683.30
4	1451.40	1485.35	1395.40
5	6417.87	6182.40	6333.50
6	4758.70	4811.43	4669.60
7	5385.40	5476.62	5086.80
8	5693.30	5841.46	5256.00
9	5738.10	5803.62	5481.70
10	3316.70	3385.96	3258.50
11	6190.80	6329.71	5958.90
12	6100.20	6193.26	5911.20
13	6275.90	6379.02	6056.70
14	5484.10	5652.47	5163.00
15	6193.17	5761.09	5568.00

Table 5.26 The percent dose differences of $D_{50\%}$ for COMPASS and 3DVH software compared with TPS.

Plan number	% Dose diff. compared with TPS	
	COMPASS	3DVH
1	1.21	-2.38
2	1.64	-0.67
3	2.19	-4.02
4	2.34	-3.86
5	1.33	-2.39
6	1.11	-1.87
7	1.69	-5.54
8	2.60	-7.68
9	1.14	-4.47
10	2.09	-1.75
11	2.24	-3.75
12	1.53	-3.10
13	1.64	-3.49
14	3.07	-5.86
15	-6.98	-10.09
Mean ± SD	-1.26 ± 2.35	-4.06 ± 2.45

%Dose diff. = (COMPASS - TPS)/TPS)*100, (3DVH - TPS)/TPS)*100

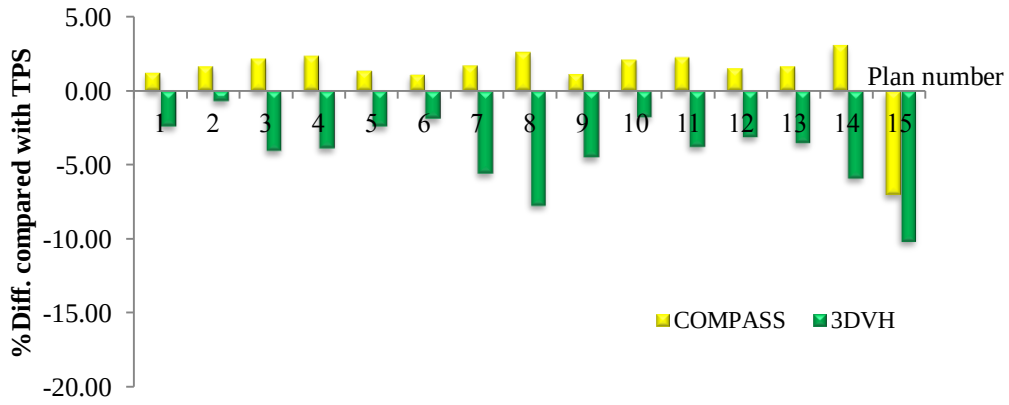


Figure 5.19 The percent dose differences of $D_{50\%}$ for COMPASS and 3DVH compared with TPS.

The $D_{2\%}$ of fifteen VMAT plans were reported from DVHs in calculated dose of TPS, COMPASS (dose reconstruction) and 3DVH software which is shown in Table 5.27. The mean percent differences of $D_{2\%}$ in COMPASS (dose reconstruction) and 3DVH software when compared with calculated dose in TPS were within 3.25 ± 2.32% (ranging from -3.11 to 7.49%) and -0.19 ± 2.27% (ranging from -5.23 to -3.05%), respectively. This is shown in Table 5.28. Figure 5.20 shows the bar graph of percent differences of $D_{2\%}$ compared with TPS.

Table 5.27 The quantitative dose report in value of $D_{2\%}$ for TPS, COMPASS and 3DVH software.

Plan number	Prescribed dose (cGy)	Dose criteria (cGy)	$D_{2\%}$ (cGy)		
			TPS	COMPASS	3DVH
1	3000	3300	3251.38	3495.01	3350.60
2	6000	6600	6236.59	6416.32	6401.90
3	4600	5060	4988.97	5158.94	4883.90
4	1400	1540	1486.44	1545.30	1462.10
5	6000	6600	6628.84	6576.50	6544.07
6	4500	4950	4905.45	5019.31	4976.90
7	5200	5270	5488.85	5734.25	5570.30
8	5400	5940	5806.91	6095.57	5860.20
9	5400	5940	5901.56	6095.09	5834.00
10	3000	3300	3453.26	3566.28	3484.90
11	6000	6600	6331.01	6520.05	6188.20
12	6000	6600	6276.01	6459.23	6178.40
13	6000	6600	6433.03	6607.93	6327.80
14	5200	5270	5632.13	5963.74	5736.10
15	6000	6600	6401.19	6202.17	6060.90

Table 5.28 The percent dose differences of $D_{2\%}$ for COMPASS and 3DVH software compared with TPS.

Plan number	% Dose diff. compared with TPS	
	COMPASS	3DVH
1	7.49	3.05
2	2.88	2.65
3	3.41	-2.11
4	3.96	-1.64
5	1.30	0.50
6	2.32	1.46
7	4.47	1.48
8	4.97	0.92
9	3.28	-1.14
10	3.27	0.92
11	2.99	-2.26
12	2.92	-1.56
13	2.72	-1.64
14	5.89	1.85
15	-3.11	-5.32
Mean ± SD	3.25 ± 2.32	-0.19 ± 2.27

%Dose diff. = (COMPASS - TPS)/TPS)*100, (3DVH - TPS)/TPS)*100

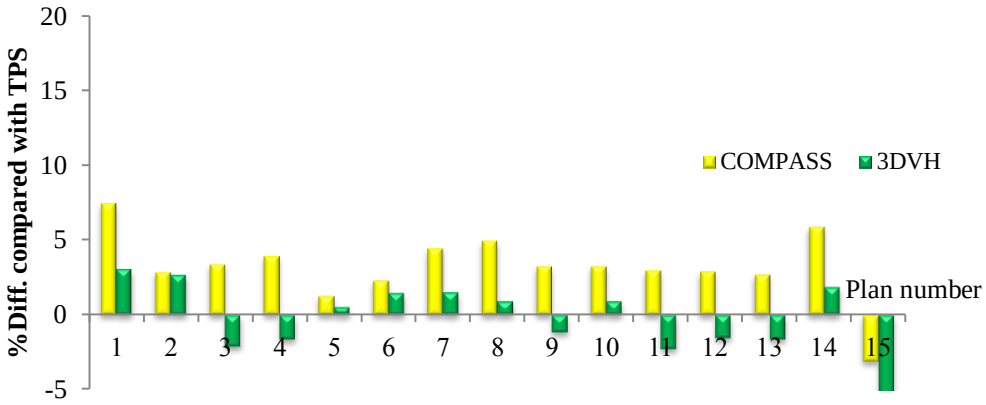


Figure 5.20 The percent dose differences of $D_{2\%}$ for COMPASS and 3DVH software compared with TPS.

The D_{mean} of fifteen VMAT plans were reported from TPS, COMPASS (dose reconstruction) and 3DVH software which is shown in Table 5.29. The mean percent differences of D_{mean} in COMPASS (dose reconstruction) and 3DVH software when compared with TPS were 0.96 ± 2.19% (ranging from -6.59 to 2.55%) and -4.23 ± 2.12% (ranging from -9.39 to -1.70%), respectively. This is shown in Table 5.30. Figure 5.21 shows the bar graph of percent differences of D_{mean} compared with TPS.

Table 5.29 The quantitative dose report in value of D_{mean} for TPS, COMPASS and 3DVH.

Plan number	D_{mean} (cGy)		
	TPS	COMPASS	3DVH
1	3157.00	3160.26	3058.90
2	6097.50	6151.56	5956.50
3	4862.10	4975.25	4672.90
4	1439.90	1469.59	1387.50
5	6372.22	6149.90	6309.90
6	4732.90	4776.50	4652.40
7	5374.40	5438.93	5099.20
8	5657.80	5774.24	5209.10
9	5707.20	5771.02	5385.20
10	3273.90	3325.98	3180.90
11	6172.40	6306.30	5929.40
12	6043.30	6134.31	5869.50
13	6247.60	6343.67	6034.30
14	5449.40	5588.13	5174.60
15	6126.40	5722.71	5551.10

Table 5.30 The percent dose differences of D_{mean} for COMPASS and 3DVH compared with calculated dose in TPS.

Plan number	%Dose diff. compared with TPS	
	COMPASS	3DVH
1	0.10	-3.11
2	0.89	-2.31
3	2.33	-3.89
4	2.06	-3.64
5	0.99	-2.54
6	0.92	-1.70
7	1.20	-5.12
8	2.06	-7.93
9	1.12	-5.64
10	1.59	-2.84
11	2.17	-3.94
12	1.51	-2.88
13	1.54	-3.41
14	2.55	-5.04
15	-6.59	-9.39
Mean ± SD	0.96 ± 2.19	-4.23 ± 2.12

%Dose diff. = (COMPASS - TPS)/TPS)*100, (3DVH - TPS)/TPS)*100

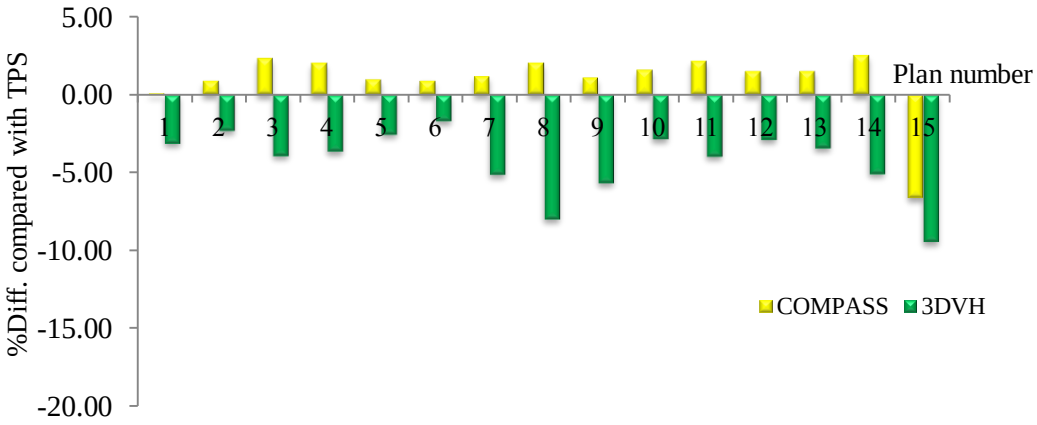


Figure 5.21 The percent dose differences of D_{mean} for COMPASS and 3DVH software compared with TPS.

The summary data of DVHs evaluation in PTV for COMPASS and 3DVH software is shown in Table 5.31. The data showed the means of percent differences and standard deviation of the quantitative dose report compared with TPS. Figure 5.22 shows the means percent differences of quantitative dose report compared with TPS for COMPASS and 3DVH software.

Table 5.31 The means of percent dose differences of the quantitative dose report compared with the dose calculated in TPS.

Indices	Means of % difference (compared with TPS)	
	COMPASS	3DVH
$D_{98\%}$	-4.10 ± 3.88	-8.34 ± 4.82
$D_{95\%}$	-2.21 ± 3.13	-7.90 ± 4.02
$D_{50\%}$	1.26 ± 2.35	-4.06 ± 2.45
$D_{2\%}$	3.25 ± 2.32	-0.19 ± 2.27
D_{mean}	0.96 ± 2.19	-4.23 ± 2.12

%Dose diff. = (COMPASS - TPS)/TPS)*100, (3DVH - TPS)/TPS)*100

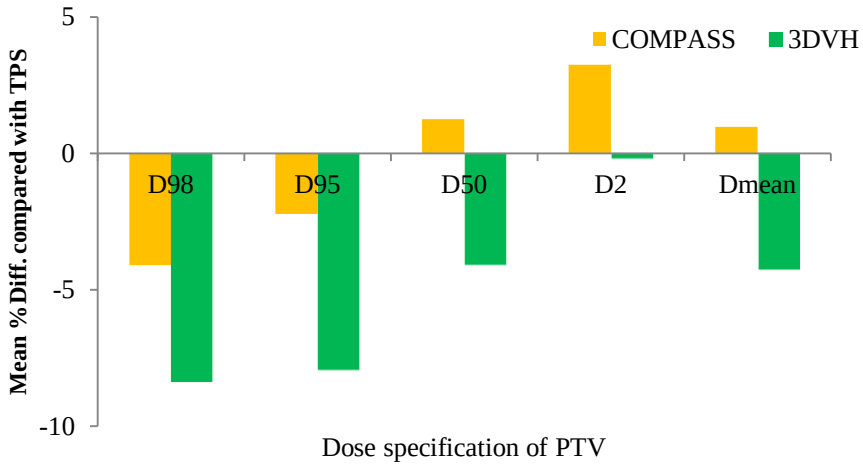


Figure 5.22 The means percent dose differences of quantitative dose report for COMPASS and 3DVH compared with calculated dose in TPS.

For OARs, the evaluation of DVHs was performed in term of D_{mean}. The OARs in head region of this study included eye balls, lens, optic nerves, cochlears, and brain stem. The results are shown in Table for 5.32 and Table 5.33 for COMPASS and 3DVH software, respectively.

Table 5.32 The percent dose differences of D_{mean} in OARs for COMPASS software compared with TPS.

OARs / Plan	Eye balls		Lens		Optic nerves		Cochlears		Brain stem
	Lt.	Rt.	Lt.	RT.	Lt.	Rt.	Lt.	Rt.	
1	11.43	15.03	19.25	34.50	11.32	14.65	3.62	16.01	-1.01
2	2.56	5.33	26.55	15.59	17.41	10.00	2.66	-3.46	5.43
3	4.38	12.41	5.59	14.83	11.86	17.33	-8.86	-3.68	-7.97
4	2.41	14.53	4.04	18.15	13.64	15.79	-9.84	-20.82	-9.57
5	-14.94	6.19	-1.21	29.16	1.97	-3.28	-15.84	18.49	-0.07
6	-15.71	-9.94	-14.37	-2.13	-19.70	-24.96	-15.23	-24.04	-19.59
7	-5.78	3.38	-15.05	-4.09	-5.16	1.24	-2.20	-10.60	-6.84
8	18.72	8.90	35.73	11.59	23.52	11.59	-4.05	-1.27	-7.67
9	-	10.92	-	9.77	-	3.51	-8.11	3.81	-8.93
10	10.55	8.28	16.83	3.26	29.19	17.12	-	-	-13.83
11	-1.97	-6.62	-7.16	-9.03	-8.62	-11.30	-13.17	-12.88	-11.62
12	14.80	10.45	23.28	18.03	8.49	4.24	-18.93	-15.30	-7.29
13	7.67	-1.71	21.90	0.33	-4.16	-8.38	-16.16	-21.60	-14.20
14	15.92	16.77	30.17	28.34	25.35	23.46	-16.01	-7.28	-16.99
15	-6.81	-0.18	-11.47	-2.78	-7.16	-1.52	-17.40	-4.08	-4.99
Mean	3.09	6.25	9.58	11.04	7.00	4.63	-9.97	-6.19	-8.34
SD	13.88	14.22	14.84	14.03	13.08	11.70	9.25	10.00	6.58

Table 5.33 The percent dose differences of D_{mean} in OARs for 3DVH software compared with TPS.

OARs / Plan	Eye balls		Lens		Optic nerves		Cochlears		Brain stem
	Lt.	Rt.	Lt.	Rt.	Lt.	Rt.	Lt.	Rt.	
1	1.48	-1.05	-0.18	-4.34	2.25	-4.34	2.07	-2.03	-2.26
2	-4.66	-6.15	-2.68	-6.08	-8.41	-6.33	-7.43	-5.34	-10.54
3	-1.31	-4.47	-0.15	-1.73	-0.06	-0.98	-7.14	4.57	-1.67
4	-2.06	-2.70	0.86	-1.99	0.97	-0.39	-8.46	-7.84	-1.74
5	-17.12	-2.70	-5.35	-7.98	-4.13	-3.28	-2.61	-7.65	-2.11
6	-2.59	-3.74	-0.93	-3.28	-2.30	-4.28	-3.83	-10.45	-4.92
7	-6.98	-6.30	-6.41	-8.80	-4.39	-2.27	-7.51	-8.87	-4.38
8	-5.55	-6.59	-8.42	-11.82	-11.06	-11.82	-4.34	-5.92	-7.84
9	-	-8.15	-	-6.37	-	-4.28	-9.28	-15.65	-8.13
10	-3.56	-4.91	-3.66	-2.85	-19.74	-3.37	-	-	-9.42
11	-3.46	-3.96	-0.88	-2.51	-5.23	-2.46	-2.66	-3.20	-0.28
12	5.10	4.88	2.41	3.87	-3.52	-4.51	15.94	9.31	4.26
13	-4.94	-2.17	-4.52	2.00	-7.84	-2.89	9.67	-11.38	-1.20
14	3.36	-0.26	7.82	2.36	-10.32	-1.58	-0.33	-1.64	-5.59
15	-3.87	-2.72	-8.62	-2.86	-6.41	-5.46	-6.59	-12.08	-3.95
Mean	-3.31	-3.49	-2.29	-3.45	-6.66	-3.85	-3.70	-5.58	-4.32
SD	5.06	3.07	4.31	4.16	6.56	2.64	6.63	6.68	4.02

The summary data of DVHs evaluation in OARs for COMPASS and 3DVH software are shown in Table 5.34. The data showed the means of percent difference of the D_{mean} for each organ compared with TPS. Figure 5.23 shows the means percent differences and standard deviation of the D_{mean} compared with TPS for COMPASS and 3DVH software.

Table 5.34 The mean of percent dose differences of D_{mean} in OARs compared with TPS for COMPASS and 3DVH software.

Organs	Mean of % Difference (compared with TPS)	
	COMPASS	3DVH
Eye Ball Lt.	3.09±3.88	-3.31±5.06
Eye Ball Rt.	6.25±14.22	-3.49±3.07
Lens Lt.	9.58±14.84	-2.29±4.31
Lens Rt.	11.04±14.03	-3.45±4.16
Optic nerve Lt.	7.00±13.08	-6.66±6.56
Optic nerve Rt.	4.63±11.70	-3.85±2.64
Cochlear Lt.	-9.97±9.25	-3.70±6.63
Cochlear Rt.	-6.19±10.00	-5.58±6.68
Brain stem	-8.34±6.58	-4.32±4.02

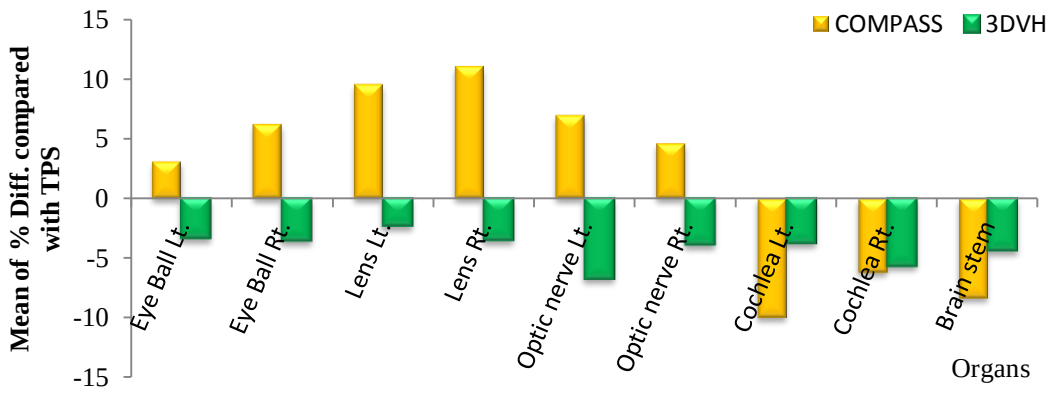


Figure 5.23 The mean of percent dose differences of D_{mean} in OARs for COMPASS and 3DVH compared to TPS.

5.3.2. Evaluation of QA software Gamma index criteria

The verification of fifteen VMAT treatment plans in head region were undertaken for 3D gamma passing using ArcCHECK, 3DVH and COMPASS software.

The percent gamma pass of ArcCHECK, 3DVH and COMPASS software for gamma value should be less than 1 and it was limited for 3% dose difference and 3 mm DTA. The mean and standard deviation of percent gamma pass of ArcCHECK measurement, COMPASS and 3DVH software were 98.87± 0.84, 99.19 ± 0.49, and 94.98 ± 3.49, respectively. This is shown in Table 5.35. Figure 5.24 shows the bar graph of percent gamma pass of ArcCHECK, COMPASS, and 3DVH software.

Table 5.35 The percent gamma pass for ArcCHECK, COMPASS and 3DVH software in VMAT pretreatment verification.

Plan number	Percent of gamma pass		
	Arc CHECK	COMPASS	3DVH
1	99.50	99.72	99.60
2	99.00	99.14	96.50
3	99.00	98.51	92.00
4	98.30	99.72	95.20
5	99.50	98.55	92.70
6	98.90	99.38	96.60
7	98.50	99.23	96.80
8	97.90	99.70	94.50
9	100.00	98.80	97.50
10	99.30	99.69	98.00
11	99.50	98.90	87.00
12	98.10	98.69	92.20
13	98.70	98.57	90.30
14	96.90	99.50	97.50
15	100	99.80	98.30
Mean ±SD	98.87± 0.84	99.19 ± 0.49	94.98 ± 3.49

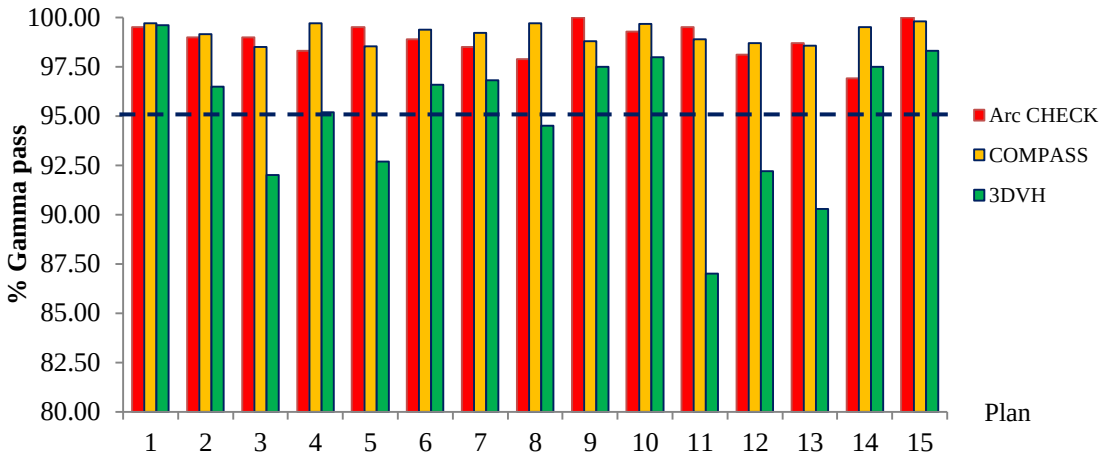


Figure 5.24 The percent gamma pass for ArcCHECK, COMPASS and 3DVH software in VMAT pretreatment verification.

CHAPTER VI
DISCUSSION

6.1 Study of detector properties

6.1.1 Initial phase and time dependence

In this study, we investigate the effect of warming up the device before measurement. The MatriXX signal when warming up the device before measurement for 15 minutes shows less variation of MatriXX response than no warming up the device. From the recommendation, the MatriXX detector should pre-irradiate as 10 Gy after warming up of the device. We observe the results by separating the data in warming up of the device condition into 2 parts. The first part is 1 to 10 numbers of measurements that have the normalized signal ranging from 0.9934 to 1.0009 with percent variation about 0.2%. For the second part, it is 11 to 20 number of measurement that have the normalized signal ranging from 0.9997 to 1.0013 with percent variation about 0.05%. The signal of the first measurement has lowest signal and the percent deviation of the signal after first measurement is 0.05%. So the pre-irradiated about 200 cGy is recommended for stable MatriXX signal.

6.1.2 Gravitational effect of gantry rotation

The effect of gravitation for MatriXX detector response in the gantry rotation of 20° increment measurement shows that the variation of signal is 0.19%. This mean that no effect of gravitational when the MatriXX detector is attached on the gantry with gantry holder.

6.1.3 Dose and energy response

The MatriXX signal increase linearly with the dose delivered with the regression coefficients of 1 for both 6 and 10 MV photon beams. The ratio of average collected MatriXX signal between 6 and 10 MV is 1.01%, so the response of MatriXX

detector does not depend on the energy. The results agree with Herzen J. et al. [17] and Li J. et al. [18].

6.1.4 Repetition rate effect

The Matrixx detector show increasing response with the decreasing of the repetition rate of 6 and 10 MV photon beams and the most deviation compared with 400 MU/min is observed at 100 MU/min. For VMAT technique the repetition rate are used in the range from 100 to 600 MU/min for modulated beam, the range could be acceptable because the variations are 0.32% and 0.25% for 6 and 10 MV photon beams, respectively.

6.1.5 Field size effect

The field size response of MatriXX detector in relative output factor show the increasing with larger field size in 6 and 10 MV photon beams. These results demonstrate the effect from phantom scatter. The percentage differences of relative output factor of MatriXX detector from CC13 ionization chamber are less than 1%. The results agree with Li J. et al. [18] who reported significant field size dependence of MatriXX which agreed with ionization chamber within 1%.

6.1.6 Reproducibility

The variation of MatriXX signal in short term measured every 5 minute over 1 hour (0.11%) is less than the variation in long term measured every week over 3 months (0.54%). The results agree with Li J. et al. [18] who reported the MatriXX showed higher fluctuation in long term reproducibility.

6.1.7 Statistical uncertainty

The response of the MatriXX detector in the function of the delivered dose is investigated. Doses are varied from 1 cGy to 300 cGy. The results show high percent deviation of all detectors in MatriXX array at low delivered dose. The highest percent variation is 1 cGy delivered dose, the percent deviation decrease when the dose delivered is high. The variation is less than 1% with delivered dose of 10 cGy to

300 cGy. This result should concern when measuring in the low dose area. This work agree with Li J. et al. [18] who reported that MatriXX detector show negligible errors (<1%) when measuring more than 10 MU, corresponding to approximately 8 cGy.

6.2 Basic clinical application

The comparison of the DVHs in commercial QA software with TPS is performed to verify the software. The basic treatment plan with four field box technique and simple organs are taken for testing. The results show percent difference when comparing QA software algorithm from 3DVH and COMPASS with the TPS calculation.

6.2.1 DVHs comparison between COMPASS dose computation (independent QA software) and TPS

The percent dose difference from TPS of PTV range from 2.06% to 2.25% and OARs range from 2.21% to 2.34%. The dose calculation of COMPASS software is higher than TPS. This result can be explained in term of the difference in concept of dose calculation. The dose calculation of COMPASS software is manipulated by collapsed cone convolution/superposition. For TPS, dose is calculated in AAA algorithm with calculate dose in voxel. The difference of the calculation algorithm may cause slightly shift of DVHs and process of adjusting beam parameter in the commissioning of matrix that percent dose difference from treatment planning is around 2%.

6.2.2 DVHs comparison between COMPASS dose reconstruction (MatriXX measurement) and TPS

The percent dose difference from TPS for PTV ranged from 2.29 to 4.58% and OARs ranged from 0.64 to 11.86%. The dose reconstructions based on MatriXX measurement of COMPASS software were higher than TPS.

The 1 – 2 structure is the highest difference (11.86%). This can be attributed to the volume of 1-2 structure which illustrates small volume and some area is located at the edge of beam. In addition, the smoothing iteration and 2 mm large

voxel size of process in COMPASS dose reconstruction so the interpolation of dose will be effect to the small volume.

6.2.3 DVHs comparison between 3DVH software (ArcCHECK measurement) and TPS

The percent dose difference from TPS for PTV range from -1.68 to 1.46 % and OARs range from -2.73 to 1.26%. The dose base on ArcCHECK measurement and PDP algorithm of 3DVH software are less than TPS. The DVHs of 3DVH software are generated in PDP algorithm which correct and estimated dose to patient using error in measurement and treatment plan calculation. So the difference of doses in difference volumes in 3DVH software for PTV and OARs from the treatment planning show small shifted.

6.3 Advanced clinical application

In this study, we evaluate the DVHs generating in COMPASS and 3DVH software using DVHs analysis for patent specific QA of VMAT plan in head region. In addition, we report in gamma index criteria and explore the correlation between gamma index and dose difference of both QA softwares.

6.3.1 Evaluation of QA software using DVHs analysis

The QA software are evaluated using HI, $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$, D_{mean} of PTV and D_{mean} of OAR from DVHs.

The mean and standard deviation of the homogeneity index in PTV of TPS, COMPASS and 3DVH software are 0.11 ± 0.04, 0.18 ± 0.05 and 0.19 ± 0.05, respectively. The high homogeneity index in COMPASS and 3DVH can be explained from the effect in the difference algorithm of software.

The mean percent dose difference from TPS for the COMPASS software of $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$, D_{mean} in PTV are -4.10±3.88%, -2.21±3.13%, 1.26±2.35%, 3.25±2.32% and 0.96±2.19%, respectively. The mean percent dose difference of $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$, D_{mean} in PTV for the 3DVH software are -8.34±4.82%, -7.90±4.02%, -4.06±2.45%, -0.19±2.27% and -4.23±2.12%,

respectively. The results are shown in Table 5.31. The DVHs differences between 3DVH and COMPASS software can be explained as follows;

The results of advanced clinical application show the larger dose difference from TPS in 3DVHs software and smaller dose difference in COMPASS software that are contrast to the basic clinical application. In clinical plan, the COMPASS software consider the tissue inhomogeniety in CT images using collapsed cone convolution/superposition while the 3DVH software use the dose error between measured in Arc CHECK and calculated from TPS and applied the PDP algorithm to obtain the 3D dose. The inhomogeneity is included in the dose error, special calculation is not taken. The size and shape of tumor and organ at risks also influence the dose report.

Plan number 1 is the example of large dose differences in both QA softwares. Plan number 7 and 9 are the example of large dose differences in 3DVHs software. The DVHs are illustrated in Figure 6.1, 6.2 and 6.3 for plan number 1, 7 and 9, respectively. Plan number 6 illustrate DVHs which are comparable between 3DVH, COMPASS and TPS.

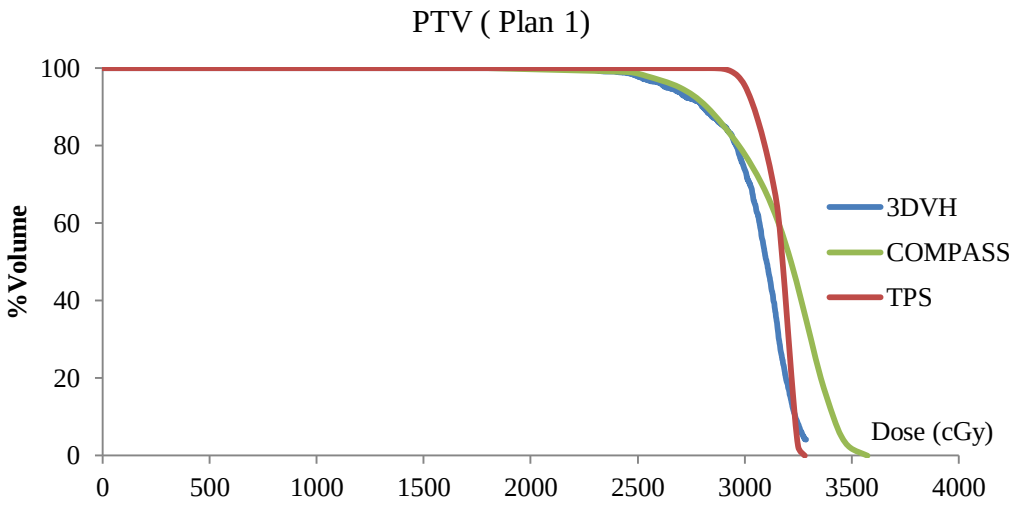


Figure 6.1 Dose volume histograms of 3DVH, COMPASS software and TPS in plan number 1.

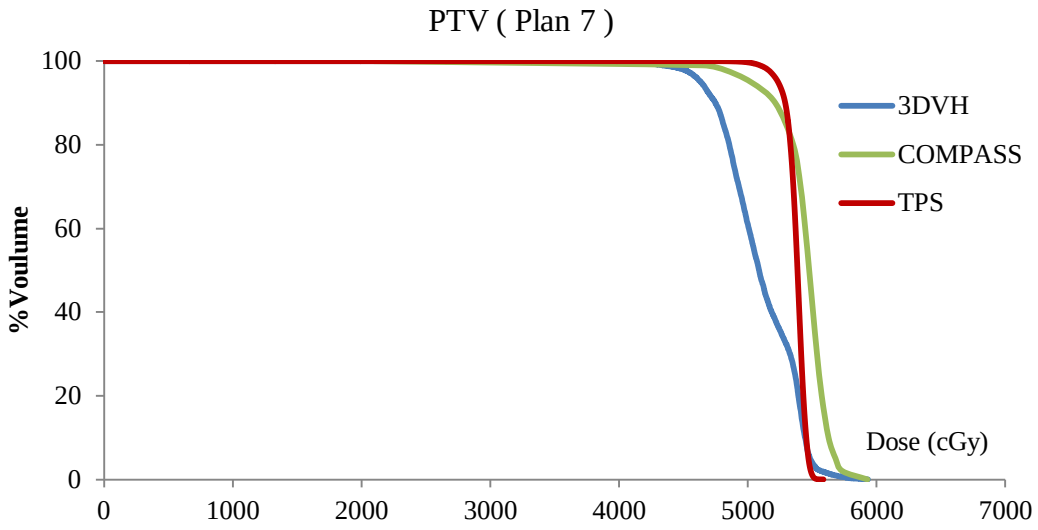


Figure 6.2 Dose volume histograms of 3DVH, COMPASS software and TPS in plan number 7.

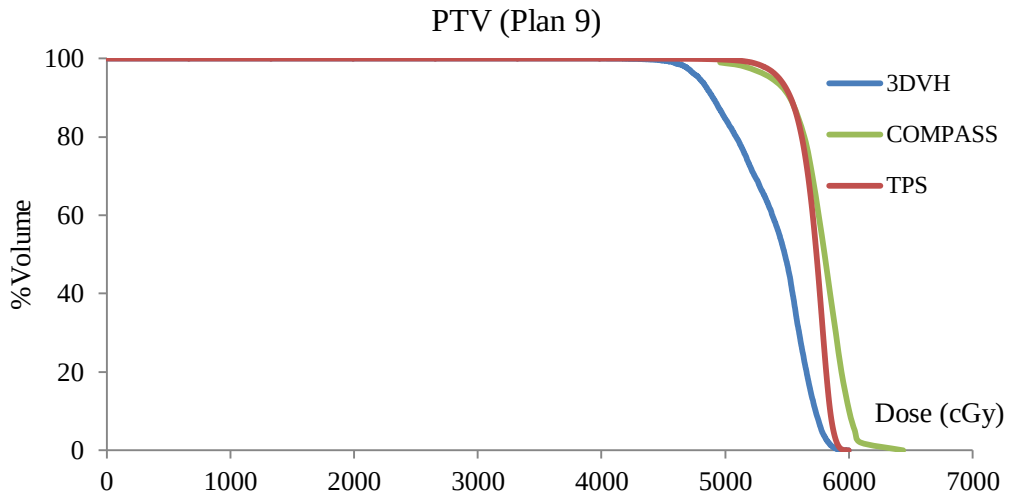


Figure 6.3 Dose volume histograms of 3DVH, COMPASS software and TPS in plan number 9.

Plan number 1, the DVHs from 3DVH and COMPASS software are deviated from TPS. The 3 locations of PTV in brain as shown in Figure 6.4 that result in a complicate plan with high dose gradient in many areas and effect to high percent dose difference for both QA softwares.

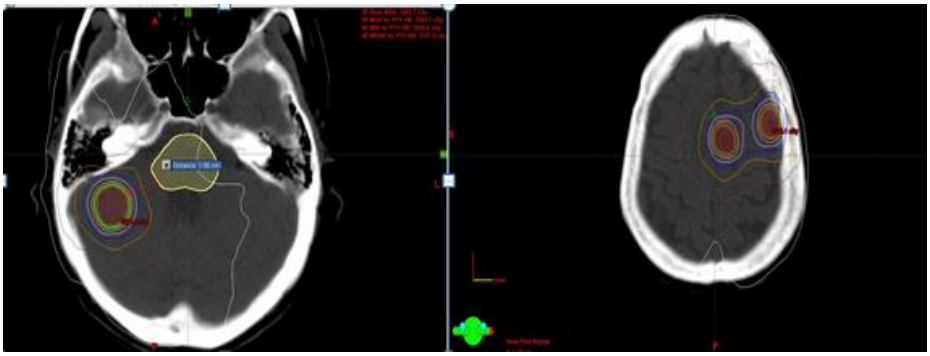
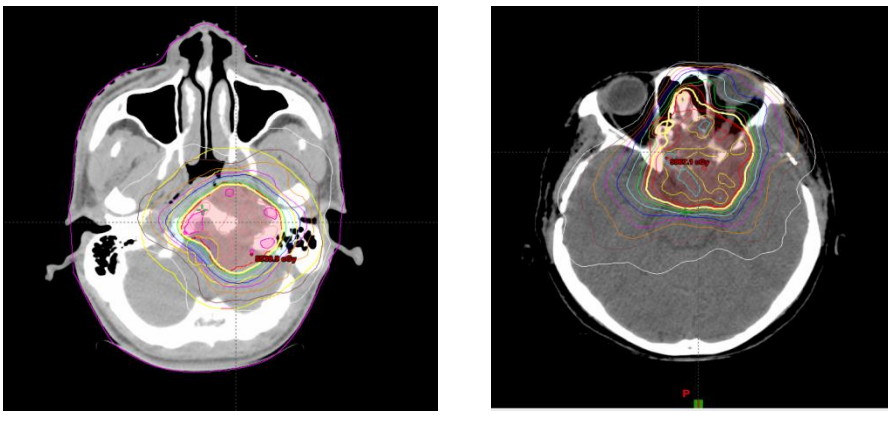


Figure 6.4 The PTV locations in plan number 1.

Plan number 7 and 9, the DVHs of 3DVH are lower than COMPASS software and TPS. The location of PTV in Figure 6.5 and 6.6 are located in inhomogeneity regions that include the area of air and bone. The inhomogeneity may effect to generate the 3D dose resulted in the dose deviated from TPS in the 3DVH software which less considered the inhomogeneity effect.



(a) (b)

Figure 6.5 The PTV locations in plan number 7 (a) and plan number 9 (b).

Plan number 6, the percent dose differences from TPS of COMPASS and 3DVH software are slightly difference. These can be explained from the location of PTV that is located in homogeneity area. This is shown in Figure 6.6 and 6.7.

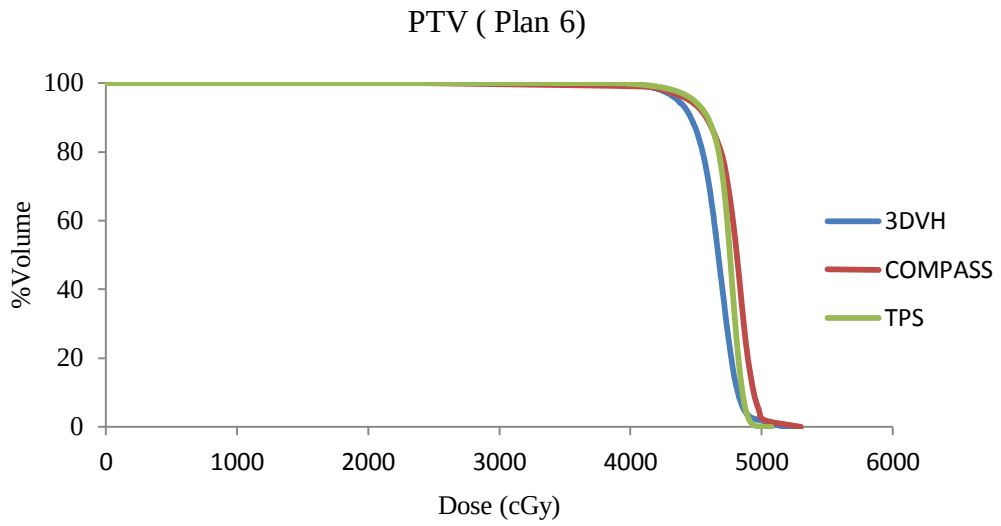


Figure 6.6 Dose volume histograms of 3DVH, COMPASS software and TPS in plan number 6.

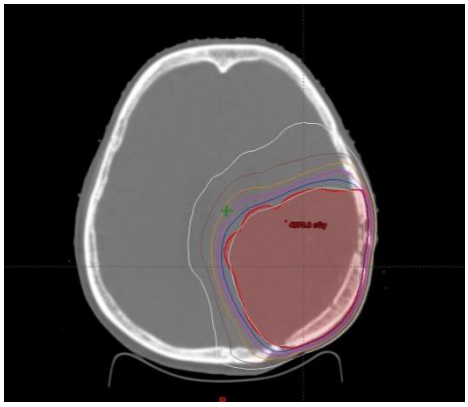


Figure 6.7 The PTV locations in plan number 6.

To evaluate the DVHs in OARs of head region, the results are shown in Table 5.32 and 5.33 with large standard deviation of percent dose difference in 3DVH and COMPASS software. Some part of OARs is in the PTV resulted in high dose gradient. This can effect to the response of detectors and may cause to the COMPASS

misinterpretation. In addition, the volume sampling can effect to the high dose differences in COMPASS reconstruction. This is because of the OARs that have a small volume. So when interpolation with 2 mm voxel size to the 3D dose that can be received the errors and get the large dose differences. Also for 3DVH software, Carasso P. [22] showed the slightly difference in the calculation of dose coverage in the PTV which could be from the insufficient spatial resolution of the detector. They considered the lower dose point surrounding the radiation fields could be caused by the interpolation of the dose measured around diode in areas with high dose gradient. The example of brain stem location and DVHs are shown in Figure 6.8 and 6.9.

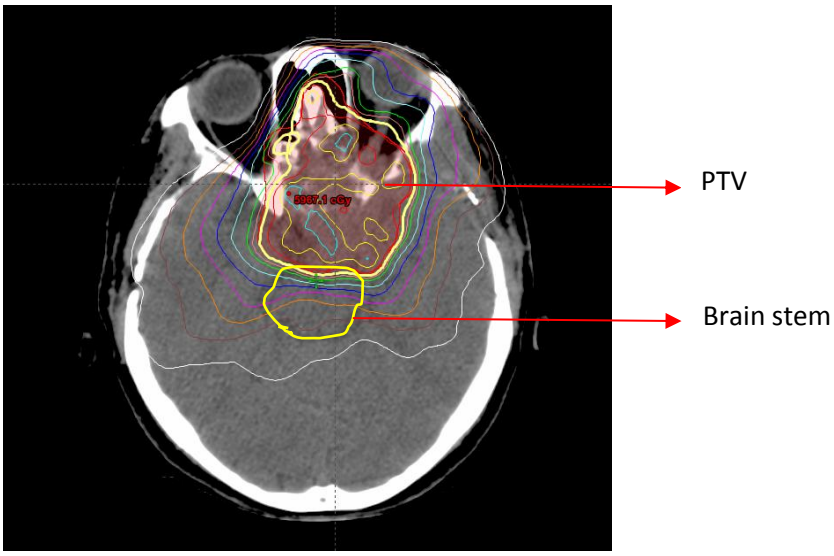


Figure 6.8 The Brain stem locations in plan number 9.

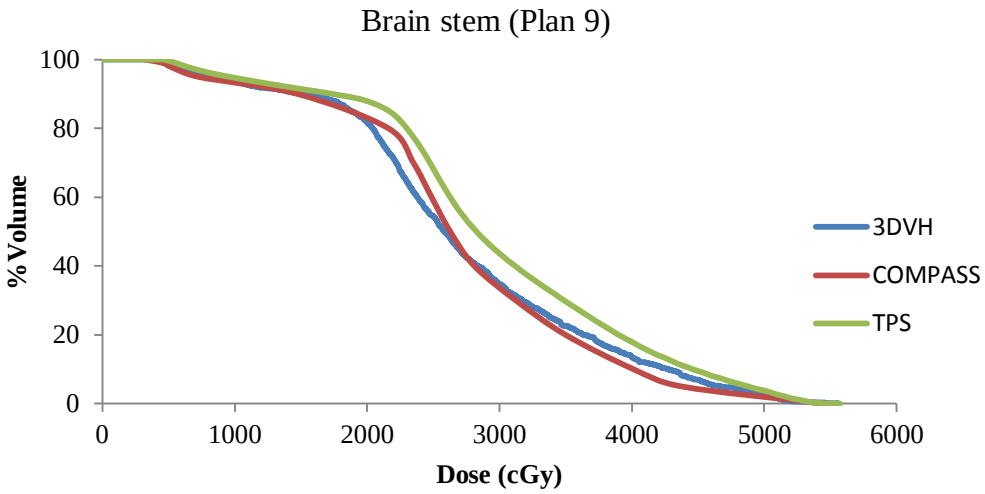


Figure 6.9 Dose volume histograms of brain stem in 3DVH, COMPASS software and TPS of plan number 9.

The comparison of previous works for percent dose difference is shown in Table 6.1 and 6.2. There is no data for head region. Our work agree with the study in prostate region.

Table 6.1 Comparison of previous works in percent mean dose difference from TPS of COMPASS reconstruction.

Study	Treatment site	Organ	Technique	% Mean dose difference
Boggula R. et al. [20]	Prostate (5 plans)	PTV $D_{95\%}$ PTV D_{mean}	IMRT	1.12% 1.66%
Boggula R. et al. [21]	Prostate (3 plans)	PTV $D_{95\%}$ PTV D_{mean} OARs	VMAT	1.08% 1.00% < 9%
This study	Head (15 plans)	PTV $D_{95\%}$ PTV D_{mean} OARs	VMAT	2.21% 0.96% -0.97 to 11.04%

Table 6.2 Comparison of previous works in percent mean dose difference from TPS of 3DVH software.

Study	Treatment site	Organ	Technique	% Mean dose difference
Carrasso P. [22]	Head and neck	PTV D_{mean} OARs	IMRT	-6.3 to 2.4% -1.1 to 5.7%
This study	Head (15 plans)	PTV D_{mean} OARs	VMAT	-4.23% -6.66 to -2.29%

6.3.2 Evaluation of QA software using gamma index criteria.

Normally, we used the percent gamma pass with criteria 3% dose difference and 3 mm DTA for verification plan. Table 5.35 show the comparison of percent difference of gamma pass from ArcCHECK, COMPASS and 3DVH software. The mean percent gamma pass of ArcCHECK and COMPASS are more than 95%.

The mean percent gamma pass of 3DVH software is lower than ArcCHECK. The highest difference between 3DVH software and ArcCHECK can be explained from different calculation processing in softwares while using the same detector for measurement. The ArcCHECK uses planar dose distribution for evaluation plan and the 3DVH software used the PDP algorithm for evaluation plan as a 3D gamma pass in volume of treatment site. The difference of algorithm illustration may cause the deviation of gamma pass. These results agree with Paowarin et al. [23] who reported the results gamma analysis of 3DVH software was lower than ArcCHECK.

For comparison of the mean percent gamma pass of COMPASS and 3DVH, the mean percent gamma pass of COMPASS software was higher. This is because the gamma index of COMPASS can be determined from area of interested such as a PTV, OARs or body. For this study, we evaluated the gamma index from body of treatment site to get the same condition with the ArcCHECK and the 3DVH software. The high value of gamma pass in COMPASS software may cause from the process of generating which counted all voxel for gamma index comparison.

The comparison of percent gamma pass of previous works can be shown in Table 6.3 and Table 6.4.The works have been done for prostate, paraspinal, anal and body but still lack of head region in VMAT technique. Our result demonstrate the high percent of gamma.

Table 6.3 Comparison of this study with the previous work in gamma pass (3% dose difference and 3 mm DTA) of COMPASS dose reconstruction.

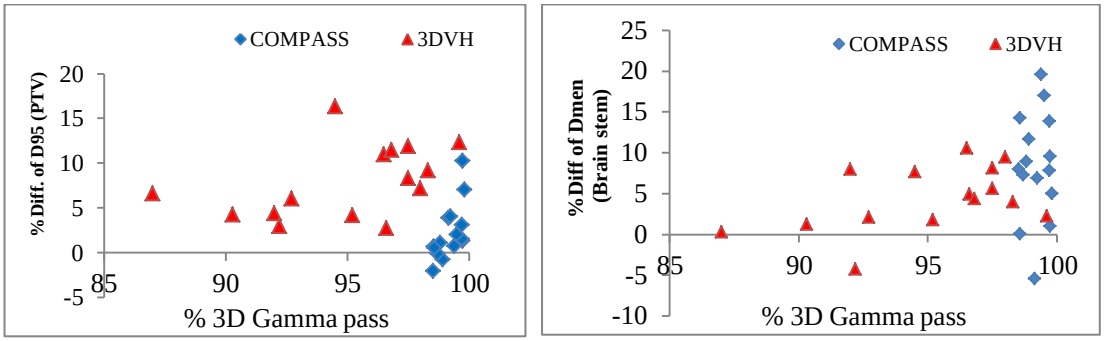
Study	Treatment site	Organ	Technique	%Gamma pass
Boggula R. et al.[20]	Prostate (5 plans)	PTV	IMRT	≥ 99%
Boggula R. et al. [21]	Prostate (4 plans)	Prostate	VMAT	94.22-100%
Boggula R. et al. [21]	Prostate (4 plans)	Paraspinal	VMAT	96.32-100%
Boggula R. et al. [21]	Prostate (4 plans)	Anal	VMAT	61.67–100%
This study	Head (15 plans)	Body	VMAT	99.19%

Table 6.4 Comparison of this study with the previous work in gamma pass (3% dose difference and 3 mm DTA) of 3DVH software.

Study	Treatment site	Technique	%Gamma pass
Paowarin et al.[23]	Head and neck (14 plans)	IMRT	95.10%
This study	Head (15 plans)	VMAT	94.98%

6.3.3 Correlation between gamma index and dose difference

We explore the correlation between gamma index and dose difference in organ of interest such as PTV and brain stem. This result is shown in Figure 6.3.



a) b)

Figure 6.10 The correlations between percent gamma pass and percent dose different compared with TPS a) $D_{95\%}$ of PTV b) D_{mean} of Brain stem.

From Figure 6.10, these results show that there are weak correlation between percent gamma pass and dose in patient. The COMPASS illustrate high percent gamma pass but varied of dose difference in PTV. The 3DVH show high percent gamma pass with the trend of high dose difference. These results agree with Nelms BE. et al. [24] and Carrasco P. et al. [22]

Further investigation

This work focus on using the DVHs analysis in COMPASS and 3DVH software by comparing with TPS in the dose specification that we follow from ICRU83 dose report. The results of PTV demonstrate comparable of both COMPASS and 3DVH with TPS, but large variation in the dose difference of OARs. A further study could be investigated to include more patient plans to find the limitation of the dose difference for using in clinic. In order to ensure the accuracy of the dose generating, the volume dose in PTV and OARs could be measured by film or TLD for more data to compare in the dose difference of both QA softwares in Rando phantom.

CHARPTER VII
CONCLUSION

In this study, we investigate the MatriXX characteristics, DVHs and percent gamma pass evaluation in the two commercial QA softwares and the correlation between percent dose difference and percent gamma pass by comparing with ArcCHECK.

The study of MatriXX characteristics illustrate that all the dosimetric parameters are suitable for using in the clinic. The MatriXX as a direct reading device demonstrate the linearity response with the 10 to 2500 cGy dose range, no gravitational effect of gantry rotation, no energy independence. The response in repetition rate is less than 1%. The field size effect is good agreement with CC13 ionization chamber within 1%. The short and long term reproducibility can be accepted with percent deviation less than 1%. The MatriXX shows large errors when measuring at low dose (<10 cGy). For using MatriXX detector, warming up the device about 15 minute and 200 cGy pre-irradiated for stable signal are enough. Dose recommend for measurement should be more than 10 cGy.

The basic clinical application are studied in DVHs comparison between COMPASS dose computation (using collapsed cone convolution/superposition algorithm), COMPASS dose reconstruction (data from Matrixx detector) and 3DVH software (data from ArcCHECK detector) with the TPS in homogeneous phantom in four fields box technique. The COMPASS dose computation can be used as independent QA software with accuracy in the dose difference from TPS in PTV around 2.16%. The COMPASS dose reconstruction shows maximum percent dose difference from TPS in PTV as 4.58% while 3DVHs software illustrate 1.68%. The COMPASS dose reconstruction obtains high dose variation of 11.78% from TPS in OARs due to small volume of OARs. In this work, the main cause of dose difference from TPS in homogeneous phantom plan is the difference of algorithm to generate the 3D dose.

For the advanced clinical application, we evaluate the two commercial QA softwares using DVH analysis and the percent gamma pass of fifteen VMAT plan in head region. The homogeneity index for COMPASS, 3DVH and TPS are 0.18 ± 0.05, 0.19 ± 0.05 and 0.11 ± 0.04. The HI from measurement is higher than dose calculation in TPS.

The mean percent dose difference from TPS for the COMPASS software of $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ and D_{mean} in PTV are -4.10±3.88%, -2.21±3.13%, 1.26±2.35%, 3.25±2.32% and 0.96±2.19%, respectively. The mean percent dose difference of $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{2\%}$ and D_{mean} in PTV for the 3DVH software are -8.34±4.82%, -7.90±4.02%, -4.06±2.45%, -0.19±2.27% and -4.23±2.12%, respectively. The contrast of percent dose differences in advanced clinical applications are obtained when verifying real patient plans. The lower dose differences from TPS of the COMPASS software are caused from the algorithm in COMPASS that can correct of the inhomogeneity to generate 3D dose more than 3DVHs software. In addition, the size and shape of tumor and organ at risks also influence to the dose report. The low dose areas of organs at risk with a small volume are observed with large deviation of percent dose difference for COMPASS and 3DVH software. However, both of QA softwares are suitable to use in 3D pre-treatment verification of the region that the PTV is located in homogeneity area and the report of dose differences in absolute dose are recommended.

The percent gamma pass of COMPASS and 3DVH are compared with ArcCHECK which are used routinely in the clinic, they are 99.19 ± 0.49, 94.98 ± 3.49 and 98.87±0.84 for COMPASS, 3DVH and ArcCHECK, respectively. The high percent pass in ArcCHECK do not relate to the percent gamma pass in 3DVH and the dose report in dose volume histograms. The percent gamma and dose in patient are poor correlation. The errors of dose in patient are still occurring while the gamma pass is too high. So the pre-treatment verification reported with DVHs analysis are recommend.

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APPENDICES

APPENDIX A

Gamma evaluation [25, 26]

The gamma method is designed for the comparison of two dose distributions: one is defined to be the reference information $D_r(r_r)$ and the other is queried for evaluation $D_c(r_c)$. A schematic representation of the gamma analysis tool for two dimensional dose distribution evaluations is shown in Figure A.1. The acceptance criteria are denoted by ΔD_M for the dose difference and Δd_M for the distance to agreement. For a reference point at position r_r, receiving dose D_r, the surface representing these acceptance criteria are an ellipsoid defined by:

$$1 = \sqrt{\frac{\Delta r^2}{\Delta d_M^2} + \frac{\Delta D^2}{\Delta D_M^2}} \qquad \text{A.1}$$

Where: $\Delta r = |r_r - r_c|$ is the distance between the reference and compared point and $\Delta D = D_c(r_c) - D_r(r_r)$ is the dose difference at the position r_c relative to the reference dose D_r in r_r. For the compared distribution to match the reference dose in r_r, it need to contain at least one point (r_c, D_c) lying within the ellipsoid of acceptance, i.e. one point for which:

$$\gamma_r(r_c, D_c) = \sqrt{\frac{\Delta r^2}{\Delta d_M^2} + \frac{\Delta D^2}{\Delta D_M^2}} \leq 1 \qquad \text{A.2}$$

A quantitative measure of the accuracy of the correspondence is determined by the point with the smallest deviation from the reference point, i.e. the point for which $\gamma_r(r_c, D_c)$ is minimal. This minimal value is referred to as the quality index $\gamma(r_r)$ of the reference point. The pass–fail criterion therefore becomes

$\gamma(r_r) \leq 1$ is acceptance criteria (passed)

$\gamma(r_r) > 1$ is not acceptance criteria (fails)

An implicit assumption is made that once the passing criteria are selected, the dose difference and DTA analyses have equivalent significance when determining calculation quality.

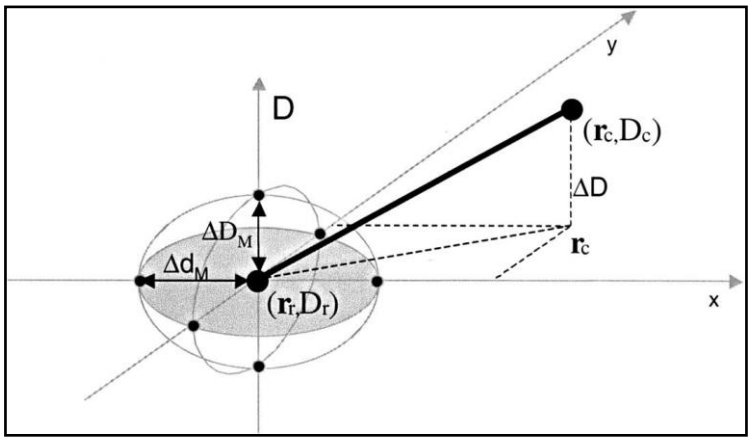


Figure A.1 Schematic representation of the theoretical concept of the gamma evaluation method.

APPENDIX B

Sample size determination

This study used the same patient plan for measuring by three- dimensional diode arrays and two dimensional ionization arrays compare to treatment planning system. The sample size is determined using two related group equation at 95% confident interval.

$$n = (Z_{\alpha/2})^2 \sigma^2 / d^2 \qquad \text{B.1}$$

Where:

$Z_{\alpha/2}$ = 1.96 (CI 95%)

σ = 0.06 (variance of % pass) [27]

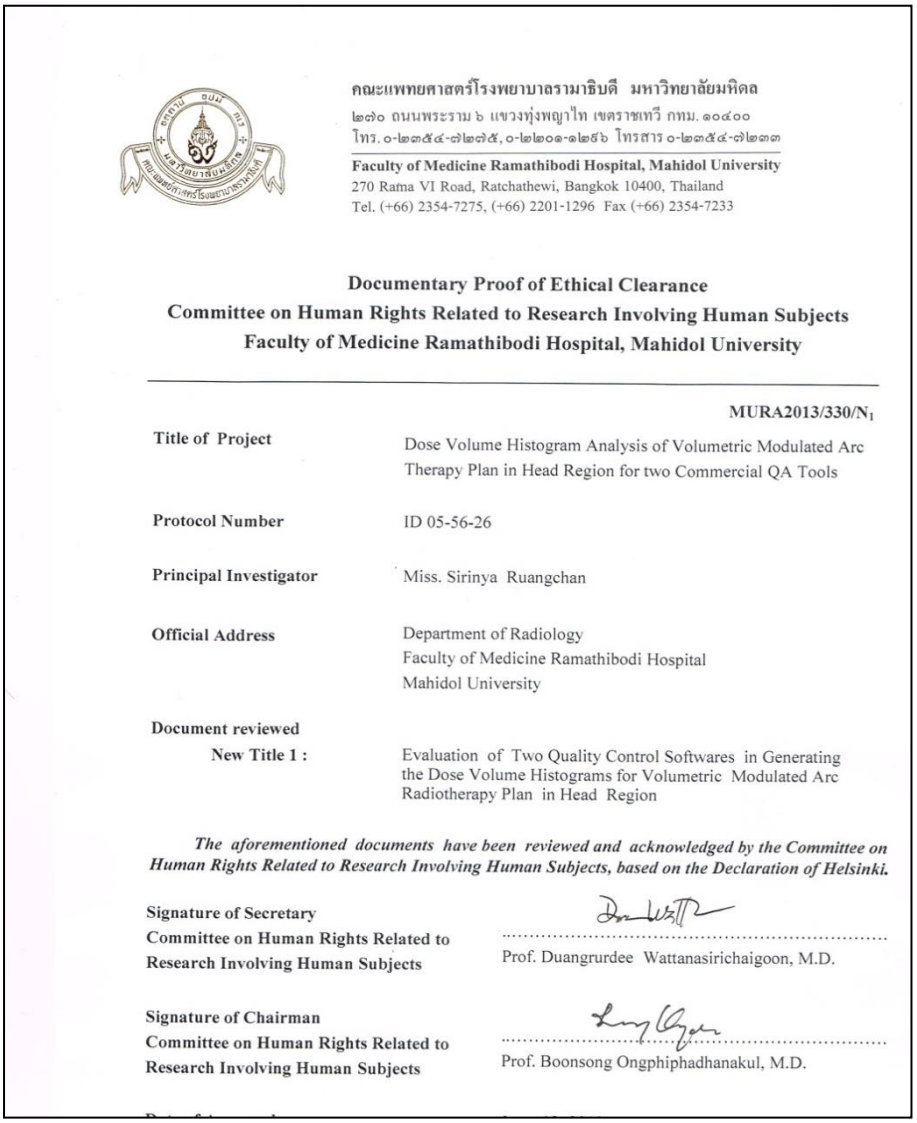
d = 3 (the dose acceptable between TPS and dose measurement) [26]

$\therefore$ n = 15

APPENDIX C

Documentary proof of ethical clearance

This study were performed in solid water phantom and patients data as CT images, however, the ethical was approved by Ethic Committee of Faculty of medicine Ramathibodi hospital. This is shown in Figure C.1.



คณะแพทยศาสตร์โรงพยาบาลรามาธิบดี มหาวิทยาลัยมหิดล
๒๗๐ ถนนพระราม ๖ แขวงทุ่งพญาไท เขตราชเทวี กทม. ๑๐๔๐๐
โทร. ๐-๒๓๕๔-๗๒๗๕, ๐-๒๒๐๑-๑๒๕๖ โทรสาร ๐-๒๓๕๔-๗๒๓๓

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Documentary Proof of Ethical Clearance
Committee on Human Rights Related to Research Involving Human Subjects
Faculty of Medicine Ramathibodi Hospital, Mahidol University

MURA2013/330/N1

Title of Project	Dose Volume Histogram Analysis of Volumetric Modulated Arc Therapy Plan in Head Region for two Commercial QA Tools
Protocol Number	ID 05-56-26
Principal Investigator	Miss. Sirinya Ruangchan
Official Address	Department of Radiology Faculty of Medicine Ramathibodi Hospital Mahidol University
Document reviewed **New Title 1 :**	Evaluation of Two Quality Control Softwares in Generating the Dose Volume Histograms for Volumetric Modulated Arc Radiotherapy Plan in Head Region

The aforementioned documents have been reviewed and acknowledged by the Committee on Human Rights Related to Research Involving Human Subjects, based on the Declaration of Helsinki.

Signature of Secretary
Committee on Human Rights Related to
Research Involving Human Subjects
.....
Prof. Duangrurdee Wattanasirichaigoon, M.D.

Signature of Chairman
Committee on Human Rights Related to
Research Involving Human Subjects
.....
Prof. Boonsong Ongphiphadhanakul, M.D.

Figure C.1 Documentary Proof of Ethical Clearance

BIOGRAPHY

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