EVALUATION OF OPTIMUM MEASUREMENT DEVICE, TIME ANALYSIS AND WORKLOAD OF PERFORMING QUALITY ASSURANCE TASKS BY PHYSICISTS ON MEDICAL LINEAR ACCELERATOR

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by

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LIST OF ABBREVIATIONS

AAPM	American Association of Physicists in Medicine
AgBr	Silver Bromide
AM	Acquisition Module
AXSym	Axial Symmetry
CBCT	Cone Beam Computed Tomography
cm	Centimetre
CT	Computed Tomography
CT Sim	Computed Tomography Simulator
cGy	Centi-Gray
CU	Calibration Units
Co-60	Cobalt-60
DICOM	Digital Imaging and Communications in Medicine
EPID	Electronic Portal Imaging Device
FMEA	Failure Modes and Effects Analysis
Gy	Gray
Hospital USM	Hospital Universiti Sains Malaysia
HWKKS	Sabah Women and Children Hospital
IPEM	Institute of Physics and Engineering in Medicine
IAEA	International Atomic Energy Agency
IMRT	Intensity Modulated Radiotherapy
IGRT	Image-Guided Radiation Therapy
ICRU	International Commission on Radiation Units and Measurements
kV	Kilo Voltage
LINAC	Linear Accelerator
MeV	Mega Electron Volts
MV	Mega Voltage
MLC	Multi-Leaf Collimators
mm	Millimetre
Min	Minutes
MOH	Malaysian Ministry of Health (KKM)
MU	Monitor Units

NHEWS	National Healthcare Establishment and Workforce Statistics
OD	Optical Density
ODI	Optical Distance Indicator
PMMA	Polymethylmethacrylate
QAP	Quality Assurance Program
QC	Quality Control
QUATRO	Quality Assurance Team for Radiation Oncology
ROI	Region of Interest
SSD	Source to Surface Distance
TRSym	Transverse Symmetry
TRS-398	IAEA Technical Reports Series No. 398
TG	Task Group
VMAT	Volumetric Modulated Arc Therapy
WISN	Workload Indicators of Staffing Needs
2D	Two-Dimensional
3D	Three-Dimensional
4DITC	4D Integrated Treatment Console

KAJIAN MENILAI ALAT PENGUKURAN YANG OPTIMUM, ANALISA MASA DAN BEBAN TUGAS AHLI FIZIK DALAM MELAKSANAKAN PROGRAM PENJAMINAN MUTU (QAP) BAGI PEMECUT LINEAR PERUBATAN

ABSTRAK

Pelaksanaan dokumen manual Program Penjaminan Mutu (QAP) dalam perkhidmatan Radioterapi oleh Kementerian Kesihatan Malaysia (KKM) adalah untuk memastikan penggunaan radiasi mengion dijalankan secara selamat serta efektif dan seterusnya mengurangkan kesilapan (*error*) dalam rawatan kanser kepada pesakit. Dengan teknik perawatan maju dan terkini serta pertambahan mendadak jumlah pesakit-pesakit kanser, pelaksanaan manual QAP ini adalah sangat penting dan amat bertepatan dengan masa. Malangnya, pelaksanaan ini juga akan membawa kepada implikasi lain seperti komitmen masa kerja yang bertambah kepada ahli Fizik. Seperti yang dinyatakan dalam laporan NHEWS (2010), perkhidmatan radioterapi di negara ini berdepan dengan kekangan sumber seperti kekurangan ahli fizik serta kekurangan peralatan pengukuran kawalan kualiti dan ini merupakan halangan besar bagi implementasi program QAP dengan berkesan. Justeru itu, adalah sangat penting untuk mengoptimumkan sumber yang sedia ada. Kajian ini telah mengesyorkan beberapa peralatan pengukuran kawalan kualiti yang boleh dioptimumkan untuk tujuan aktiviti kawalan kualiti tertentu. EPID memenuhi kriteria peralatan pengukuran kawalan kualiti tersebut kerana mampu mencatat bacaan keputusan sisihan piawai 0.77 peratus bagi profil kerataan (Flatness) dan sisihan piawai 0.33 peratus bagi profil simetri (Symmetry). Di samping itu, EPID juga sesuai digunakan untuk membuat ujian pengesahan medan cahaya kolimator dengan medan radiasi. Dua jenis pendekatan

digunakan untuk menilai beban tugas ahli fizik iaitu kaedah WISN dan kaedah orang-jam (Man-Hours). Jumlah masa untuk aktiviti kawalan kualiti bagi setiap pemecut linear perubatan ialah 62 orang-jam (Man-Hours) setahun atau bersamaan jumlah 5.2 orang-jam (Man-Hours) sebulan. Ini bersamaan dengan lima orang ahli fizik untuk setiap pemecut linear perubatan. Bagi aktiviti kawalan kualiti spesifik pesakit, keputusan sebanyak 42 orang-jam (Man-Hours) setahun atau 3.5 orang-jam (Man-Hours) sebulan telah diperolehi dalam kajian ini. Ini bersamaan dengan empat orang ahli fizik untuk menjalankan aktiviti tersebut. Aktiviti kawalan kualiti spesifik pesakit ini telah mencatat keputusan masa tertinggi berbanding aktiviti kawalan kualiti yang lain. Hasil keputusan kaedah WISN dan kaedah orang-jam (Man-Hours) ini, dapat disimpulkan bahawa jumlah ahli fizik yang diperlukan di Hospital Wanita dan Kanak-kanak Sabah ialah sembilan orang. Semasa kajian ini dijalankan, jumlah sebenar ahli fizik yang berkerja di hospital berkenaan adalah seramai enam orang. Ini menunjukkan kekurangan ahli fizik seramai tiga orang atau bersamaan dengan nisbah keputusan 0.67, menggunakan kaedah WISN. Kajian penilaian pelaksanaan manual QAP dalam perkhidmatan radioterapi seumpama ini adalah amat kurang malah mungkin tiada dijalankan di negara ini. Kaedah pendekatan *Failure Modes and Effects Analysis* (*FMEA*) untuk menilai program kawalan kualiti ini telah dicadangkan. Kajian ini telah dijalankan ke atas empat buah pemecut linear perubatan di dua buah hospital.

EVALUATION OF OPTIMUM MEASUREMENT DEVICE, TIME ANALYSIS AND WORKLOAD OF PERFORMING QUALITY ASSURANCE TASKS BY PHYSICISTS ON MEDICAL LINEAR ACCELERATOR

ABSTRACT

The implementation of the Radiotherapy Quality Assurance Program (QAP) safety standard by Malaysia Ministry of Health (KKM) is to ensure safe and efficacious application of ionizing radiation and minimize error in the treatment of cancer. With the new advance treatment technique and with the increasing number of cancer patients, the QAP implementation is crucially important. But this also demands a lot of physicist's working time. Lack of physicist and quality control (qc) device were among the problem encountered by most of the radiotherapy services in this country as reported by NHEWS Report (2010) and this has become a major issue for the QAP system to be in place. Therefore, it is particularly important to optimize whatever resources available. This study has made some recommendations regarding the qc tools suitably optimize for specific tasks. EPID is the best option for the quality control (qc) device. It had recorded flatness standard deviation of 0.77 percent, while the measured standard deviation of symmetry was 0.33 percent. EPID also provide sufficiently accurate measurement for the light and radiation field congruent test. With task timing, the Total Man Hours per linac for the machine qc was 62 Man-Hours per year or 5.2 Man-Hours per month. For a typical radiotherapy clinic, this translates to approximately five physicists per linac machine. The patient specific qc task had recorded approximately 42 Man-Hours per year of physicist's working time, higher compared the other qc tasks. This is equivalent to 3.5 Man-Hours per month or approximately four physicists that required to perform this task. Both calculation in

the WISN method and Man-Hours method had concluded that nine physicists are required in Sabah Women and Children Hospital (HWKKS), while the actual number of physicists working there at the time of this study was six. It means shortage of three physicists or equivalent to 0.67 by ratio calculation of the WISN. At the time of this research, there are limited or probably no evaluation study on qc device as well as the timing qc task study with respect to the implementation of the QAP radiotherapy standard in this country. By evaluate these QAP requirements, the gap between optimal and actual use of resources was identified. Different approach of methods such as using the Failure Modes and Effects Analysis (FMEA) in the qc program was recommended. The research was conducted on four medical linac in two hospitals.

CHAPTER 1

INTRODUCTION

1.1 Background study

Cancer has been identified as one of the leading causes of death in the Ministry of Health hospitals each year (NHEWS Report, 2010). Radiotherapy is one of the major options in cancer treatment in curing cancer disease besides the surgery, chemotherapy, hormones and immunotherapy. In radiation therapy, ionizing radiation is used as the external energy focusing on the diseased tissues while spare the healthy surrounding tissues. The International Commission on Radiation Units and Measurements (ICRU) Report No.24 (1976) stated that the dose delivered must be within 5% of the prescribed dose. To achieve the requirements, the accuracy within each step of the radiotherapy process must be better than 5% (Kutcher et al., 1994).

With the advancement of complex treatment techniques, the quality assurance program is an uphill task but still must be implemented to ensure the safe and efficacious application of ionizing radiation minimizing error in the treatment of cancer. In line with this, the Ministry of Health (MOH) Malaysia, has introduced guideline manual called the Quality Assurance Program (QAP) Standard of Safety and Performance Tests Implementation Manual for Radiotherapy Services to be used in all radiotherapy centre in Malaysia.

1.1.1 Quality Assurance Program (QAP) implementation manual for Radiotherapy Services, Malaysia Ministry of Health (MOH)

The term quality assurance (QA) describes a program that is designed to control and maintain the standard of quality set for that program (Khan, 2010). Quality control (qc) is one part of overall quality assurance. Qc is the regulatory process through which the actual quality performance is measured, compared with existing standards, and the actions necessary to keep or regain conformance with the standards (Podgorsak et al., 2005). In Malaysia, the reference of qc procedures is based on the Quality Assurance Program (QAP) Implementation Manual for Radiotherapy Services. It was introduced on 30th of July 2012 by the Malaysia Ministry of Health (MOH) and was revised in 2016. The contents of the guideline manual are the combinations of tests from number of published American Association of Physicists in Medicine (AAPM) committee Task Group (TG) namely the AAPM TG 40 and AAPM TG 142 for the linac quality assurance, AAPM TG 135 for the robotic radiosurgery quality assurance, AAPM TG 66 for the computed tomography simulator quality assurance and AAPM TG 148 for the helical tomotherapy qa. The focus of current study is on the linac qc and the contents of procedures, whose frequency and tolerance are shown Appendix G.

1.2 Problem statement

Implementing the qc tasks according to the QAP standard demands a lot of time of the physicists and the time trends will further increased with the implementation of new advance treatment technique and with the increase in number of patients. Patient safety related incidences in the Bialystok Oncology Centre, Poland in 2001, (Oliveira et al.,2004), Epinal France in 2004, (Ash, 2007) and

Beatson Oncology Centre, Glasgow in 2006, (William, 2007) had shown the importance and significant of the implementation of the qa program. As stated from the literatures, the important and necessary aspects of the qa program to succeed are the resources namely staffing, quality control tools and timely guidelines (Kutcher et al., 1994). Lack of physicist and qc tools are amongst the common shared problem in most radiotherapy department. This study is made to evaluate these QAP requirements to our experience and practices.

It was also identified that there is lack of local cancer institution data reference on the physicist workforce in this country (NHEWS Study, 2010). The physicist workforce data were inadequate in this country and this has created problem to conduct studies of physicist staffing required. Without such data, it was difficult to balance clinical needs with number of staff and competency required and this gives the impression lack of direction (Klein, 2008). Some of the justification for the physicist post is based on reference such as the American College of Radiology staffing level suggestions, the IPEM guidelines or from the Abt study (Klein, 2008). Therefore, data in this research (through the qc task workload) can be used to provide relevant assessment of physic staffing.

There are limited numbers of oncology qc devices in the radiotherapy services (NHEWS Report, 2010). Therefore, it is particularly important to optimize qc device that available such as Electronic Portal Imaging Device (EPID) and film. At the time of this research, there are limited or probably no benchmarking local study on qc device for the implementation of the QAP radiotherapy standard in this country. Various qc devices were investigated in this research to justify the suitability to be used for advances techniques qc.

Timing study to accomplish the qc tasks was as well limited. This research had recorded the average time of tasks completion to quantify both the workload and qc devices work process. Having the data based on time and work analysis approach, will greatly assist the justification of physics staff required and the selection of the qc devices. Additional to that, one of the requirements emphasized by QUATRO, is that the qc procedures must be available in the oncology and radiotherapy department (Izewska, 2007). The technical steps described in this paper was intended to meet the requirements and to complement the QAP Manual by providing some of the technical steps as reference guidelines. This can be used as the qc procedures since the technical procedures are according to the manufacturer or published scientific papers. Evaluate both current qc practices and physic staffing assessments are essential steps to analyse the gap between optimal and actual use of resources. By exchanging of experience in the qc practices and staffing assessment, it will benefit the development of the radiotherapy QAP standard by providing different perspectives of methods and protocols in qc procedures such as using the Failure Modes and Effects Analysis (FMEA).

1.3 Significant of the study

As mentioned earlier, one of the challenges on the implementation of the QAP guidelines is inadequate of physic qc tools (NHEWS Report 2010, Kutcher et al., 1994). In addition to the required regular qc procedures, linac beam properties need to be verified after undergone major repairs (Ritter et al., 2014). The time required for scanning using water phantom after major repair is not known and without guarantee assured that the linac totally functioning. The complexity of the repair lead to uncertain time to performed verification testing. Thus, a contingency plan for quick validation of machine beam properties is prudent (Ritter et al., 2014). Qc devices that able to reduce time for constancy routine checks are indeed very much needed (Kutcher et al., 1994). A reliable, readily available robust, high-resolution device is needed as an alternatives to the water phantom scanning.

The evolution of the qc test methods is parallel with the advances of technologies in radiotherapy treatment. To achieve high tumour control rates with high accuracy, an assessment such as the qc test is important (Thwaites et al., 2005). With the increasing of patients treated with these advance technologies, unfortunately more time is devoted to these qc tests and is becoming a critical issue for busy department. Hence, these qc tests should be simple, rapid and reproducible (Kutcher et al., 1994 and Klein et al., 2009). It is important to understand the time needed to accomplish these qc tasks.

Physicists play a big part in the radiotherapy department. With the collaboration between the radiation oncologist, they provide effective appropriate radiologic care for radiotherapy patient (Khan, 2016). They involve in the early stages of selection of the linac's specification and participate in the acceptance and commissioning (Khan, 2016). This as well as covering other modalities in radiotherapy department such as the Brachytherapy system, Computed Tomography Simulator (CT Sim) and Treatment Planning System. They also prepare and optimize treatment plans including the advance treatment technique apart from doing the qc task and calibration of the linear accelerator systems.

Physicist is also responsible for the radiation protection of patients, staff as well as conducting clinical research. At higher position, they might have to carry out administrative tasks (Podgorsak et al., 2005). Physicist is also supervising third parties engineer to carry out any repair and equipment maintenance in the department. Considering these functions, it is very important to highlight the workload magnitude by providing timing data particularly performing the qc tasks as required by the Malaysian Ministry of Health (KKM). This is prime important because when the physicist workload is too much then it would not contribute positively to the futures of the radiotherapy. By addressing the workload magnitude, identify optimum staffing requirement and optimum use of qc devices, it will benefit in the healthcare quality and safety.

1.4 Objectives of study

The aim of this research is to evaluate the current radiotherapy QAP standard manual introduced by Malaysia Ministry of Health's and to analyse the magnitude of issues regarding the implementation. The study will come out with the results obtained at three levels.

1. To optimise the selection of the measurement device for qc tasks.
2. Timing analysis of qc tasks process as reference and could provide technical guidelines references for the physics communities.
3. To assess the physicist workload of performing the qc tasks and define the justification of reasonable physics staffing requirements based on the WISN method and Man-Hour's method.

1.5 Scope of study

The workload of the physicist will be access based on the WISN method and Man-Hour's method. The scope of this paper is to encompass on the qc tasks of the linac exclude the brachytherapy, treatment planning system and computed tomography simulator. Yearly qc activities data was excluded from this research since in most radiotherapy centres in Malaysia, the annual qc comes under the Hospital's Concession Company responsibility. Focus will be on all the qc activities that needed to be performed on monthly basis, quarterly basis and semi-annually basis. These qc workload components are accordance to the requirements as stated in the QAP standard manual for the Radiotherapy Services. Ranges of qc tasks, frequency of measurements and acceptable tolerance were studied.

Detector such as the ion chamber, film and EPID were also studied. These detectors will be undergone tests such as the beam flatness with symmetry as well as the light and radiation field congruent test. Other two dimensions (2D) detectors were also covered. These devices were investigated on its capabilities to be used for advance techniques treatments. Guidelines to perform the test with these devices were referred either from scientific papers or from the manufacturer recommendations, to fully optimise the qc devices and assist in the justification and selection of the measurement device for qc tasks.

Data of total time spent to complete the qc tasks were gathered. These include the qc tasks using the qc devices for both mechanical and dosimetry qc parameters. The average of time was analysed. The research was conducted on four medical linac's. The Clinac iX and Trilogy, both of Varian Medical Systems (Palo Alto, CA), located in Sabah Women and Children Hospital (HWKKS), while the Primus of Siemens Medical Solutions (Forchhiem, Germany) and also another Clinac iX of Varian Medical Systems are located in Hospital Universiti Sains Malaysia (HUSM), Kubang Kerian.

1.6 Outline of research

The background study of the implementation of the Quality Assurance Program (QAP) for Radiotherapy Services in Malaysia and the objectives of the research study are presented in Chapter 1. The performance criteria and safety standard for the linac was also presented in this chapter. The motivation of this research which is to analyse the magnitude of issues regarding the implementation of the QAP was explained. Problems statement that involved patient safety issues due to lack of proper qc system implementation, lack of local cancer institution data references on the physicist workforce in this country, limited number of oncology devices in the radiotherapy services and limited data on timing study of qc tasks was also highlighted in this chapter. Finally, in this chapter, the scope of the study was explained. The study will focus only on linac's qc. The annual qc was excluded from this study because it was done by the third party.

Chapter 2 present scientific literatures that is significant to support this study. The main obstacles to the implementation of the radiotherapy QAP standard are the resources namely workforce, qc tools and time. To investigate these factors, four areas of study were done. First study (2.3) discussed on the study of flatness and symmetry of the beam profiles, while the second study (2.4) was on the study of light and radiation field congruent respectively. These two studies were performed to evaluate the precision, accuracy, linearity, spatial resolution, physical size, readout convenience and convenience of use of the qc devices. The specifications of the qc devices that been used were explained in detail. Third study (2.5) was the study of qc tasks process timing. Each qc tasks timing data will be compared. Final and fourth study (2.6) was to investigate the workload of physicist.

Chapter 3 introduce the detectors, phantoms and software that used in this study. The description of these physic devices technology was discussed. Methodology of how to derive the optimal measurements and various options that available were also explained in this chapter. Two methods, the WISN method and the Total Man-Hour method that were used to evaluate the fourth study, were discussed. Both methods were using the qc tasks elements that contained in the Quality Assurance Program (QAP) Manual for Radiotherapy Services, Malaysia Ministry of Health (MOH) as explained in Sub-Chapter 2.1.1.

Finding results of test measurements were presented and evaluated in Chapter 4 of Result and Discussion. The flatness and symmetry measurement of the qc detectors that were presented here. In this chapter also, the qc tasks timing data will be compared. This study come out with the data analysis to highlight which qc tasks that the physicists spent the most of their qc time. The outcome result using the WISN's method and the Total Man-Hour method were compared and discussed in this chapter. Finally, in Chapter 5, the conclusion of this study was discussed. Recommendations were presented here as well as the ideas for future research directions.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The issues of the physicist’s staffing and quality control equipment had been highlighted and published in numbers of publications (Dunscombe et al., 2014, Phungrassami et al., 2013). An adequate QA program requires increased staffing and up-to-date equipment, both of which can be expensive (Khan, 2010). It has been recognized that inadequency of physics support translates into substandard or less than optimal patient care (Khan, 2010).

2.1.1 Elements of QAP Manual for Radiotherapy Services, Malaysia MOH.

The AAPM TG-40 Report (1994), presents comprehensive QC protocols covering the technology of its time for Cobalt-60 units, CT Simulators, radiotherapy equipment and others (Smith, 2015). Methodology of AAPM TG-40 is more performance based, where it evaluates the quality of the machine and processes by mechanical comparison of prescribed test’s result with the expected results (Klein et al., 2009).

The AAPM TG-142 had been published in 2009. It applies performance base recommendation but incorporate process orientation concept and advancements in linear accelerator technology and treatment techniques since 1994 (Klein et al., 2009). This qc protocol includes tests such as the MLCs, asymmetric jaws, dynamic and virtual wedges, EPID, CBCT and static kV imaging. The TG-142 has also recommended the increased precision in the qc task with the increased number of treatments in the IMRT, TBI, SRS and SBRT (Smith, 2015). Standard Imaging has published User's Guide to TG-142 (Fulkerson, et al., 2013) served as the guidelines in performing qc tasks according to TG-142.

2.2 Study on the qc devices.

Study of dosimetry measurements using detector array have been published by many author (Ritter et al., 2014, Low et al., 2011, Sathiyan et al., 2010 and Birmpakos et al., 2016). The qc tools must provide reliable values of measured parameters and can be used to judge whether tolerance criteria had been achieved (Fontenot et al., 2014). In current study, number of phantoms and detector array were used for constancy checks. According to Ritters, (2015), constancy test is a big part of TG-142 LINAC QA. Properties of dosimeters such as the precision, accuracy, linearity, dose rate dependence, energy dependence, spatial resolution, physical size, readout convenience and convenience of use are the important qualities that dosimeter must have and been discussed by Izewska et al., (2005). Macaulay et al., (1999) had stated that this black box should only be used for constancy check of the particular parameter rather than its absolute values. To study these dosimeter's properties, tests of flatness, symmetry and light and radiation field congruent test were performed and analysed for constancy. Further discussion in 2.3 and 2.4.

2.2.1 Ion chamber

Ion chambers are considered the gold standard in clinical radiation dosimetry due to its high accuracy. The principle of an ion chamber had been described by Tan, (2016) and Izewska et al., (2005). Basically, the ion chamber contained three electrode which is polarizing electrode, collecting electrode and guard electrode that is filled with air (Figure 3.1). The electrode is quite sensitive and will produce ion pairs in the air cavity once been exposed to the radiation (Tan, 2016). A guard electrode used to reduce chamber leakage and intercepts the leakage current and allows it to flow to ground, bypassing the collecting electrode. This resulting improved field uniformity in the active or sensitive volume of the chamber and produce more charge collection (Izewska et al., 2005). The ion pairs that collected by this collecting electrode, was at high bias voltage and measured by the electrometer (Tan, 2016). The mass of air in the chamber volume is influenced by the changes of ambient temperature and pressure. Therefore, it had to be corrected prior measurements (Izewska et al., 2005).

Basic standard design of water phantom had been explained by Khan, (2010). Measurement procedures to obtains the absorbed dose in water using an ionization chamber in external beam radiotherapy can be found from published code of practice, (Andreo et al., 2000). This includes the reference conditions of measurements for absorbed dose in water at setup of 100 cm SSD and setup of 10 cm × 10 cm field size. For the electron beam energy study, the 10 cm x 10 cm applicator was used and was attached to the gantry head to provide dose homogeneity in the irradiated area as well as to collimate the beam (Gluhcheva et al., 2015). Other references guidelines and recommendations for periodic qc measurement were described by Khan, (2010), Podgorsak et al., (2005) and Fulkerson et al., (2013). Qc test using ion chamber with water phantom are essential after linac had undergone major repairs (Ritter et al., 2014).

2.2.2 Electronic Portal Imaging Device (EPID)

The electronic portal imaging flat panel is about 1.2 cm below the surface housing of the EPID detector as stated by Varian Medical System, see Figure 3.15. Description of designs for an EPID is described by Tan, (2016), see Figure 3.3. To obtain improved image quality, both Dark-Field (DF) and Flood-Field (FF) were calibrated (Winkler et al., 2005, Herman et al., 2001) with and without applying x-ray radiation respectively. The calibration will eliminate the background noise (DF) and provide a uniform response (FF) for imaging. This is followed by the quantitative assessment of the EPID performance using the PipsPro software and QC-3 phantom. The QC-3 phantom was placed on the EPID housing surface at an angle of 45 degrees towards the linac. The phantom is rotated to 45 degrees relative to the EPID scan lines to prevent aliasing in the image of the bar patterns (Rout et al., 2014). Two images were acquired for each acquisition. The PipsPro software analyse the information from the high contrast rectangular bars made of lead and plastic that having spatial frequencies of 0.10, 0.20, 0.25, 0.43 and 0.75 lp/mm (Koutsofios et al., 2006).

For the assessment of the linearity of dose response, the procedures described by Deshpande et al., (2013), Herman et al., (2001) and Esch et al., (2004) were followed. The linearity of dose response was performed to determine stability of the integrated EPID response per Monitor Unit. Measurements were performed with different monitor units (MU) at the static field of 10cm x 10cm at 400 MU/min at source to detector distant (SDD) of 100 cm. Figure 2.1 show linearity of the detector response graph (Esch et al., 2004).

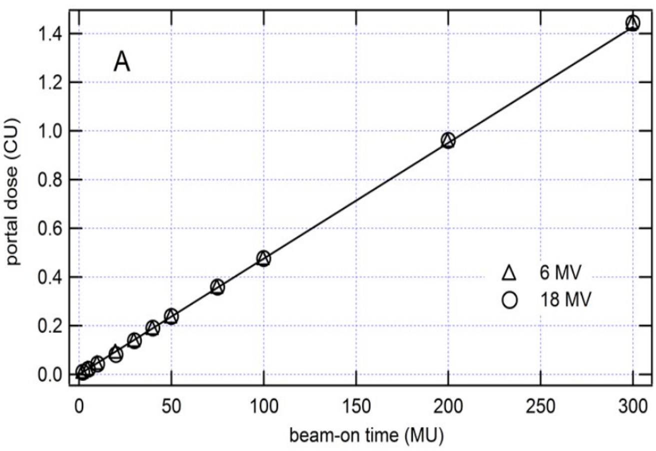

Figure 2.1 Graph study by Esch et al., (2004) showing the linearity of the detector response

Monitoring of flatness can be used as an indicator of monitoring the energy since there is connection between the energy change and flatness change (Hossain et al., 2016). Study of flatness constancy tests was done to observe the output changes trend by linac photon beam energy. Liu et al., (2002) has concluded that EPID can be used as a secondary device to monitor the x-ray beam flatness and symmetry. Andersson, (2011) had proved that the EPID was able to detect drifts and deviations therefore suitable as a qc device for linac output (Figure 2.2). Sathiyan et al., (2010) and Surendran et al., (2014) had reported that EPID had shown good resolution and offers a possibility for real time measurements with reliable portal dosimetry and can be reduce the time for complex qc treatment procedure. Evaluations using Varian's ARIA treatment planning system was studied by Mekuria et al., (2015) and the findings had reported that it was comparable with other method evaluations result and also faster.

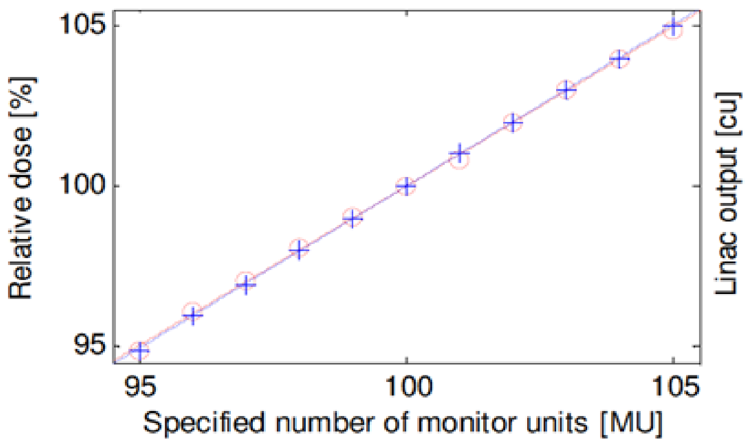

Figure 2.2 Graph study by Andersson, (2011) showing similar output result of EPID (Red) and ionization chamber (Blue) for the 6 MV photon energy.

The Multi Leaf Collimator (MLC) leaf position and collimator test study using EPID detector can be found from study by Bawazeer, et al., (2014). The work of Surendran et al., (2014) stated that the MLC qc with EPID had provided time saving and assured information on position and speed of the MLC. Picket Fence test was one of the tests that had been conducted to check the positional accuracy of the MLC. The test verified the accuracy position of each MLC leaf individually as well as show the actual irradiated gap width. This study followed the work by Antypas et al., (2014). One of the proposed methodologies is to conduct the test by creating a uniform pattern using specified intervals. This will produce a series of narrow bands after irradiation. Width of the narrow bands is then measured and checked for discrepancies. Study by Losasso et al., 1998 had stated common mechanical components problems related with the MLC and had recommended qc targeted to check these known problems.

2.2.3. Film

Film had provided method to perform quality control tests of radiation beams such as light and radiation treatment field congruence and both beam flatness and symmetry test (Pai et al., 2007 and Khan, 2010). Dosimetry aspects of the radiochromic film had been addressed by Niroomand et al., (1998). It helped in providing some background idea on radiochromic film such as the physical-chemical behaviour and advantages over the radiographic film. The radiochromic films used at that time of writing were from GafChromic HD-810 film and GafChromic MD-55-2 film which were different type from the radiochromic film used in this study.

The EBT3 film calibration follows the Film QA-Pro software vendor methods and it also can be found from literature by Hossein, (2015). The film irradiation procedure, image measurements and analysis was according to the paper by Lewis et al., (2012). The advantages of EBT3 radiochromic film compared to previous types of radiochromic film were mentioned in other scientific publication. The EBT3 radiochromic film was designed to overcome the limitations in using radiochromic film for external beam therapy qa. Investigation of the EBT3 radiochromic film features on its suitability on its application to IMRT qa, in combination with a flatbed document scanner and comparison the results with the EBT2 film as a reference has been done by Borca et al., (2012).

Due to the radiochromic film characteristic that it will continue to polymerise after the irradiation took place, several studies had concluded that a minimum of more than two hours or 24 hours to 48 hours had to be given to the irradiate film to be stabilize before scanning been done. (Niroomand et al., 1998, Alber et al., 2008). This had caused delay to the whole process. In this study, the radiochromic Gafrochromic film, the irradiated EBT3 film was investigated in terms of time and optical density to observe the variation of significant errors. Figure 2.3 shows result study by Borca et al., (2012).

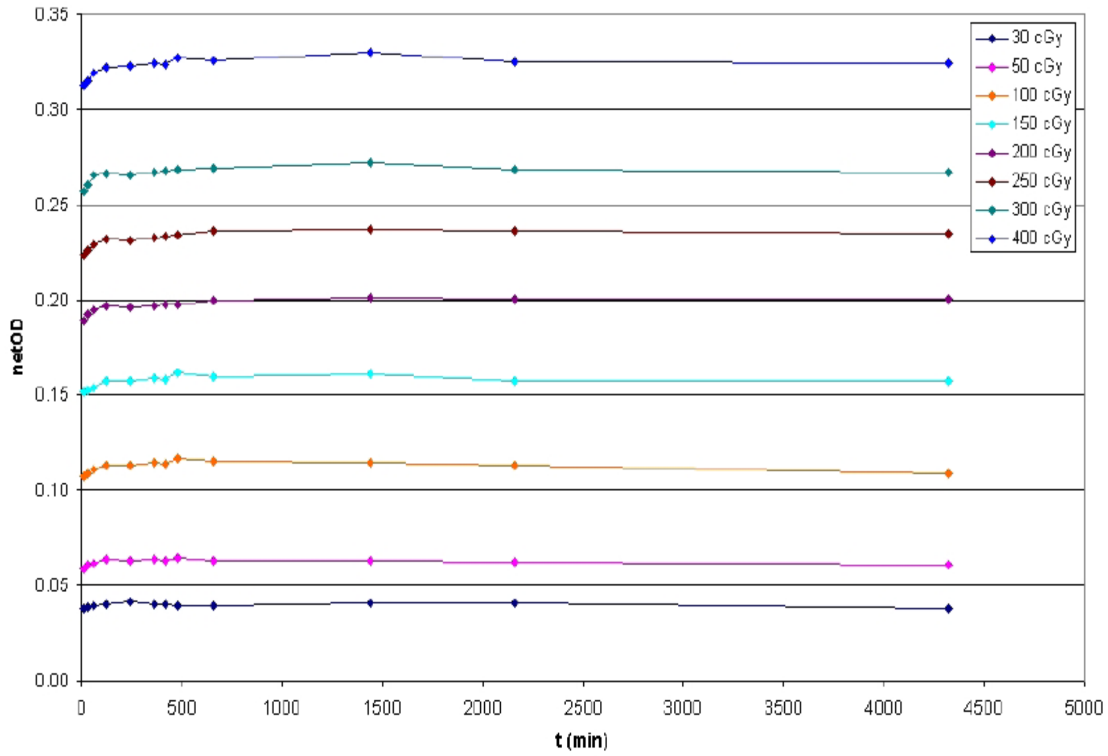

Figure 2.3 Change of the film coloration as a function of the time after irradiation (Borca et al.,2012)

Dosimetric characterization and use of radiochromic film for Intensity Modulation Radiation Therapy (IMRT) dose verification were explained in numbers of publication (Alber et al., 2008, Low et al., 2011 and Lewis et al., 2012). The need for high spatial resolution in these difficult geometries with modulated fields tends to rule out the use of an ion chamber or a diode (Hossein, 2015). The scanning procedures followed according to the Ashland Film QA Pro manufacturer's guidelines. Settings were made for Transmission mode by selected the positive film mode. Setting of 72 dpi resolution and the 48-bits RGB image type setting, without image correction were used. Prior to film scanning, the scanner was ensured to be properly warm up. The 4t time window rules method applied in this study (Lewis et al.,2012). With the improvements in protocol of measurement and analysis, it is possible to obtain measurement results within 30 minutes rather than having to wait overnight, or longer, as has been the custom with radiochromic film. This had been addressed by Lewis et al*.,* (2012).

The radiographic film had a long history in the dosimetry and had become an integral part in routine qa. In this study, the methodology of radiographic film in irradiation, processing, scanning and guidance to obtained levels of accuracy were discussed by Pai et al*.,* (2007) in AAPM Task Group-69. Qc tasks on the film processor and dark room were done and validated by others and these qc tasks were according to the Table II film processor test list of the qc guidelines (Pai et al., 2007). The radiographic film was purposely analysed with the FilmQA Pro software (Ashland) to study the film result.

The radiographic film is not water-equivalent because of the silver atoms in the emulsion layers and this makes film becomes increasingly sensitive at lower photon electron energies thus make the film dependent on both depth and field size of the photon beam. Alber et al., (2008) also reported that film dosimetry using EDR2 film had shown deviations within the acceptable tolerance. This concludes that EDR2 film can be used as a 2D detector for the IMRT verification. Several different software for analysis of data had been used. The FilmQA Pro that used is the 30 days trial version software. It is recommended by the manufacturer of EBT3 film (Ashland) because the program is running multi-channel dosimetry (Hossein, 2015). The SNC Machine QA software Version 1.1.7 (Sun Nuclear) was also applied for radiochromic film analysis. Resolution of 72 dpi and 48-bits RGB image type setting was selected according to the manufacturer’s recommendation.

2.2.4 Matrixx (IBA Dosimetry GmbH, Germany)

MatriXX had been used by Ritter, et al., (2014) study to assess linac's performance. MatriXX had efficiently assessing the constancy of beam properties and detect clinical significant changes in output, beam penumbra, and beam energy. This device can be used to verify beam properties after a minor repair or performing periodic validations of linear accelerator performance constancy. According to Ritter, et al., (2014), the estimation time of setup, data acquisition and analysis for two photon energies would take approximately one and the half hours.

Study had shown that this device can be used for quantifying absolute dose with required accuracy level therefore it can be used for routine qc checks such as flatness, symmetry, field width, and penumbra checks of linac beam. This can be an alternative to time-consuming measurements with film or ion chamber (Sathiyan et al.,2010). Surendran et al., (2014) comparison study of portal dosimetry and MatriXX had concluded that both systems were equally good for IMRT and Rapid Arc patient specific qa. The verification protocol using MatriXX to detect clinical significant errors in Rapid Arc treatment plan was further discussed by Wagner et al., (2011). Prior used for verification, MatriXX was set in the acquisition of "Movie Mode" with sampling time of 200 milliseconds, maximum number of samples to 5, and the number of movie images to 2000. The measurements were normalized to maximum dose. The device needs to be warm up from 15 minutes to 30 minutes and given pre-irradiation with 10 Gy before measurement (Wagner et al., 2011). Matrixx array detector is use with the OmniPro ImRT analysis software to analyze basic single profile metrics, such as flatness, symmetry, field size and penumbra. Mascia,

(2013) study had reported that MatriXX detector device able to measure these parameters and can be used as benchmarked against other array devices.

2.2.5 Others Two Dimension (2D) Array Detector

QA BeamChecker Plus is another 2D arrays device used to verify that the linac performance was not changing beyond the tolerance, over time. The device was placed on the couch at source to surface distant (SSD) of 100 cm and irradiated with photon or electron beams. Measurements will be compared to the baselines values of each beam energy to get constancy, flatness and symmetry results. A temperature and pressure correction are made to the reading at the center chamber on subsequent times/days to get constancy measurements results. Fulkerson et al., (2013) had described several tests that can be performed using this device such as the Optical Distant Indicator (ODI) test and laser test.

7600 Double Check Pro is a ten channels electrometer using air ion chamber technology for dose measurement. Flatness and symmetry reading is automatically calculated by system software. Prior irradiation, detector is required to have high signal strength so that longer sample time will be achieved and this will increase the signal-to-noise ratio, therefore improving the accuracy. At the time of this study, no other publication paper on these two devices were found.

2.3 TEST 1: Flatness and Symmetry test

In this test, qc devices were investigated in the sensitivity to measure changes in flatness and symmetry as well as producing consistence result. Hossain, (2014) had reported the characteristic of the long term behavior from the linac output trend. The finding shows some variations were observed in the output trend and based from this result, frequency and action levels were modified. The flatness test is a good indicator to observe changes in the photon beam energy (Gao et al., 2016, Goodall et al., 2015). Figure 2.4 shows illustration of typical energy beam profile curve of linac (Gluhcheva et al.,2015).

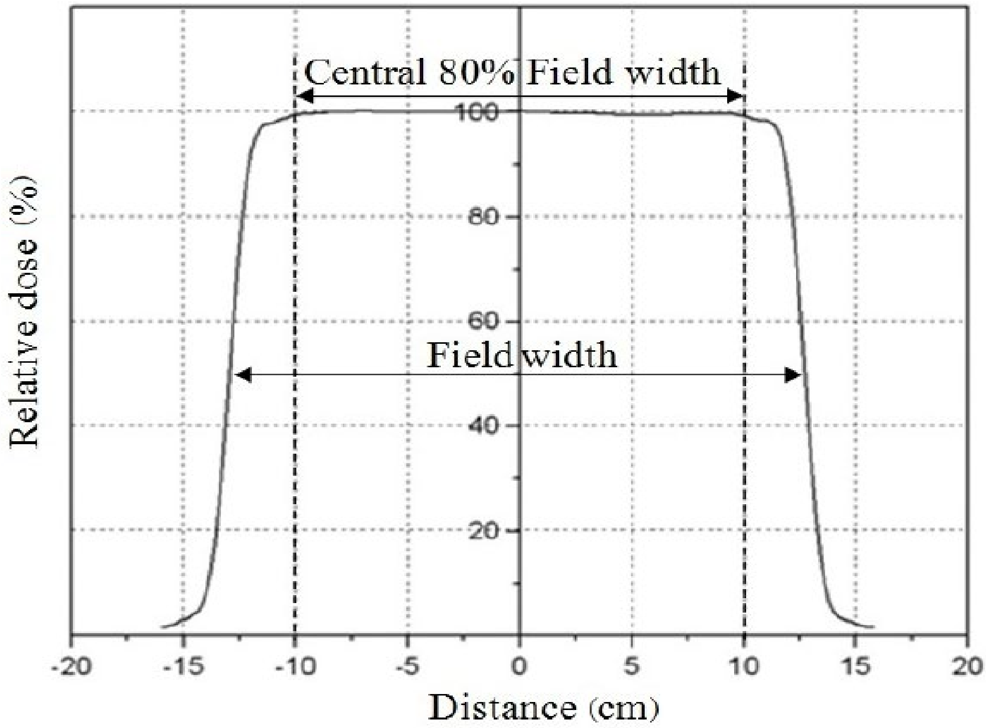

Figure 2.4 Simplified illustration of typical profile curve of energy beam of linac.

The beam flatness F is assessed by finding the maximum dose, D_{max} and minimum dose, D_{min}, point values on the beam profile within the central 80% of the beam width and then using (2.1) as given in Khan, (2010) and Podgorsak et al.,(2005).

$$F = 100 \times (D_{max} - D_{min}) / (D_{max} + D_{min}) \qquad - \ (2.1)$$

The beam symmetry, S, is defined as any two dose points on a beam profile equidistant from the central axis point, and it should be within 2% of each other. (Podgorsak et al.,2005). The symmetry is given in (2.2).

$$S = 100 \text{ x } (area_{left} - area_{right}) / (area_{left} + area_{right}) \qquad - (2.2)$$

2.4 TEST 2: The light and radiation field congruent test

This test is important and has been emphasized in AAPM Task Group report (Klein et al., 2009, Kutcher et al., 1994). Basically, the test is to verify the x-ray beams are faithfully represented by the light fields for all orientation. Several methods, tools and software were used in this study. One of the methods that had been used for quite some time is to measure light and radiation fields congruent using a mm graph paper that was attached on the patient couch at the reference distance which is the source to surface distant or known as SSD to verify the field light (Horton et al.,2005). After this been verified, then the next step is to replace it with film and irradiate it.

Method of using films to ensure the light and radiation fields so that it agreed with each other and ensure it agree with the indicated jaw settings was found to be tedious work process (Njeh et al., 2012). Additional to that, the pin pricking holes has to be done based on the light field on the film. After developing the irradiate radiographic film, then it was visually compared with a marker pin pricking holes made on the film. Study of the light and radiation field congruent using EPID and film had been published by Njeh et al.,(2012) and by Abdallah et al.,(2015). In Abdallah et al., (2015) study, both methods, subjectively and by using Mat Lab computer program were used. Film used in this study was irradiated based on the reference setup as recommended by Lewis et al., (2012) on radiochromic film and

Pai et al., (2007) on radiographic film. For exposures, the radiochromic film was placed on the coach with 5 cm of the buildup material above and below the film with the SSD of 100 cm (Lewis et al., 2012). The exposed film then analysed with FilmQA Pro software (Ashland) to check any light and radiation field deviation. The procedures of analysis using FilmQA Pro had been described by Hossein, (2015).

Another method to measure light and radiation fields congruent is by using the FC-2 phantom and Light Field Cross Hair phantom (Standard Imaging). With similar reference setup, both phantoms (FC-2 phantom and Light Field Cross Hair phantom) were placed on the couch and irradiated. The images then exported to PipsPro Radiation Light Field Module Software for analysis (Fulkerson et al., 2013). The third method to measure light and radiation fields congruent is using the Iso-align qc tools. Study by Njeh et al., (2012) had reported using similar device to Iso-align but different model, in the study of light and radiation fields congruent.

2.5 TEST 3: Timing study analysis of qc tasks process

Test study presented here was based on the requirements by the QAP standard.

2.5.1. Mechanical Test

In mechanical tests, both mechanical motions of linac system and patient couch were verified for precision and accuracy (Horton et al., 2005). Methods of the qc tests have been provided by Fulkerson, et al., (2013), Horton et al., (2005), Khan, (2010) and Mayles et al., (1999).

2.5.2. Multi Leaf Collimator (MLC)

The description of the MLC can be found from study by Jeraj et al., (2004). The MLC consists of movable leaves that made from tungsten alloy that possess high densities, hard, simple to fashion, reasonably inexpensive and have a low coefficient of thermal expansion. The mechanism of moved and controlling large number of narrow, closely abutting individual leaves will produce desired field shape which can used to block some fractions of the radiation beam (Jeraj et al.,2004).

With this, efficiency of treatment delivered is increased (Boyer et al., 2001). With the MLC, leaves can produce fixed shape in fields to conform to the cancer's tumor area. Compared to the use of beam blocks, the use of MLC is likely to save time during patient setup for treatment. Additional to that, any adjustment in the field shape can be made faster and conveniently. (Boyer et al.,2001). Few published scientific papers on MLC qc using EPID for the IMRT and VMAT study has been done (Agnew et al., 2014). Qc issues specific to IMRT delivery with an MLC can be found from literature by Losasso et al., (1998).

Common issues with the MLC are related to mechanical worn out issues as the leaves are motor mechanism driven. (Agnew et al.,2014 and Losasso et al.,1998). Therefore, to verify leaf positions and carriage movement accuracy and calibrations, one of the tests required is the Picket Fence (Surendran et al., 2014 and Agnew et al.,2014). Analysis was done by using SNC Machine software Versionn1.1.7 (Sun Nuclear)**.** Other tests to verify MLC alignment such as the leaf position accuracy test, setting x-ray field and MLC light field coincidence test were also recommended. Fulkerson et al., (2013) had described the setup of the MLC phantom workflow to perform the MLC qc test. Specialized In-Air Comparison Jig phantom (Standard