DIODE DOSIMETRIC CHARACTERISATIONS AND ASSESSMENTS FOR *In-vivo* DOSIMETRY IN RADIOTHERAPY TREATMENT

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DIODE DOSIMETRIC CHARACTERISATIONS AND ASSESSMENTS FOR *In-vivo* DOSIMETRY IN RADIOTHERAPY TREATMENT

by

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LIST OF ABBREVIATIONS

AAPM	American Association of Physicists in Medicine
APPA	Anterior Posterior Posterior Anterior
ADU	Analog Digital Unit
cGy	centigray
CIRS	Computerized Imaging Reference Systems
CT	Computed Tomography
D1	Diode 1
D2	Diode 2
D3	Diode 3
d_{max}	Depth at maximum dose
FS	Field size
Gy	Gray
IAEA	International Atomic Energy Agency
IC	Ionisation chamber
ICRU	International Commission on Radiation Units and Measurements
IBA	Ions Beam Applications
IGRT	Image Guided Radiation Therapy
IKN	Institut Kanser Negara
IL	Isodose Line
IMRT	Intensity Modulated Radiation Therapy
IVD	*In-vivo* dosimetry
K_{pl}	Plastic to water correction factor
Lat	Lateral
LINAC	Linear accelerator
Lt	Left
MOH	Ministry of Health, Malaysia
MRI	Magnetic Resonance Imaging
MU	Monitor Unit
MV	Megavoltage
N_{dw}	Absorbed dose to water
n-Si	Negative – Silicon

PDD	Percentage depth dose
PET-CT	Positron Emission Tomography – Computed Tomography
p-Si	Positive – Silicon
QA	Quality Assurance
QC	Quality Control
Rt	Right
SCF	Supraclavicular
Si	Silicon
SSD	Source to surface distance
Std Dev	Standard Deviation
TBI	Total Body Irradiation
TG	Task group
TLD	Thermoluminescense detector
TMR	Tissue maximum ratio
TPS	Treatment Planning System
TRS	Technical Reports Series
2D	Two dimensional
3D	Three dimensional

ANALISIS SIFAT DIOD DOSIMETRI UNTUK DOSIMETRI *In-vivo* DALAM RAWATAN RADIOTERAPI

ABSTRAK

Diod adalah merupakan sistem radiasi dosimetri yang digunakan secara meluas dalam rawatan radioterapi dan digunakan dalam dosimetri *in-vivo*. Adalah penting untuk memahami sifat pengesan radiasi sebelum ianya digunakan dalam rawatan klinikal. Dalam kajian ini, sifat tiga (3) diod bagi model IBA EDP-15^{3G} dianalisa dan dibanding dengan kebuk pengionan yang telah dikalibrasi. Pemecut linear bertenaga 6 MV digunakan dengan membandingkan saiz bidang, jarak sumber ke pengesan, unit monitor, *tray,* baji dan bacaan diod di belakang *cerroband*. Ketebalan sebenar diode, kebolehan bacaan berulang, kesan radiasi di bawah diod, kesan diod dengan perbezaan sudut radiasi dan kesan suhu terhadap diod juga dilakukan. Daripada penentuan sifat diod dosimetri ini, sistem perancangan berkomputer klinikal dan kebuk pengionan yang telah dikalibrasi digunakan untuk mengesahkan ketepatan bacaan diod dalam pelbagai teknik rawatan. Hasil kajian mendapati diode EDP-15^{3G} adalah sensitif terhadap sudut radiasi, baji, jarak sumber radiasi dan suhu. Sudut yang diukur untuk diod adalah kurang daripada 2% pada sudut ± 41 °, ± 37 ° dan ± 72 ° untuk diod 1, diod 2 dan diod 3. Didapati bahawa faktor pembetulan SSD meningkat selari dengan pertambahan SSD. Faktor pembetulan SSD dari SSD 75 cm ke 140 cm bagi diod 1 ialah 0.995 - 1.025, cm bagi diod 2 ialah 0.975 - 1.046 dan cm bagi diod 3 ialah 0.989 - 1.021. Faktor pembetulan baji adalah meningkat selari dengan peningkatan sudut baji. Faktor pembetulan baji bagi diod 1 ialah 1.003 - 1.023, bagi diod 2 ialah 1.009 - 1.033 dan bagi diod 3 ialah 1.011 - 1.056. Perbezaan purata peratus yang diukur dan suhu sisihan piawai bagi diod 1, 2 dan 3 ialah 0.53 ± 0.19% / ° C, 0.56 ± 0.16% / ° C dan 1.02 ± 0.33% / ° C. Didapati bahawa setiap diod mempunyai sifat yang berbeza dan perlu dianalisis secara berasingan. Penggunaan diod terhadap pesakit tanpa pemahaman yang jelas akan memberikan bacaan yang salah. Daripada simulasi *phantom* yang dilakukan dengan menggunakan teknik kalibrasi dan faktor pembetulan yang betul bacaan ± 3% boleh dicapai bagi rawatan standard dan ± 5% bagi rawatan *Total Body Irradiation* (TBI).

DIODE DOSIMETRIC CHARACTERISATIONS AND ASSESSMENTS FOR *In-vivo* DOSIMETRY IN RADIOTHERAPY TREATMENT

ABSTRACT

Diode is a kind of radiation dosimetry system that has been applied widely in radiotherapy treatment and very useful for *in-vivo* dosimetry (IVD). It is duly important to understand the characteristic of detector before it can be used in clinical treatment. In this study, characteristics of three (3) diodes IBA EDP-15^{3G} model were analyzed and compared to calibrated ionization chamber. The 6 MV linear accelerator (Linac) was used with different field sizes (FS), source to surface distance (SSD), linac monitor unit (MU), tray field (TF) wedge field (WF) and diode reading behind cerroband. Actual diode thickness, diode reproducibility, perturbation effect and diode effect with radiation beam angle and temperature were performed. From the determination of diode dosimetric characteristic, a clinical computerized treatment planning system (TPS) model Elekta Monaco and calibrated ionization chamber were used to verify the accuracy of diode reading in different treatment techniques. In this study, EDP-15^{3G} diode was sensitive with angle of incidence, wedge, SSD and temperature. The measured angle for diode were less than 2 % at angle ± 41°, ± 37° and ± 72° for diode 1, diode 2 and diode 3 respectively. SSD correction factors have increased proportionally by increasing the SSD. SSD correction factor from SSD 75 cm to 140 cm 0.995 to 1.025, 0.975 to 1.046 and 0.989 to 1.021 for diode 1, diode 2 and diode 3 respectively. Wedge correction factors have increased proportionally by increasing the wedge angle Diode wedge correction factor resulted in the range of 1.003 to 1.023, 1.009 to 1.033 and 1.011 to 1.056 for diode 1, diode 2 and diode 3 respectively. The measured average percentage difference and standard deviation temperature for diode 1, 2 and 3 were 0.53 ± 0.19 %/°C, 0.56 ± 0.16 %/°C and 1.02 ± 0.33 %/°C respectively. Each diode has their own characteristics and should be analysed individually. The use of diodes to patients without clear understanding will give false reading. From the observation of phantom simulation results, it can be concluded that by applying proper calibration and correction factors, ± 3% reading is achievable for standard treatment and ± 5% reading for Total Body Irradiation (TBI) treatment.

CHAPTER 1

INTRODUCTION

1.1 Background research

Radiotherapy is a one of modality for treating cancer patients. Radiotherapy can be used alone or in combination with chemotherapy. Almost half of cancer patients have undergo radiotherapy as part of their treatment plan. Radiotherapy is also delivered to treat benign (not malignant) tumour and others condition, for example blood disorders.

A LINAC is a device that most commonly used in radiotherapy. In current practice, LINAC comes with specific TPS. All machine data will be entered into TPS. A set of data was collected by using 3-D water phantom and also entered into TPS. A set of data depends on type of TPS and algorithm being used. Data verification will be carried out after that to confirm machine is ready for clinical works.

In normal practice, beam data verification need to be performed before implementing start clinical work and whenever the software and hardware being updated or upgraded. In some cases, like Intensity Modulated Radiation Therapy (IMRT) planning technique, TPS verification or patients’ specific QC will be carried out prior to the treatment. During treatment, no specific dosimetry QC for patients will be done.

In-vivo dosimetry (IVD) is an important method to monitor and compare dose measured from the detector such as diode with the theoretical values, as calculated by TPS or manual calculation. IVD is also a tool for the detection of set-up error during radiotherapy treatment. Currently in the market, many methods of measurements can be used for IVD such as diode, TLD and film. Diode gives an advantage compared to others due to it enables to give an immediate reading during treatment.

A silicon diode dosimeter is designed with p-n junction and referred as n-Si or p-Si depending on base material (Izewska and Rajan, 2005). An n-type diode is formed by doping acceptor impurities into a region of n-type silicon. A p-type diode is formed by doping donor impurities into a p-type substrate (AAPM, 2005). Institut Kanser Negara (IKN) has a p-type diode, model EDP-15^{3G}. End of model number has referred to water equivalent build-up in mm.

1.2 Problem statement

The International Commission of Radiation Units and measurements (ICRU) has recommended an overall accuracy in dose delivery of ±5% (ICRU, 1976) based on an analysis of dose response data and an evaluation of errors in dose delivery. This is very important to achieve good treatment outcome. IVD is an important tool to monitor patient’s actual reading when receiving the treatment.

IKN posses a new p-type diode detector of *in-vivo* dosimetry (IVD) system, model IBA system. Before the system can be used for clinical, fully understanding of diode characteristics is great important. All standard radiotherapy parameters during treatment will be taken into consideration for analysing diode characteristics to achieve a high level of accuracy.

This study also provides a suggestion to start IVD programme in clinical setting. IKN will be getting a good benefits’ from this study.

1.3 Objectives of research

The objectives of this thesis are:

1. To identified/investigate diode characteristics and to understand its capabilities and limitation to be used as IVD in radiotherapy treatment. This characterization will give guidance on correction method and evaluate its efficacy.
2. To validate diode reading with patient simulation. It will be tested with rando / CIRS phantom as a method of verification and compared with TPS as well as IC.

1.4 Research scope

In this research, a total of 5 phases studied were conducted. First phase research was the study of diode characteristics in external beam radiotherapy. In phase 2, study has been focused on comparison of diode, IC and TPS in standard treatment. Thorax phantom image model CIRS002LFC was obtained from CT Simulator and planned with TPS model Monaco, Elekta. Phase 3 study was performed in order to simulate the real clinical cases in standard treatment. Phase 4 study focused on TBI data collection and diode characteristics. Phase 5 study was performed on the application diode in special treatment TBI. Since TBI treatment has not been started in IKN, suggestion of treatment technique was needed and relevant data was collected. Study has been focused to 6 MV energy due to diode thickness equivalent to 1.5 cm equivalent with 6 MV d_{max}. Furthermore, 6 MV is the practical energy used in most cases.

1.5 Clinical significance / Significance of the study

By conducting this research, the study of the diode characteristics will be fully understood. High accuracy of diode reading during measurement will be achieved and will be beneficial to the patients in terms of clinical outcome.

1.6 Thesis Organizations

This thesis is structured into 5 chapters. Chapter 1 briefly describes about the background, problem statement, objectives of research, the scope of the study, clinical significance / Significance of the study and how the dissertation is being organized.

Chapter 2 presents the literature review on diode theoretical aspect, radiotherapy treatment and the related studies that had been carried out in this field. Chapter 3 focuses on research methods that were implemented throughout this study.

The results and discussion are then presented in Chapter 4. The conclusion and suggestion for further works are given in Chapter 5. This Chapter is followed by references and appendix.

CHAPTER 2

THEORY AND LITERATURE REVIEW

2.1 Introduction

Dosimetry is great significant in radiotherapy. For a better treatment, radiation dose to patients should receive as prescribed by Oncologist. Radiotherapy treatment is a comprehensive workflow where patient will undergo preparation of immobilization, imaging acquisition includes CT, MRI, PET images and others if required, target and organ at risk delineation, manual or computerized TPS, IGRT, treatment delivery and routine follow up.

Throughout the workflow, periodic routine QC for LINAC, CT Simulator, computerized TPS and others have been performed to ensure that all machines are capable to give a better accuracy and safety during patients treatment. In additional, software updates and hardware upgrades are also being carried out from time to time. Sensitivity of machine with environment also contributes a major factor in order to achieve a high accuracy treatment delivery. Involvement of dedicated staffs during all this process is utmost important.

There are many processes in radiotherapy from patient simulation to treatment and each process may introduce an uncertainty errors (Thwaites *et. al.*, 2005). IVD is the only way to monitor actual doses received by the patients during treatment. Understanding of IVD characteristcs is crucial before it can be used in clinical.

2.2 Radiation dosimetry

A radiation dosimeter is an instrument to measure ionising radiation. There are many types of dosimeters where it has capability to measure either directly or indirectly and besides proper calibration is needed (Izewska and Rajan, 2005). The choice of a radiation dosimeter and its reader must be made with caution, taking into account the needs of the measurement situation. Ionisation chambers are recommended for beam calibrations and other dosimeters, such as film, TLD and diode are appropriate for the analysis of the dose distribution or point dose verification (Izewska and Rajan, 2005).

2.2.1 Properties of dosimeters

2.2.1(a) Accuracy and Precision

The precision of dosimetric measurements specifies the reproducibility of the measurements under similar conditions and can be estimated from the data obtained in repeated measurements evaluated as the standard deviation of the measurement results. The accuracy of dosimetric measurements is the proximity of their expectation value to the ‘true value’ of the measured quantity (Izewska and Rajan, 2005).

2.2.1(b) Linearity

Preferably, the dosimeter reading linearly proportional to the dosimetric quantity is ideal but beyond a certain dose range a non-linearity sets in. The linearity characteristics depend on the physical characteristics of the dosimeter. Figure 2.1 shows samples of linearity characteristics of typical dosimetry systems. Curve A first exhibits linearity with dose, then a supralinear behaviour, and finally saturation. Curve B first exhibits linearity and then saturation at high doses. Generally, a non-linear behaviour should be corrected. (Izewska and Rajan, 2005).

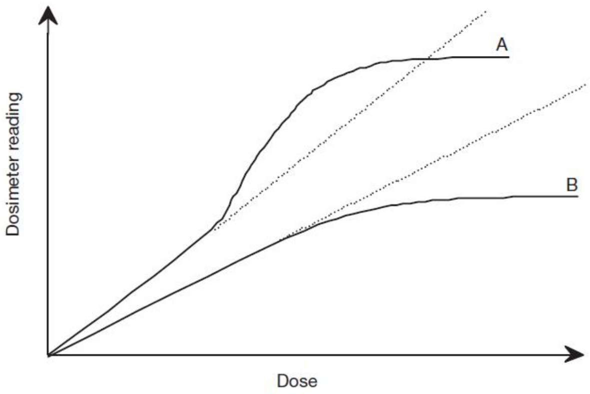


Figure 2.1 Linearity characteristics of two dosimetry systems. (Izewska and Rajan, 2005)

2.2.1(c) Energy dependence

The response of a dosimetry system is generally a function of radiation energy. Normally dosimetry systems are calibrated at a specified radiation energy and used over a much wider energy range, the variation of the response of a dosimetry system requires additional correction. (Izewska and Rajan, 2005).

2.2.1(d) Directional dependence

Directional dependence is referred to dosimeter respond with the angle of incidence of radiation. Dosimeters generally exhibit directional dependence, because of their design and physical size. LINAC calibration using ionization chamber is used in the same set-up as that in which they are calibrated. Directional dependence is important in clinical applications and it requires additional correction (Izewska and Rajan, 2005).

2.2.1(e) Spatial resolution and physical size

Each dosimetry has different capabilities depends on physical size and spatial resolution. In radiotherapy, ionisation chamber is suitable for calibration. Film dosimeters have excellent 2-D and gels 3-D resolution, where the point measurement is limited only by the resolution of the evaluation system. TLD and diode come in very small dimensions and suitable for point dose measurement (Izewska and Rajan, 2005).

2.2.1(f) Readout convenience

Direct reading dosimeters are generally simple and convenient than passive dosimeters. Ionization chamber or diodes are referred to direct reading where TLDs and film referred to passive dosimetry. TLDs and film required specifics procedure before the actual reading is obtained (Izewska and Rajan, 2005). Immediate action or correction can be done for direct reading dosimeter compared to passive dosimeters.

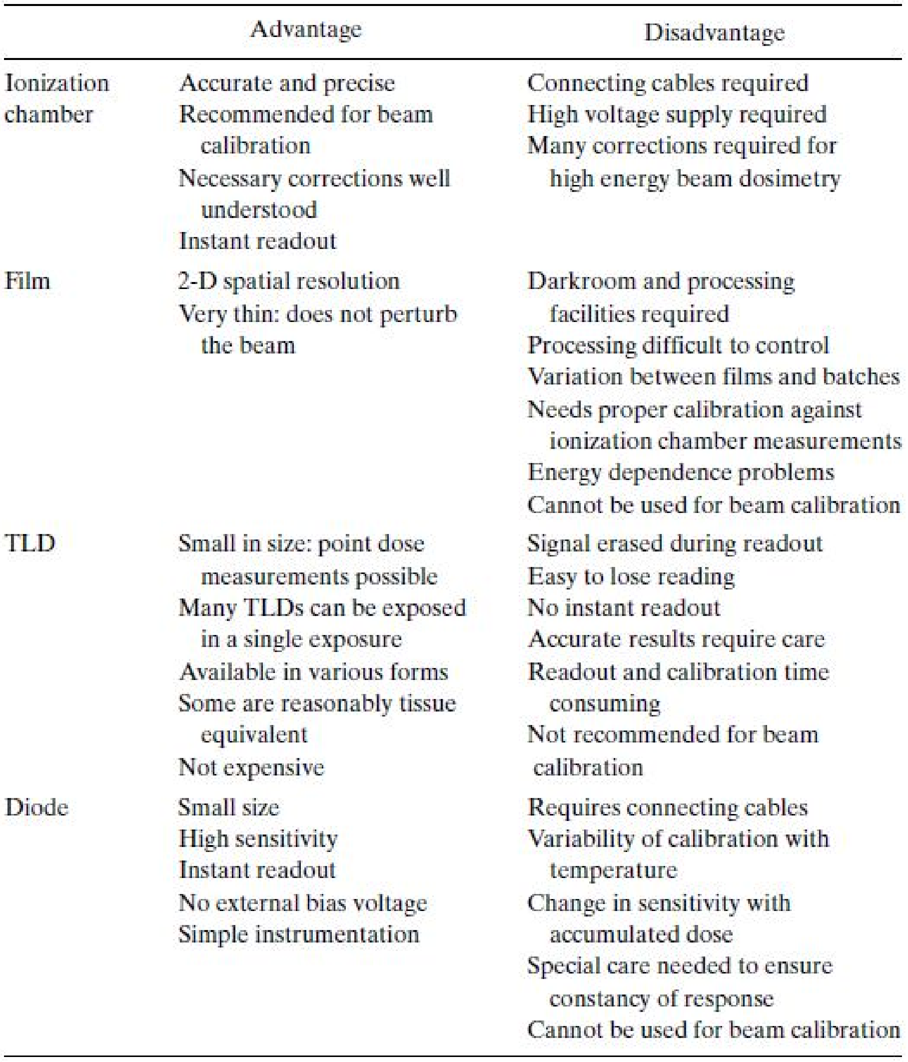
2.2.1(g) Convenience of use

Ionization chambers are reusable and no or little change in sensitivity within their lifespan makes it suitable for calibration of radiotherapy equipments. Semiconductor dosimeters are reusable, but with a gradual loss of sensitivity within their lifespan. Films and gels are not reusable. Some dosimeters measure dose distribution in a single exposure like films and gel. In terms of handling some dosimeters are quite rugged (for example IC), while others are sensitive to handling (like TLDs) (Izewska and Rajan, 2005).

2.2.2 Type of dosimetry

Radiation dosimetry systems come in many design and function. The 4 most commonly used radiation dosimeters are IC, radiographic films, TLD and Diode. The advantages and disadvantages of these 4 dosimeters are summarized in Table 2.1.

Table 2.1 Advantages and disadvantages of the four frequently used dosimetric systems (Izewska and Rajan, 2005)



	Advantage	Disadvantage
Ionization chamber	Accurate and precise Recommended for beam calibration Necessary corrections well understood Instant readout	Connecting cables required High voltage supply required Many corrections required for high energy beam dosimetry
Film	2-D spatial resolution Very thin: does not perturb the beam	Darkroom and processing facilities required Processing difficult to control Variation between films and batches Needs proper calibration against ionization chamber measurements Energy dependence problems Cannot be used for beam calibration
TLD	Small in size: point dose measurements possible Many TLDs can be exposed in a single exposure Available in various forms Some are reasonably tissue equivalent Not expensive	Signal erased during readout Easy to lose reading No instant readout Accurate results require care Readout and calibration time consuming Not recommended for beam calibration
Diode	Small size High sensitivity Instant readout No external bias voltage Simple instrumentation	Requires connecting cables Variability of calibration with temperature Change in sensitivity with accumulated dose Special care needed to ensure constancy of response Cannot be used for beam calibration

2.2.3 *In-vivo* dosimetry (IVD)

There are many steps in radiotherapy treatment from simulation to treatment delivery and each of these steps may introduce uncertainties (Thwaites *et. al.*, 2005). Specific patient groups or unusual treatment conditions might be crucial be given as a final check of the actual treatment by using IVD. *In-vivo* dose measurements can be used for entrance dose measurements serve to check the treatment machine output and performance as well as the accuracy of patient set-up (Thwaites *et. al.*, 2005). In-vivo dosimetry also capable to determine the intracavitary dose in readily accessible body cavities such as the oral cavity, bladder and rectum by using special *in-vivo* detector design (Izewska and Rajan, 2005; Van Dam and Marinello, 2006).

In-vivo dose measurements can be applied to check the dose delivery to the target volume and dose to organs at risk (e.g. lungs during TBI) or in situations in which the dose is difficult to foresee (e.g. non-standard SSD) (Thwaites *et. al.*, 2005). If entrance dose measurements are applied, the entrance dose has to be calculated manually to the corresponding target dose using treatment set-up details (Thwaites *et. al.*, 2005).

2.3 Diode Dosimetry

2.3.1 Theory of diode

Important elements in the silicon diodes used for *in-vivo* dosimetry is the p-n junction. A p-n junction is an internal boundary between p-type and n-type regions in a single crystal. Diodes are termed n-type or p-type depending upon whether the silicon substrates are doped with phosphorous (where majority-carriers are electrons) or boron (where majority-carriers are holes). An n-type diode is formed by doping acceptor impurities into a region of n-type silicon pentavalent (group V) element (e.g., phosphorous) called a “donor.” Each donor can contribute a free electron to the silicon. Therefore, the majority carriers in n-type silicon are electrons, and holes are the minority carriers. (AAPM, 2005; IAEA, 2013).

A p-type diode is formed by doping donor impurities into a p-type substrate with trivalent (group III) element (e.g., boron) called an “acceptor.” Each acceptor can accept an electron, resulting in a mobile hole in silicon that is equivalent to a positively charged carrier. In p-type silicon, holes are the majority carriers while electrons are the minority carriers . (AAPM, 2005; IAEA, 2013).

At the transition from p- to n-type material, a charge-free “depletion layer” is formed, over which an electrostatic potential difference is created (about 0.7 V for a silicon diode). As a result an electric field (E) is created over the depletion layer (Figure 2.2). By contrast to most other applications in electronics, in dosimetry no external bias is applied to the diode, which is then used in the “unbiased” or “short-circuit” mode (Van Dam and Marinello, 2006).

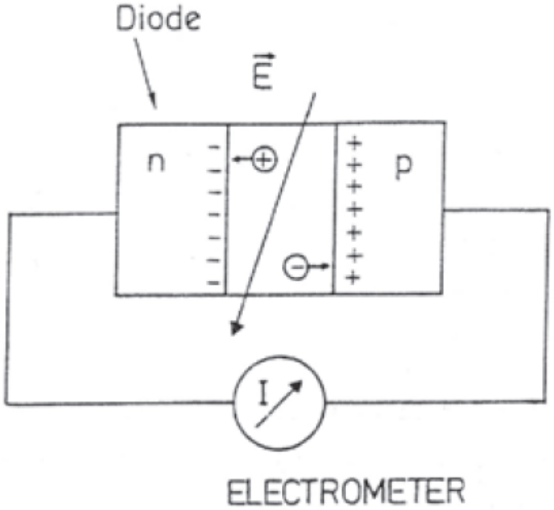


Figure 2.2 Theory of diode detection in short-circuit mode. (Van Dam and Marinello, 2006)

When the diode is irradiated, an ionisation “electron-hole” pair may be created in the depletion layer (Figure 2.2). The electrons and holes are attracted by p- and n-sides of the junction, respectively. Due to the high doping level at the n-side of a p-type diode, a lot of crystal imperfections or “recombination centres” are present at that side, which leads to a high probability of recombination for the holes. So only the minority charge carriers, electrons in this case, contribute to the ionisation signal. Due to this process the charge equilibrium between n- and p-sides of the diode is disrupted by the radiation. When connecting both sides externally to each other, a current will be detected at radiation, which, when the diode is in the unbiased mode, is proportional to the number of electron-hole pairs produced, i.e. to the dose (AAPM, 2005; Van Dam and Marinello, 2006; IAEA, 2013)

Diodes for dosimetry are function without an external reverse bias voltage to minimize leakage and can be measured in short circuit mode (current) or open circuit mode (voltage). Short circuit mode is the mode of choice since it has the benefit of producing a linear relationship between the charge generated in the diode and the dose. In short circuit mode, shown in figure 2.3, the electrometer must have low dynamic input impedance, as provided by an operational amplifier with a feedback loop and a low offset voltage as the diode signal is quite high, the electrometer used only needs to have moderate gain. It is common for diode systems to have a multichannel electrometer (IAEA, 2013).

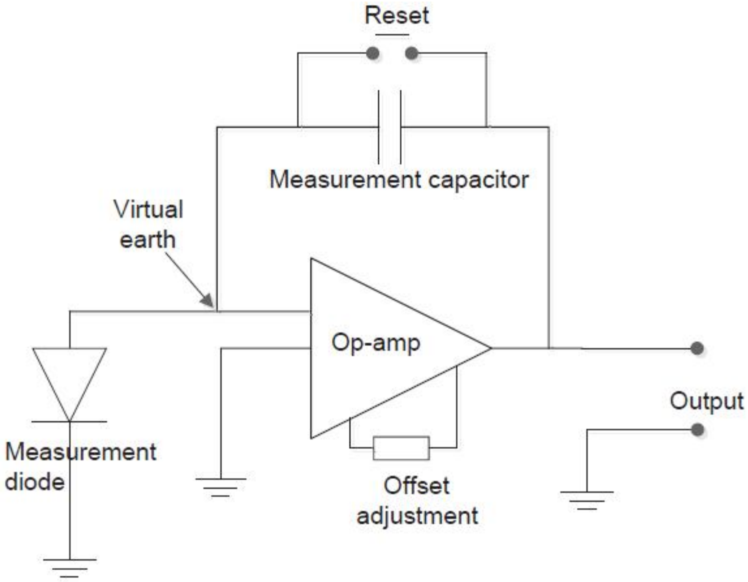


Figure 2.3 Diode measurement circuit (IAEA, 2013).

2.3.2 Characteristics of diode

The response of the diode in a current mode is complex and can be affected by dose rate, temperature, radiation and material. Changing the dose rate of ionising radiation effects the injection level and recombination properties of charge carries in a base of the detectors. Long term irradiation of the diode during the clinical or in vivo is leading to accumulation of radiation defects and reducing of diffusion length and as a result sensitivity of the detector. Changing of temperature affects recombination activity and response of the diode (Rosenfeld, 2006).

2.3.2(a) Temperature effects and accumulated doses.

The sensitivity of diode usually increases with temperature because internal resistance of a diode decreases (Van Dam *et. al.*, 1990; Jornet, *et. al.*, 1995). The diode required 2 to 3 minutes to reach a stable state with approximately 32°C when it is placed on a patient. The diodes should be left to reach body temperature for at least 3 minutes before the measurement is begun if the sensitivity variation found to be significant. Then, correction is made for the difference in temperature between calibration and measurement (IAEA, 2013). No temperature correction is needed for *in-vivo* dosimetry if it remains smaller than 0.4% per °C. (Van Dam and Marinello, 2006). Diode also depends on the accumulated dose received by the diode (IAEA, 2013).

2.3.2(b) Background signal.

If the background signal of the diode is varied by 4 mGy/min between room and body temperature, the diode will generate a dark current due to thermally generated charge carriers. To get the satisfactory background measurement, several minutes are needed to disturb the equilibrium of the circuit as well as may cause a change in diode response. (IAEA, 2013).

2.3.2(c) Radiation damage.

Radiation damage occurs when silicon atoms are displaced from their lattice sites and introduces recombination centres which capture charge carriers leading to the reduction in sensitivity and to an increase in dose rate dependence. P-type diodes are commonly less affected by radiation damage compared with n-type diodes. The amount of damage also depends with radiation energy (IAEA, 2013).

2.3.2(d) Energy dependence.

Silicon is not equivalent with human tissue. Different types of material used to provide equivalent build-up to make it suitable with specifics energy. The response of a diode should be measured as a specific energy and particular attention should be paid when measuring outside the field or under shielding blocks, because of the large spectral differences with in-field positions (Van Dam and Marinello, 2006).

2.3.2(e) Angular dependence.

Diode is designed with reference to clinical application needed. Most of cases, diodes will be positioned perpendicular to the radiation and thus correction factors can be ignored (IAEA, 2013). Directional dependence of diode response for large angle should be taken into consideration for example in case of tangential irradiation of the breast (Van Dam and Marinello, 2006).

2.3.2(f) Signal stability after irradiation.

The stability of the reading which is displayed after irradiation should be checked for time periods corresponding to those encountered in clinical practice. The drift should not exceed 1% in 1 hour when used for conventional treatments. For particular applications such as integration of the dose during total body irradiation performed at low dose-rate, the checks should be extended to a period of several hours (Van Dam and Marinello, 2006).

2.3.2(g) Intrinsic precision.

The intrinsic precision is given by the reproducibility of the measurements for at least 10 times irradiations at the same dose. The standard deviation should not exceed 1% (Van Dam and Marinello, 2006).

2.3.2(h) Influence of dose-rate.

During the irradiation, electron-hole pairs are formed at a rate which increases as a function of dose rate. If this dose rate is high a phenomenon of “pile up” occurs where ions are produced at such a high rate that the recombination cannot “keep pace” and more charge carriers escape recombination compared with lower dose rates. The dose rate dependence of a diode should be taken into account for LINACs, but may be ignored for cobalt and TBI conditions. Dose rate at the LINAC machine can be adjusted from low to high according to the machine specifications. Normally high dose rate will be used in clinical setting to speed up the treatment time. The diode should be calibrated in the dose rate range in which it will be used in clinical treatments (Van Dam and Marinello, 2006).

2.4 Calibration procedure

2.4.1 Entrance

Before diode can be used clinically, diode should be calibrated against IC. In radiotherapy, absorbed dose to water was calibrated using IC (Almond *et. al.*, 1999; IAEA, 2000b). Calibration of diode against an IC in standard set-up to get diode calibration coefficient for absorbed dose to water, N_{cal}. IAEA (2013) proposed calibration method for photon as Figure 2.4.

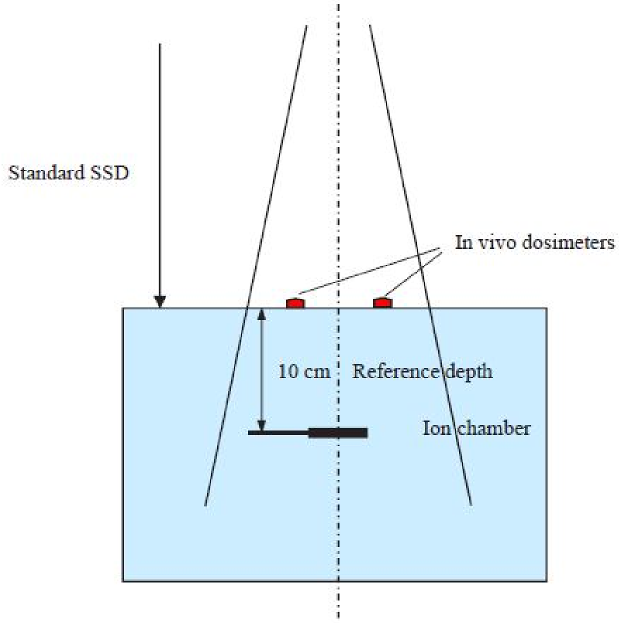


Figure 2.4 Set-up of *in-vivo* dosimeters for photon calibration (IAEA, 2013).

The calibration was carried out with the IC was placed at the reference depth, standard set-up (SSD 100 cm and FS 10x10 cm^2) and preferred using solid water phantom. The diodes were positioned at phantom surface near to the central beam axis.. The dose measured by the IC must therefore be increased according to the PDD at the measurement depth.

The irradiation of treatment machine was set to deliver D_0 = 200 cGy at d_{max}. The actual delivered dose was measured with the IC at the reference depth and was calculated following the established protocol (IAEA, 2013) like IAEA TRS-398 Code of Practice (IAEA, 2000) and AAPM TG-62 (Almond *et. al.*, 1999). The diodes calibration was equal to the dose at d_{max} in water.

The calibration coefficient N_{cal} is given by:

.

$$\text{Ncal}= \frac{D_0}{M}\left(\frac{\text{SSD} - d_s}{\text{SSD} + d_{max}}\right)^{-2} . k_{pl} \qquad (2.1)$$

where
$D_0 = D/(PDD/100)$,
M is the in-vivo dosimeter reading,
and k_{pl} is the plastic to water correction. k_{pl} is defined in equation 2.4.

In order to minimize any subsequent SSD correction factor, a specific SSD correction should applied. The dosimeter reading was multiplied by equation 2.2 for both calibration and for use on patients (IAEA, 2013).

$$\left(\frac{\text{SSD} - d_s}{\text{SSD} + d_{max}}\right)^{2} \qquad (2.2)$$

where *ds* is the distance from the surface of the phantom to the centre of the sensitive volume of the dosimeter.

If a solid non-water phantom was used for calibrations, additional correction factor, plastic-to-water correction factor, k_{pl} (equation 2.3) should be applied (IAEA, 2013).

$$k_{pl} = \frac{\left(\frac{M_w}{D_w}\right)}{\left(\frac{M_{pl}}{D_{pl}}\right)} \tag{2.3}$$

where M_w, M_{pl} are the chamber readings corrected for temperature and pressure, and D_w and D_{pl} are the absorbed dose to water at d_{max} or specifics depth in water and in plastic, respectively. The final equation is given by:

$$k_{pl} = \frac{M_w}{M_{pl}} \times \frac{P_{pl}}{P_w} \times \frac{T_w + 273}{T_{pl} + 273} \tag{2.4}$$

Where M_w and M_{pl} are the chamber corrected readings in water and in plastics respectively. P_w and P_{pl} are the preasure readings in water and in plastics respectively. T_w and T_{pl} are the temperature readings in water and in plastics respectively.

2.4.1(a) Entrance dose measurement at d_{max}

Entrance dose reading at d_{max}, D normally referred to depth of maximum dose. Actual IVD reading is calculated with calibration coefficient and all correction factors related for each individual beam:

$$D = M \times N_{cal} \times \prod_i k_i \tag{2.5}$$

where ki are the related correction factors (IAEA, 2013). For example, equation 2.6 required angle of incidence, SSD, wedge and FS correction factor.

$$D = M \times N_{cal} \times \left(\frac{SSD - d_s}{SSD - d_{max}}\right)^2 \times Ang_{CF} \times SSD_{CF} \times Wedge_{CF} \times FS_{CF} \tag{2.6}$$

2.5 Clinical application of *In-vivo* Dosimetry

IVD has been applied in clinical application with many purposes. First is to measure dose at organs at risk. Second is to verify treatment set-up and errors in the treatment and accessories. Entrance dose measurements are also capable to detect errors in the dose calculation especially with manual calculation (IAEA, 2013).

2.5.1 TPS Verification

Now days all commercial radiotherapy TPS is able to calculate point expected absolute dose at depth at d_{max} for every beam. IVD measurement can be used to verify each beam one by one. These methods also enable to estimate any doses below the diode dosimetry such as target dose or organ at risk (IAEA, 2013).

2.5.2 Total Body Irradiation

TBI is a special radiotherapy technique that delivers to a patient's whole body a dose uniform to within ±10% of the prescribed dose. Photon beams are used for this treatment with large fields to cover whole body except for a organ at risk, which are partially or fully shielded (Podgorsak, 2005).

TBI is used primarily as part of a preparatory cytoreductive conditioning regimen prior to bone marrow transplantation (BMT). The source of marrow may be the patient (autologous transplant), an identical twin (syngeneic transplant) or a histocompatile donor (allogeneic transplant). Figure 2.5 shown establish technique for TBI treatment (Podgorsak, 2005).

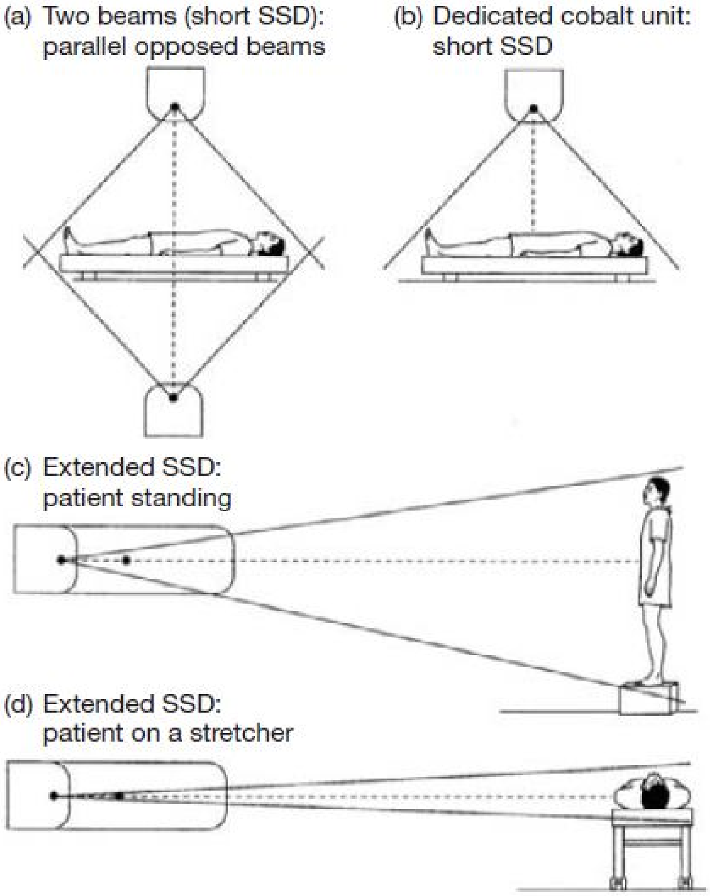


Figure 2.5 TBI treatment techniques: (a) Parallel opposed beams, (b) dedicated cobalt unit, (c) Patient standing (Extended SSD) (d) Patient on a stretcher (Extended SSD) (Podgorsak, 2005).

The TBI dose is prescribed or normalised to body isocenter and usually umbilicus is the reference point. The TBI treatment should deliver the prescribed dose to the dose prescription point and should maintain the dose throughout the body within ±10% of the prescription point dose. Uniformity of dose is able to achieve with the use of bolus or compensators (Podgorsak, 2005).

Once TBI technique has been selected, commissioning procedure should be carried out and dosimetric data for TBI like absolute beam output calibration and PDD will be collected. The requirements for accurate dose delivery in TBI are as stringent as those in standard external beam radiotherapy. It is important that in departments delivering TBI in-vivo dose measurement techniques be available to verify the patient dose directly during the treatment (Podgorsak, 2005).

2.6 Previous research done for diode dosimetry

Table shown study was done in previous study related with diode characteristics.

Table 2.2 Diode characteristics previous study.

No	Study characteristics	Literature reviews
1	Temperature	Changing of temperature affects recombination activity and response of the diode (Rosenfeld, 2006). Most of the previous study the diode response was found to increase with temperature. Ozleyis Altunko *et. al.* (2015) demonstrated that temperature correction factors EDP-5 and EDP-10 were found from slope of the linear drawings for each diode types. These factors for EDP-5 and EDP-10 were 0.29 %°C/cGy and 0.30 %°C/cGy respectively. While the more fluctuation for EDP-20 was realized. Van Dam *et. al.* (1990) study showed between 20°C and 30°C the diode response was found to increase linearly with temperature range between 1.00 and 1.07 Nilsson, *et. al.* (1988) study shown diode (EDP-8, EDP-10) response using photon with different temperature had

		shown that a steady state situation with an increase in response of 2-3% is obtain after 3-4 min. Zhu (2000) did not apply any correction for temperature because the treatment time was less than 1 minutes. Leunens and Schueren (1990) study showed with only about 10s between taping of the detector and treatment time 1 min, it was suggested not to correct for temperature.
2	Dose rate	Changing the dose rate of ionizing radiation effects the injection level and recombination properties of charge carries in a base of the detectors (Rosenfeld, 2006).
3	SSD Dependence	Huang, *et, al.*, (2003) study using IVD Model 1131 (Sun Nuclear Corporation, Melbourne, FL) showed that silicon diode detectors (Isorad-p diode and QED *p*-type diode Detectors) with 6 MV and 18 MV was decreased with decreasing SSD in range between 0.93 to 1.04. Meiler and Podgorsak (1997) study using Isorad detectors, Nuclear Associates, Carle Place, NY showed that increasing SSD for a fixed collimator setting results in decreased diode response up to 10%.
4	Field Size.	Huang, *et, al.*, (2003) study showed most of diode was increased with increase in field size except for QED diode, 4 MV and 10 MV. 4 MV diode showed the opposite behavior where DCF diode decreased with increase of field size. This is due to insufficient buildup. For the 10 MV diode the DCF roughly remained a constant when field size

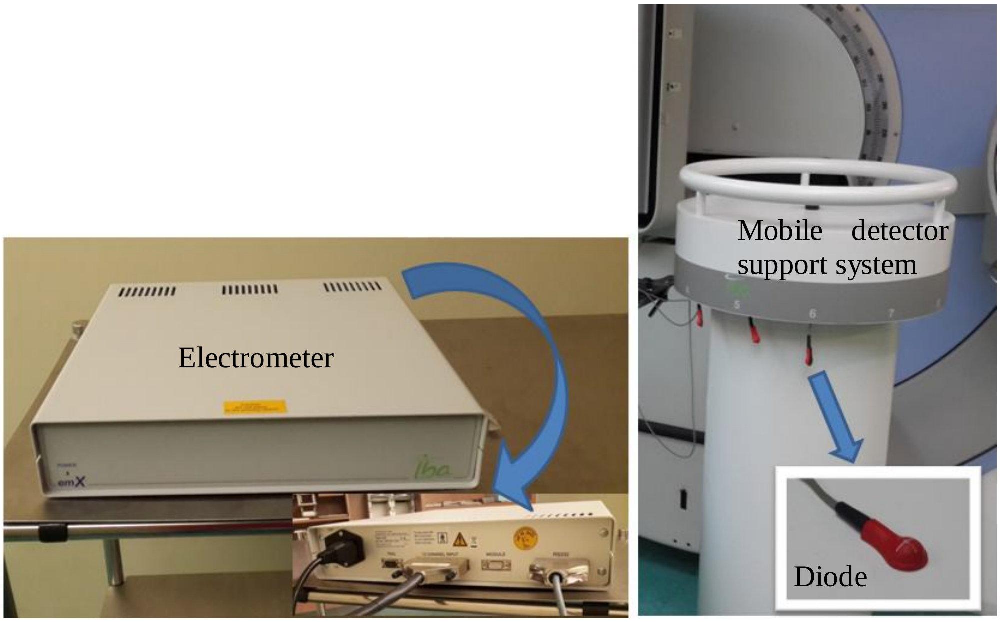
		changed. Nilsson, *et. al.* (1988) analysis diode (EDP-8, EDP-10) response using photon with different open field sizes is within 1%.
5	Directional	Nilsson, *et. al.* (1988) studied diode (EDP-8, EDP-10) response using photon with directional dependence shown variation of 10% with different angle of incidence.
6	Blocking Filter	Nilsson, *et. al.* (1988) study diode (EDP-8, EDP-10) response using photon with blocking filter is within 2%.
7	Wedge	Nilsson, *et. al.* (1988) study diode (EDP-8, EDP-10) response using photon with wedges was 3-6% Fontenla *et. al.,* (1996) study diode EDP-20 showed the wedge correction factors were ranging from 1.0l - 1.03
8	Perturbation effect	Nilsson, *et. al.* (1988) study diode profile measurement (EDP-8, EDP-10) where diode will act as a build-up material and thus increase the surface doses. Surface doses were very much increased and were more than 90% of maximum doses. The attenuation effect at 5 cm depth give a reduction of 5% over an area 1 cm^2.
9	Diode built-up	Fontenla *et. al.* (1996) study measured built-up cap for EDP-10 and EDP-20 were 4 mm and 13 mm respectively. Nominal thickness as per manufacture was 10 mm and 20 mm.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Materials

3.1.1 *In-vivo* Dosimetry (IVD) System



(a) (b)

Figure 3.1 IBA *In-vivo* dosimetry system (a) DPD-12pc Electrometer (b) Mobile detector support system and EDP-15^{3G} diode. (Courtesy IKN, 2016).

IVD is an essential element in the quality assurance for radiotherapy department. This system has capability to measure up to 12 channels in a single measurement. Omni Pro InViDos is an IVD software management system which handles all task of in vivo dosimetry. With 12 channels, this system has the ability for a wide variety of applications such as entrance dose measurement and total body irradiation measurement. Diode model EDP-15^{3G} was used for this study and 3 diodes were studied with serial number 10415, 10434 and 10435. This diode has a p-type semiconductor. Diode connected to a DPD-12pc (Scanditronix, Sweden) electrometer. All diode were mounted on the mobile detector support system. The build-up cap