A SYSTEMATIC REVIEW: DOSIMETRIC CHARACTERISTIC OF OPTICALLY STIMULATED LUMINECENCE (OSL) DOSIMETER WITH PHOTON BEAM IN RADIOTHERAPY

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By

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CERTIFICATE

This to certify that the dissertation entitled

A SYSTEMATIC REVIEW: DOSIMETRIC CHARACTERISTIC OF OPTICALLY STIMULATED LUMINECENCE (OSL) DOSIMETER WITH PHOTON BEAM IN RADIOTHERAPY

is the bona fide record of research work done by

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated and duly acknowledged. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at Universiti Sains Malaysia or other institutions. I grant Universiti Sains Malaysia the right to use the dissertation for teaching, research and promotional purposes.

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Date: 4TH JULY 2020

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ABSTRAK

KAJIAN SISTEMATIK: CIRI-CIRI DOSIMETRI OPTICALLY STIMULATED LUMINECENCE (OSL) DENGAN SINARAN FOTON DALAM RADIOTERAPI

Kemajuan dalam teknik radioterapi memberikan cabaran kepada ahli fizik untuk mencari sistem dosimetri yang paling tepat dan tepat untuk digunakan dalam pengukuran dos terutama dalam program jaminan kualiti. Makalah ini mengkaji ciri-ciri penting dosimetri Optik Stimulated Luminescence (OSL) terutamanya ketika digunakan dengan sinar foton dalam keadaan klinikal radioterapi. Prinsip asas bagaimana OSL dosimeter berfungsi juga dibentangkan dan proses yang mempengaruhi hasil pengukuran OSLD dibincangkan. Hasil yang diperoleh dari artikel yang dikaji membuktikan bahawa dosimeter OSL mempunyai ciri baik untuk digunakan sebagai dosimeter yang melibatkan sinar foton. Hasilnya menunjukkan bahawa OSLD nanoDot mempunyai pengukuran dos yang baik pada sinar foton, tindak balas dos linier pada dos rendah, dan mempunyai kebolehulangan yang baik. Hasilnya juga menunjukkan bahawa dosimeter OSL sedikit bergantung pada tenaga. Pudarnya isyarat OSL dan penurunan isyarat setiap bacaan juga menunjukkan hasil yang baik yang menunjukkan kesesuaian OSLD untuk digunakan dalam pengukuran klinikal rutin. Sistem OSLD moden seperti nanoDot memberikan alternatif kepada sistem dosimetri lain yang lebih tua seperti TLD dengan ketepatan yang sepadan dengan kecekapan yang lebih baik.

ABSTRACT

A SYSTEMATIC REVIEW: DOSIMETRIC CHARACTERISTIC OF OPTICALLY STIMULATED LUMINECENCE (OSL) DOSIMETER WITH PHOTON BEAM IN RADIOTHERAPY

The advancement in radiotherapy techniques impose a challenge for physicist to find the most accurate and precise dosimetry systems to be used in dose measurements especially in quality assurance programs. This paper reviews the important characteristics of Optically Stimulated Luminescence (OSL) dosimetry especially when in use with photon beam in radiotherapy clinical settings. Basic principle on how OSL dosimeter works is also presented and the process that affects the outcome of an OSLD measurements is discussed. The results obtained from the articles reviewed proves that OSL dosimeter has good characteristic to be used as dosimeter involving photon beam. The results demonstrate that the nanoDot OSLD have a good dose measurement at photon beam, a linear dose response at low dose, and have a good reproducibility. The results also indicate that OSL dosimeter has a little dependence on energy. The fading of OSL signal and signal depletion per readout also show good results that indicate the suitability of OSLD to be used in routine clinical measurements. Modern OSLDs system such as nanoDot provide an alternative to other older dosimetry system such as TLD with matching accuracy at better efficiency.

CHAPTER 1: INTRODUCTION

1.0 Introduction

There is an increasing interest in the use of the optically stimulated luminescence (OSL) technique for application in medical dosimetry (Yukihara,2009). This is due to the advancement of technique used with OSL in radiotherapy and radiology dosimetry. Thermoluminescence dosimetry has always been used as dosimeter for in vivo patient dose verification and in phantom studies before (Venables et al 2004). A common chip for OSL is constructed by aluminum oxide powder which is doped with carbon, giving their chemical formula is Al_2O_3:C. The advances of material used in OSL AL_2O_3 (synthetic sapphire) and efficiency of the optical stimulation technology has made OSL dosimeter a viable alternative for TLD with comparable accuracy (McKeever and Moscovitch, 2003).

The phenomena of Optically Stimulated Luminescence are almost similar with thermoluminescence. The difference is light stimulation is used instead of heat to stimulate the radiation induce luminescence. In order to determine the dose absorbed by the dosimeter after an exposure, the sensitive element of OSLD which is Al_2O_3:C, is illuminated by a series of light emitting diode (LED). The luminescence caused by this stimulation will be measured with photomultiplier tube with integral recorded counts as function of the time is proportional to the absorbed dose by the dosimeter. (Dunn et al, 2013)

The basic principle of OSL is shown in Figure 2 in term of energy band model of electron-hole production following the irradiation. Firstly, when ionizing radiation interacts with the OSL, it will excite the electron from the valence band into the conduction band and then will be trapped between conduction band and valence band and creates free holes. In order to release the trapped electron, stimulation of visible light will be used. The trapped electron then will travel back to conduction band and towards valence band. Visible light will be emitted with the intensity of light is proportional to the dose absorbed by the OSLD (Akselrod et al 2007)

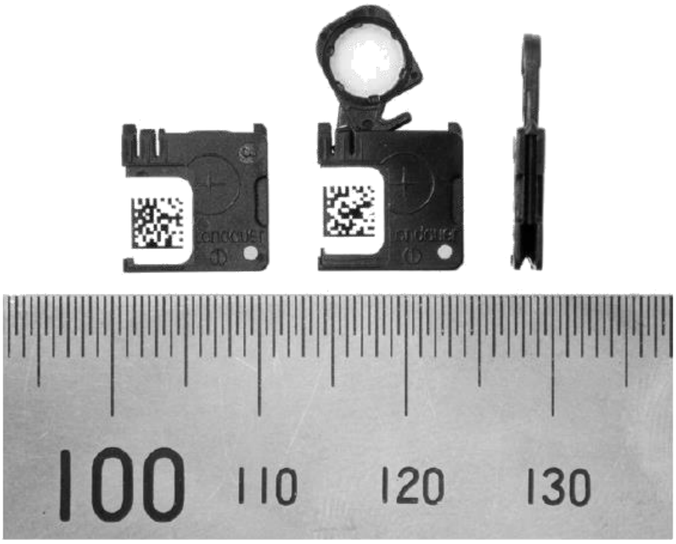

Figure 1 Shows InLight nanoDot dosimeter. Three nanoDots, showing (left) closed, (middle) sensitive element exposed, and (right) side profile. closed dosimeter dimension is 10 x 10 x 2 mm^3

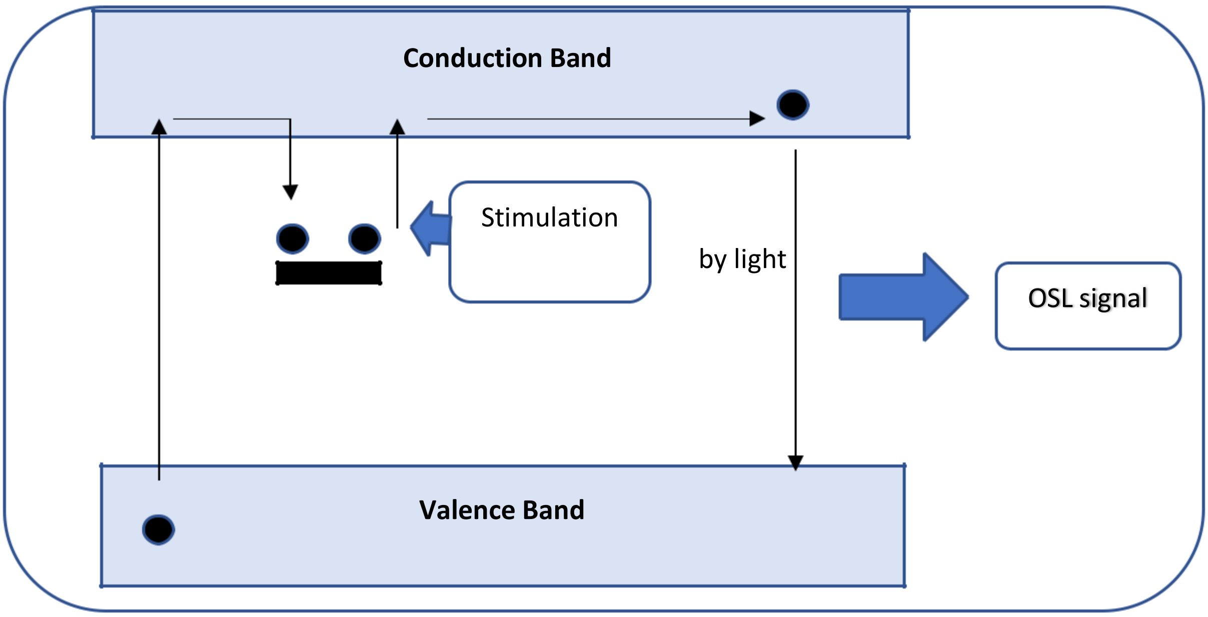

Figure 2 Shows basic principle of OSL process

1.1. Research Question

1. What is the dosimetric characteristic of OSL dosimeter system when irradiated with photon beam compared to the other dosimetric system such as TLD and Ion Chamber?
2. Which dosimeter is the most suitable to be used as dosimeter in order to measure dose and treatment planning in radiotherapy using photon beam?

1.2. Significance of Research

1. At the end of the study, the characteristic of OSL-based dosimeter can be reviewed.
2. Dosimetric performance of OSL can be compared with other dosimetry used in radiotherapy such as TLD and Ion Chamber.
3. The suitability of OSL to be used as main dosimetric system in radiotherapy treatment involving photon beam.

1.3. Aim of Research

1. To review the dosimetric characteristic of Optically stimulated luminescence (OSL) dosimeter at photon beam.

1.4. Specific Objectives

1. To review linearity dose response and output calibration of linear accelerator by using OSLD in comparison with IC.
2. To compare dose measured by OSLD with IC at dmax for photon beam.
3. To compare the suitability of OSLD to be used as dosimeter for QA program and treatment planning verification compared with TLD.

CHAPTER 2: METHODOLOGY

Following the Preferred Reporting Item for Systematic Review and Meta-Analyses (PRISMA) protocol were used for reporting. An electronic s literature search was performed using several online databases which is Science Direct, Google scholar, IOPscience, PubMed and Scopus from 2002 to 2018 were used. The search of English language studies comparing the dosimetric characteristic of OSL dosimeter at photon beam with other dosimetry such as thermoluminescence dosimeter, film dosimeter and ionizing chamber done. The eligibility criteria are the research must be published in English language, the studies published after 2000, and the characteristic of OSL dosimeter with photon beam was investigated. To retrieve the articles, the search using online database system is based on the following terms: Optically Stimulated Dosimeter (OSL), dosimetry in radiotherapy, photon dosimetry, medical dosimetry and dose measurements. The study's title and abstract will be scanned from the searches and full text article will be obtained when they appeared to meet the eligibility criteria. The eligibility of the studies was assessed independently. Five different articles that eligible based on the eligibility criteria that will be reviewed in this systematic review are listed on Table 1.

Table 1. OSL studies of interest for dosimetry in radiotherapy and respectives types of OSLDs and characteristics studied.

Publication	Type of OSLD	Characteristic studied
Yahya et al, 2017	Al_2O_3:C OSLD	Dose measurements, Dose linearity, Reproducibility
Joohari et al, 2018	NanoDot Al_2O_3:C OSLD	Dose measurements, Reproducibility
Ponmalar et al, 2017	Landauer Inc nanoDot OSLD	Dose linearity, Energy dependency, Reproducibility, Fading characteristic, Signal depletion
Dunn et al, 2013	InLight_ nanoDot_ OSLD by Landauer Inc	Reproducibility, Signal depletion, Fading characteristic, Linearity, Energy dependence
Youngjin et al, 2016	Landauer Inc nanoDot OSLD	Reproducibility, Linearity, Energy dependence

CHAPTER 3: LITERATURE REVIEW

3. Introduction to parameter to be reviewed

There are several main aspects that will be focused in this article about the characteristic of the OSL dosimeter when irradiated with photon beam in radiotherapy in order to determine the suitability of OSL dosimeter to be used when compared with other types of available dosimeter such as thermoluminescence dosimeter and ionization chamber dosimeter. The first parameter is the characteristic of dose measurement by the OSL dosimeter when irradiated with photon beam in with energy used in radiotherapy. This parameter defines the ability of the dosimeter to measures the exact amount of dose delivered by the beam. The closer the value of dose absorbed with the value of dose delivered will indicates the suitability of the dosimeter to be used as dosimeter especially in quality assurance procedure.

Next parameter which is the dose linearity discuss the behavior of the dosimeter response with the dose ranges. The most suitable dosimeter that can be used in radiotherapy is the dosimeter that is able to produce a linear dose response within the therapeutic range. Reproducibility is an aspect that ensures the dosimeter to produce an exact amount of value as it is irradiated and bleached repeatedly. The ability to produce the same amount of value repeatedly indicates that the dosimeter is suitable to be used as a routine dosimeter in radiotherapy.

Energy dependence is a parameter that shows that whether the dosimeter is suitable to be used in a certain energy of radiation. The dosimeter must have no energy dependence in therapeutic range in radiotherapy treatment in order to get the correct value of dose absorbed by the medium. The fading of osl signal is to determine whether the dosimeter can retains the amount of absorbed dose for a period of time. The longer the time taken for fading, the dosimeter will be able to be used as an audit material. Signal depletion per readout is the parameter thet measures the amount of signal of the dosimeter that is lost with each reading. The lower signal depletion per readout would enable the dosimeter to be read repeatedly without a significance error.

3.1 Dose Measurements

The dose reading of OSLD is in good agreement with ionization chamber at 6 and 10 MV x-ray, it also shows that the OSLD has good dose linearity at increase high energy x-ray (Yahya et al, 2017). In this study, the dose measurements of OSLD and TLD100 is compared with ionization chamber. The study results state that when OSL is used in dose measurement of kilovoltage x-ray beam, the dose reading was linear with the increased x-ray energy. The linearity of OSLD was also found higher compared with the TLD100. The discrepancy of dose reading with OSL is discovered to be higher as the x-ray energy increased, while lower deviation is found with lower energy x-ray. This show that the dose measurement at kilovoltage energy x-ray using OSL dosimeter is more acceptable compared with TLD and Ionization chamber at lower x-ray energy.

With high energy photon, the dose measurement using OSLD is nearer to the ionization chamber compared with TLD100 (Yahya et al, 2017). The study uses high energy of photon which is 6 and 10 MV x-ray to compare the dose measurements of high photon between OSLD and TLD100 compared with ionization chamber. The results indicate that the dose reading of OSLD were in line with ionization chamber at energy of 6 MV and 10 MV x-ray. The linearity also was good as photon energy increase. Calculation of error was done to determine the consistency and persistency of the dosimeter. The results from the calculation shows that the error value of OSL dosimeter were in line with TLD100 for low energy x-ray, but for higher energy x-ray, the error value showed lower value compared with TLD100. Thus, prove that OSLD has higher consistency and persistency compared with TLD100. This result indicate that in term of consistency of reading, OSLD has a better dosimetry property at high energy x ray.

According to the study conducted by Joohari et al, 2018, the results shows that the dose absorbed by OSL dosimeter was close with the value of ionization chamber in photon energy of 6 MV and 10 MV. The results of TLD also shows that the dose absorbed by the TLD100 was significantly lower compared with ionization chamber value. The results state that the dosimetry reading of OSLDs were closer to the ionization chamber compared with TLD100 at all measured photon and electron. The result from this study shows agreement with the result of previous study of absorbed dose (Yahya, 2017), which recommends the suitability of OSLD to be used as dosimeter for quality assurance program and dosimetry works at high energy photon.

3.2. Dose Linearity

In a study of dosimetric characteristic of nanodot OSLDs, the analysis on linear and supralinear response of OSLD shows that the supralinearity behavior starts anywhere in the dose range from 200 to 400 cGy (Ponmalar et al, 2017). The method used to investigate the response of OSLDs as a function of dose was the dosimeters will be exposed to doses ranging from 50 to 1000 cGy. The response of the dosimeter is normalized at 200 cGy. Then the corresponding linearity curve will be plotted.

The results from the study conducted by Ponmalar et al, 2017, show dose-response behavior of the nanodot OSLDs shows that the OSLD respond was linear for doses of 50 until 300 cGy. The supralinearity is then observed for doses >300 up until the maximum dose of 1000 cGy delivered in this study. The supralinearity behaviors for dose ranging from 400 to 100cGy was analyzed and the supralinearity factor is determined from ratio of supralinear response of the OSLD to the linear response. The results from this study also was found to be in agreement with study conducted by Yukihara et al, 2005, with the signal of OSLD according to the dose amount shows linear results from 0 to 2 Gy, and supralinear results at 2 to 6 Gy.

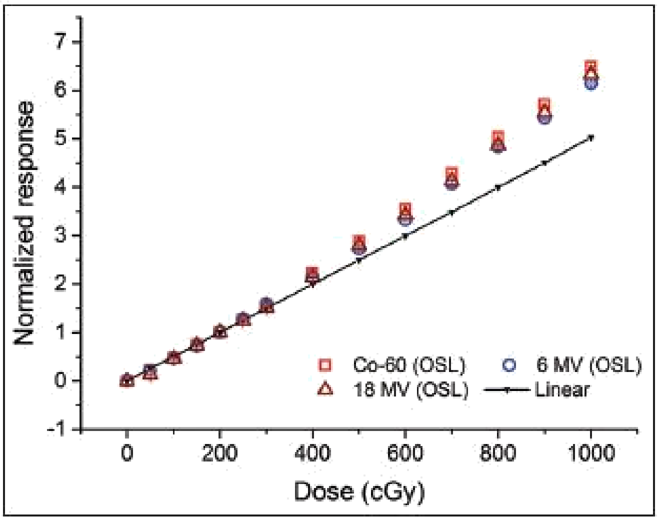

Figure 3 Dose response of nanoDot OSLD with photon beam (Ponmalar et al, 2017)

The supralinear responses of nanodot dosimeter is due to the extra luminescence emitted from deeper electron traps in dosimeter during irradiation of higher doses (Ponmalar et al, 2017). The results from this study also observed that supralinear factor will increase with increase in dose. In order to use OSL dosimeter in patient measurement, supralinearity factor will be accounted in dose calculation for high doses.

Previous study by Dunn et al, 2013, studied dose linearity of OSLD by irradiating nanoDot dosimeters to a number of accumulated doses up to 11 Gy. The NanoDot is then placed in a solid water phantom and irradiated to an accumulated dose of 0.25 Gy, with 6 MV x-rays. The process is then repeated so that each group of dosimeters received accumulated dose of 11 Gy. Then the reading was read out and plotted on graph. Graph 1 shows dose response of nanoDots dosimeter to 6 MV x-rays in range of 0 to 11Gy.

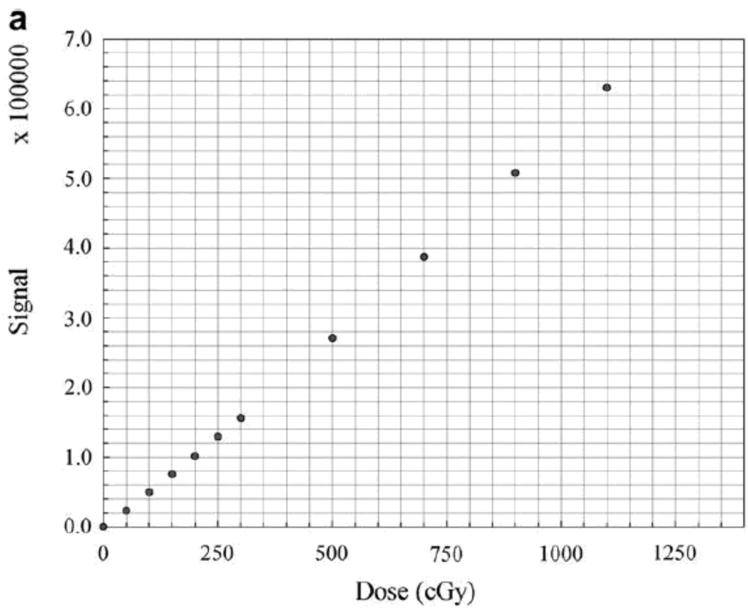

Figure 4 Dose response of nanoDot OSLD with photon beam (Dunn et al, 2013)

The nanoDots OSLDs were found to have a supralinear response with the degree of supralinearity being dependent to the accumulated dose (Dunn et al, 2013). The results from this study shows good agreement as the previous study by Manickam et al, 2017, and Yukihara et al, 2005, mentioned above. These studies demonstrated that at lower ranges, as accumulated dose increases, the OSLD sensitivity is increased 1.2 to 1.8 times higher when no accumulated dose is present, while with higher accumulated dose, 20 to 60Gy, the sensitivity stars to drop. Therefore, the usage of nanoDots with accumulated dose larger than 3 Gy preferred to be avoided. At dose level of 1 to 2 Gy, the correction applied to account the supralinearity behaviors will be small which is not more than 1%, therefore the difference in linearity of individual nanoDots at here level is not significant (Dunn et al, 2013)

3.3. Reproducibility

The approaches to compare the reproducibility of OSLD system demonstrated that nanoDots dosimeter can be conveniently reused with bleaching between irradiations provided taking care of the changes in the sensitivity of OSLD with repeated irradiations (Ponmalar et al, 2017). In the study, OSLDs were exposed with identical dose three times in order to find the reproducibility of OSLDs. The maximum percentage of difference found between bleached and accumulated response in 6 MV was 7.8% and in 18 MV was 9.9%. These results indicate that the effect due to accumulation of dose is small but still noticeable when the OSLDs were exposed at 8 Gy in single session. The finding of inter-OSL response variation was found to be less than 1.03% (Ponmalar et al, 2017) which indicates that OSLD can produce good reproducibility during multiple irradiations.

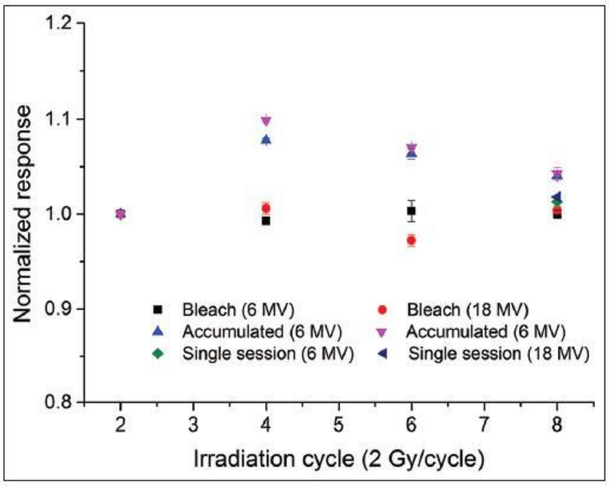

Figure 5 Shows reproducibility of OSL in repeated irradiations (Ponmalar et al, 2017)

In a study by Yukihara, 2005, the reproducibility and precision of the readout were tested using ten irradiations performed independently to the OSL dosimeter. The irradiation was carried out by 6 MV linear accelerator on a fixed dose of 0.665 Gy, with the samples position in water phantom with depth 10 cm. readout procedure will then carried out. The results of reproducibility test shows that 86% of the reading are within ±1% from the mean value. The maximum difference between the mean of ratio between recorded OSL signal to the reference OSL signal value and the overall mean was 0.7% (Yukihara,2005). The results of reproducibility characteristic evaluation of OSLD shows that the error value of the whole batch of OSLD was ±7.2 % and the error of each element was a maximum of ±1.2% with average of 0.8% (Youngjin et al, 2016), the results shows a good agreement with results from Yukihara, 2005. Both of these results show a good reproducibility value of OSL dosimeter when used in multiple independent irradiations of photon beam.

The reproducibility of OSLDs and TLD were better when the measurement is done at lower energy photon, at higher energy photon the reproducibility was significantly higher for both OSLDs and TLD100 (Joohari et al, 2018). These results are confirmed by the lower measurement error value, σ. the value of measurement error when irradiated with photon beam with energy 10 MV was 10.69 for OSLD which is lower compared to measurement error of TLD which is 15.6 indicating better reproducibility of OSLD compared to TLD at high energy photon. These results indicate the suitability of OSL dosimeter which has better reproducibility that can be used in quality assurance programme and dose measurements.

3.4. Energy dependence

The results of energy response to nanoDots OSLD show no energy dependence in energy range from 6 to 18 MV photon beam (Ponmalar et al, 2017). The variation in energy response of nanoDot OSLD is investigated using three different energy of photon beam such as 6 MV, 18 MV and ^{30}Co by maintaining similar setup during irradiation with all photon energy. The results obtained regarding the energy dependence of OSLD with photon were normalized to a relative response of 6 MV photon beam. The observed result of dependency of OSLD with photon energy beam shows a deviation of 1.5% $\pm$ 0.7% and 1.7% $\pm$ 0.6% at 18 MV and 6 MV beam. This is the evident that the nanoDots OSLD have no dependence in energy of photon beam in the energy range from 6 MV to 18 MV due to low deviation of error obtained from the results.

In a study conducted by Dunn, 2013, the results show that OSLD response show very little dependence on energy with the largest variation from the response at 6 MV photon was 1.2% $\pm$1.1% (Dunn, 2013). from this research, the manufacturers of the OSL dosimeter have claimed that there is little to no energy dependence. The result from this study are consistent with the claim because the largest discrepancy was found to be very small which is only 1.6 % at 6 MV photon energy. The results from this study also shows a good agreement with the study stated above by Ponmalar et al, 2017 which shows very little energy dependence. These results prove that OSL dosimeter is suitable to be used as dosimeter involving radiation measurement with photon energy ranging from 6 MV to 18 MV due to no significant energy dependence by the dosimeter.

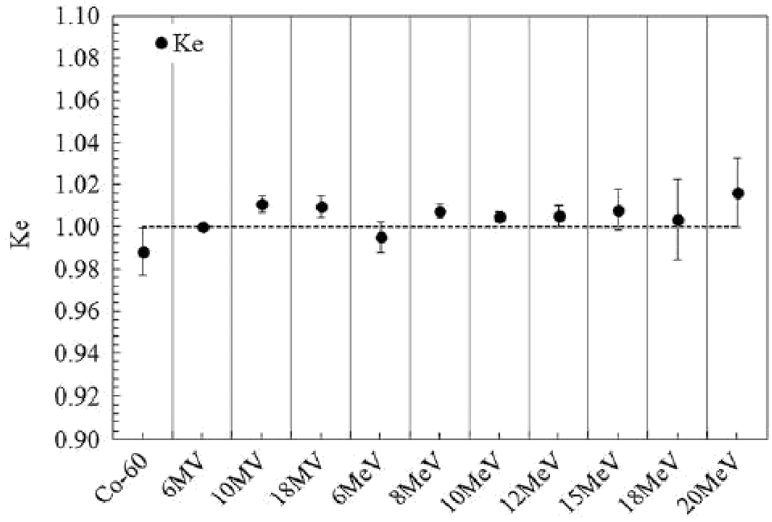

Figure 6 Shows energy dependence of OSL with photon energy. K_e defined as ratio of sensitivity at specific energy for a specific modality to the sensitivity at 6 MV (Dunn et al, 2013)

3.5. Fading of optically stimulated luminescence signal

Rapid drop in optical signal of OSLD from 40 s to 10 min was significant due to transient signal originated from the spontaneous emission of unstable nanodosimetric electron trap, the time taken to stabilize this low energy trap is approximately 8 to 10 minutes post irradiation with 6 and 18 MV photon beams (Ponmalar et al, 2017). In this study, the fading characteristic of nanoDot OSLDs was determine by investigating the decrease in optical signal at room temperature with time. After irradiation by photon beam with energy of 6 MV and 18 MV, the response of the dosimeter will be checked for a few periods of short term (seconds/minutes/hour), mid-term (few days) and lastly for long term which takes several weeks and months.

The results obtained by the study show that every one month, the fading decay rate stay constant with percentage of reduction in signal was less than one percent (<1%) (Ponmalar et al, 2017). The results show that the fading of signal in OSL was very low after 10 minutes post irradiation, this would be useful in audit program where the OSLD that has been use for any quality assurance procedure or dose verification as the dosimeter could be read after several days of irradiations.

The study conducted by Dunn et al, 2013, the results also show agreement with study conducted by Ponmalar et al, 2017, where the fading data of the dosimeter show approximately 4 to 5% reduction of their signal compared to initial post irradiation signal in a period of 9 months. The results is consistent with previous study mentioned above with very little value of signal fading few months after irradiation. These results prove that OSL dosimeter could be used in post audit program in clinical radiotherapy settings which still could be read out after a period of one week or one months.

3.6. Signal depletion per read out

Unlike TLD, the readout process of nanodot OSLDs is non destructive with only small, portion of the signal being removed per reading. Over the 190 readings of nanoDots, the signal lost that has been identified by the study was 0.03% signal per read (Dunn et al, 2013). The signal depletion per readout in this study was investigated by exposing a nanoDot to 1 Gy of 6 MV xrays. Then the nanoDot will repeatedly be read for 190 times after a week post-irradiation. The depletion of signal per read were determined by calculation of signal decrease drop over the successive readings. The process of reading a nanoDot dosimeter will partially discharges the trap charge and resulting in partially depletions of signal on each read. The results of this study show that over 190 repeat readouts, the data lost was 5.74% of the original signal. A linear trend line was constructed using this data and has a gradient of 0.028% signal depletion per readout.

Another study by Manickam et al, 2017, concludes that the rate of loss of the signal of OSD depend on dose and energy, higher rate loss in the OSL signal occurs when the OSL dosimeter were exposed with high dose of photon beam (Manickam et al, 2017). The method used to investigate signal depletion per readout was almost the same as been used by Dunn et al, 2013, where the OSL dosimeter will be exposed and read for a number of times. The OSL dosimeter will be exposed to 2 Gy which is considered low dose (LD) and 10 which is considered high dose (HD) at photon energy of 6 and 18 MV. The readout was repeated for 200 times. The results obtained from this study shows that 0.05% signal lost per readout for 2 Gy (LD) and 0.06% signal lost per readout for 10 Gy (HD). The results from this study shows that for 6 MV photon energy, the signal lost per readout was consistent with the result from previous study by Dunn et al, 2013. These small values of signal depletion per readout and nondestructive readout process suggest that nanoDot OSLD to be used in a routine and repeated clinical dose measurements and quality assurance programs with an excellent accuracy of readout.

CHAPTER 4: CONCLUSIONS

The characteristic of optically stimulated dosimetry to be used in medicine especially in radiotherapy clinical settings such as dose measurements, linearity, reproducibility, energy dependence, fading characteristic and signal depletion per readout have been reviewed in this paper. The dose measurement characteristic reviewed indicates the suitability of OSL dosimeter to be used in high energy photon beam compared to TLD due to its ability to obtain a very close reading with ionization chamber. The dose linearity characteristic also indicates that the dose response of OSLD to have a linear response which is very useful when using dose at 0 to 2 Gy which is commonly used during auditing programs. The reproducibility of the systems also indicates the suitability of OSL dosimeter to be used in various radiotherapy dosimetric measurements with high accuracy. The characteristic involving energy dependence of OSLD systems show a very good results which proves independency of OSLD to energy which enables OSLD to be used in large range of photon energy beam. The fading characteristic and the signal depletions per read out also provide evidence that nanoDot OSLDs can be used in routine clinical measurements with an excellent accuracy over a period of time.

In conclusion, the current advancement of optically stimulated dosimeter provide an increasing confidence for the usage of OSL systems to be used in clinical radiotherapy settings. The OSL systems provides a tool which offers a number of advantages for the physicist especially in several occasions. The most significant advantage of using OSLD is the reusability and the dose reading procedure that can be done in a short period of time. This paper proves the efficiency of quality assurance programs and dose verification programs can be increased by the use of optically stimulated dosimeter at photon energy beam in radiotherapy settings.

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