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An insight on using in-vivo diode dosimetry to verify the delivered doses during radiotherapy

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ABSTRACT

In-vivo dosimetry (IVD) is one of the most accurate ways for determining the dosage provided to the patient during treatment. The aim of this work is to verify whether patients were receiving the accurate prescribed dose. Which occurs by assessing the dose delivery errors, caused by human or equipment malfunctioning, using in-vivo diode dosimetry (IVDD). In total, 302 fields were performed for 80 cases, including pelvis, abdomen, thorax, and head and neck (H & N) patients. Prior to the clinical application, Alderson Rando phantom was used to evaluate the diodes' dependability as a complement to the validation process. The results revealed that the measured dose of the phantom was within ±5% of the planned dose. Additionally, patients' doses achieved 91.4% of the measured dose were within ±5% of the planned dose. Of the other 8.6%, about 5.6 % of the measured doses were more than 5% and less than 10% and only 3% were larger than 10% of the planned dose. The outlying values that were more than 5% were repeated as in-vitro measurements on a phantom and the deviations were within ±5%. This study demonstrated that diode measurements provide an immediate readout during the treatment process and it is reliable as quality assurance for linear accelerator. Moreover, IVDD is capable of detecting major and common treatment errors such as patient setup errors and incorrect source surface distance.

1. INTRODUCTION

The tolerance limit of radiation dose absorbed during radiotherapy delivery should be kept at a 5% action level, according to the International Commission of Radiological Units (ICRU) [1]. According to Swedish regulation, in-vivo dosimetry (IVD) must be performed during the first treatment session for each patient [2]. The aim of IVD is to measure the patient's dose during treatment to ensure that the actual dose received by patients matches the prescribed dose by the treatment planning system (TPS), whereas ex-vivo or in-vitro dose verification approach uses a phantom to represent the patient and is performed either after or before the treatment [3]. The use of in-vitro dosimetry pre-treatment validation is a helpful method for finding mistakes in both actual treatment and TPS. In-vivo measurements can uncover systematic mistakes early in the treatment process, which would otherwise build over the treatment course, leading to an increase or decrease in the prescribed dose [4]. Based on in-vivo measurements for routine patients' quality assurance (QA), action levels provide information to accept or reject the treatment [5].

IVD in this study was done by the diodes dosimeters. Several studies using other regimens were issued in order to evaluate the patient's dose, including, thermoluminescence dosimetry (TLD), optically stimulated luminescent dosimeters (OSLDs), radiophotoluminescence (RPL), [6] metal oxide semiconductor field-effect transistor (MOSFET) [7] and brachytherapy [8].

Patient-specific QA for intensity modulated radiotherapy (IMRT) is usually performed using two-

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dimensional (2D) arrays, electronic portal imaging devices (EPID), and films. However, in three-dimensional conformal radiation therapy (3D-CRT), most radiotherapy centers do not perform any QA for plans before treatment. The aim of this work was to verify whether patients were receiving the correct dose that matches the prescribed dose and to detect errors in treatment sessions caused by human error or equipment malfunctioning using in-vivo diode dosimetry (IVDD) for 3D-CRT.

2. MATERIALS AND METHODS

2.1. Dosimetric and handling tools

The measurements of this study were carried out at the Radiotherapy and Nuclear Medicine Department, National Cancer Institute, Cairo University, Cairo, Egypt. Computed tomography (CT) (Siemens, Somatom, Germany) simulations were performed for both patients and Alderson Rando phantom. The CT-Simulator data were transmitted to the TPS (XIO, version 5.10.03, CMS, Elekta, England). The measurements were performed using the step-and-shoot technique on a 6-MV Elekta Synergy linear accelerator. To determine the absorbed dose, a farmer type 0.6 cm^3 ionization chamber was connected to an electrometer Unidos E, and diodes were connected to a multidos electrometer (PTW-Freiburg, Germany). The measurements were carried out with a set of four EDP-10^{3G} hemispherical p-type diodes (IBA Dosimetry, Germany). The perspex phantoms were composed of slabs each of dimension (30 cm x 30 cm x 1 cm) with thicknesses of 0.1, 0.2, 0.5, and 1 cm.

2.2. Calibration and Correction factors

Diodes dosimeters were calibrated against the ionization chamber. The dose calibration factor ($F_{cal,}$) is the ratio of the absorbed dose measured with the ionization chamber (D_{ic}) at depth dose maximum (d_{max}) to the semiconductor signal (M_{Sc}) at the surface of the phantom, in accordance with equation (1) [9].

$$F_{cal} = D_{ic}/M_{sc} \qquad (\mathbf{1})$$

The dose calibration was performed under reference conditions (source surface distance (SSD) = 100 cm, beam angle set to 0°, and open field 10 cm x 10 cm). The measured dose (D_{mes}) under reference conditions in accordance with equation (2) [10].

$$D_{mes}[\mathrm{Gy}] = M_{Sc} \cdot F_{cal} \qquad (\mathbf{2})$$

The correction factors (CFs) were applied to the diode reading for non-reference conditions ($\prod_i C_i$) is determined according to equation (3) Leunens *et al.* [11].

$$D_{mes}\,[\mathrm{Gy}] = M_{Sc} \cdot F_{Cal} \cdot \prod_i C_i \qquad (\mathbf{3})$$

However, the outcome was independent on CFs, and they were extremely near to 1 that was mentioned in our previous study [12].

2.3. Alderson Rando phantom measurements

CT simulations of the H&N was scanned with a mask to represent the actual patient. The CT images were transferred to the TPS in order to outline the volume of aim and organs at risk (OARs). The phantom was established for several calculations as revealed in **Fig. 1 (a-d).**

2.4. Patients measurements

For 80 patients treated with 3D-CRT, 302 fields were acquired. Of these, pelvis (100 fields), H&N (88 fields), abdomen (74 fields), and thorax (40 fields). The measurements have been repeated two times and the average was calculated. For each field, the diode is fixed at the central axis.

2.5. The patients' measurement exceeding the action level

When the measured dose exceeds the tolerance (i.e. >5%), it is required to take action. The first step is to check diode positions, check the set-up of the patient, and the treatment plan. If the error has been discovered, it must be corrected first and a second measurement should be performed. If the tolerance signal is exceeded for several successive patients on the same day, this is an indication that there is a problem with the linear accelerator output, and that the machine output should be checked before treating other patients. If the origin of the error is not found and the tolerance level has exceeded 5% from the planned dose, it was repeated as in-vitro measurements on a phantom. **Fig 2** shows a flow chart of a system for taking action.

2.6. The dose deviation

The percentage dose differences (Δ%) between the calculated dose (D_{cal}) and measured dose (D_{mes}) were calculated using the following equation:

$$\Delta\% = \frac{D_{mes} - D_{cal}}{D_{cal}} \times 100 \qquad (\mathbf{4})$$

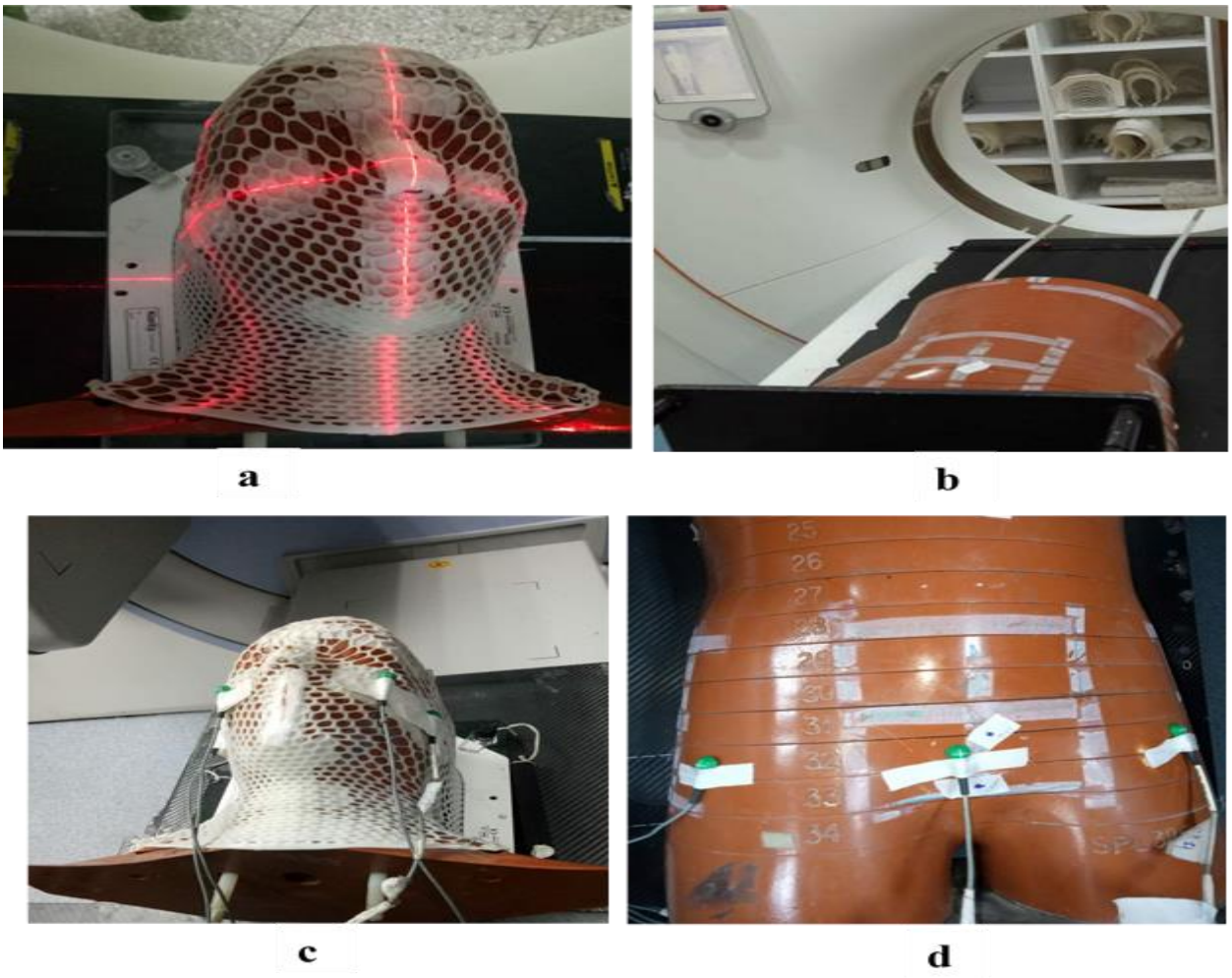

Fig. (1): Alderson Rando phantom for (a & b) CT simulation (c & d) set-up for measurements.

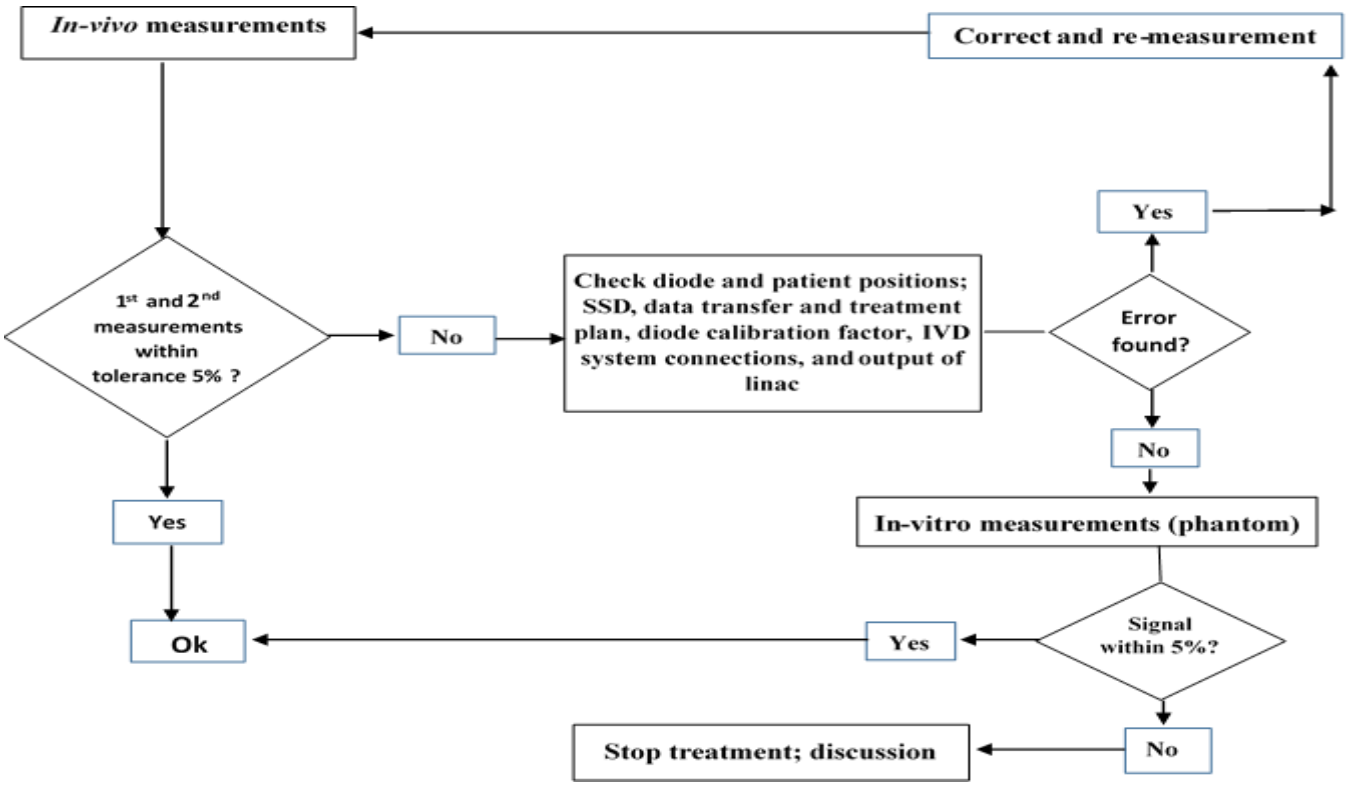

Fig. (2): The flowchart in the event of the patients' measurement exceeding the tolerance limit for taking action.

3- RESULTS

The phantom was utilized to evaluate the diodes' dependability as a complement to the validation process prior to taking measurements in clinical practice. In vitro results (using Alderson Rando phantom) demonstrated that the delivered doses were within ±5% of the planned dose (**Fig. 3)**. This indicated that the IVDD could be used to verify the delivered dose to the patient during radiotherapy treatment.

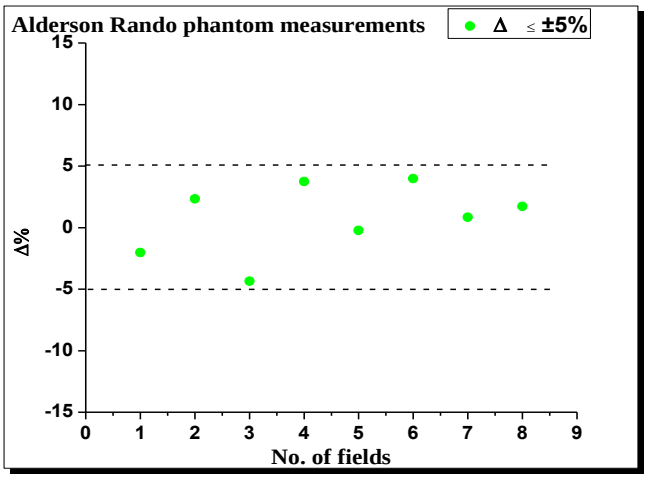

Fig. (3): Distribution of deviations for Alderson Rando phantom measurements. Δ%: the deviations between calculated and measured doses; the dashed lines indicate the ±5% dose deviation.

Patients' measurements revealed that 91.4% of the in-vivo measured doses were within ±5% of the planned doses. The remainder 8.6%, around 5.6% (17 fields) of the dose measurements ranged from more than ±5% to less than ±10% of the planned doses and only 3% (9 fields) of the dose measurements were external from the ±10% of the planned doses. Interestingly, the results of the pelvis, abdomen, and thorax demonstrated a slightly higher concordance between planned doses and measured compared to the H&N results as shown in **Table1**.

Fig. 4 (a-e) displays the distribution and deviations of in-vivo measured doses versus the planned doses and determines the values of the deviations as specific values, whether the deviations deviate towards the positive or negative value.

The outlying values that were more than 5% between planned and measured doses were repeated as in-vitro measurements on a phantom. Therefore, these outlying values when measured with phantom, the deviations (Δ%) between measured and planned doses were within ±5% as shown in **Fig. 5 (a) and (b).**

Table (1): Summary of in-vivo patients' measurements. Δ%: the deviations between calculated and measured doses; N: No. of fields; SD: mean standard deviation.

In-vivo measurement	N	Δ%	SD (%)	|Δ| ≤±5%	(±5% <|Δ|<±10%)	|Δ|≥±10%
All fields	302	-0.1	3.7	91.4% (276 fields)	5.6% (17 fields)	3% (9 fields)
Pelvis	100	-0.3	3.4	92% (92 fields)	5% (5 fields)	3% (3 fields)
Head and Neck	88	-0.5	4.1	89.8 % (79 fields)	6.8% (6 fields)	3.4% (3 fields)
Abdomen	74	0.4	3.8	91.9% (68 fields)	5.4% (4 fields)	2.7% (2 fields)
Thorax	40	0.3	3.3	92.5% (37 fields)	5% (2 fields)	2.5% (1 field)

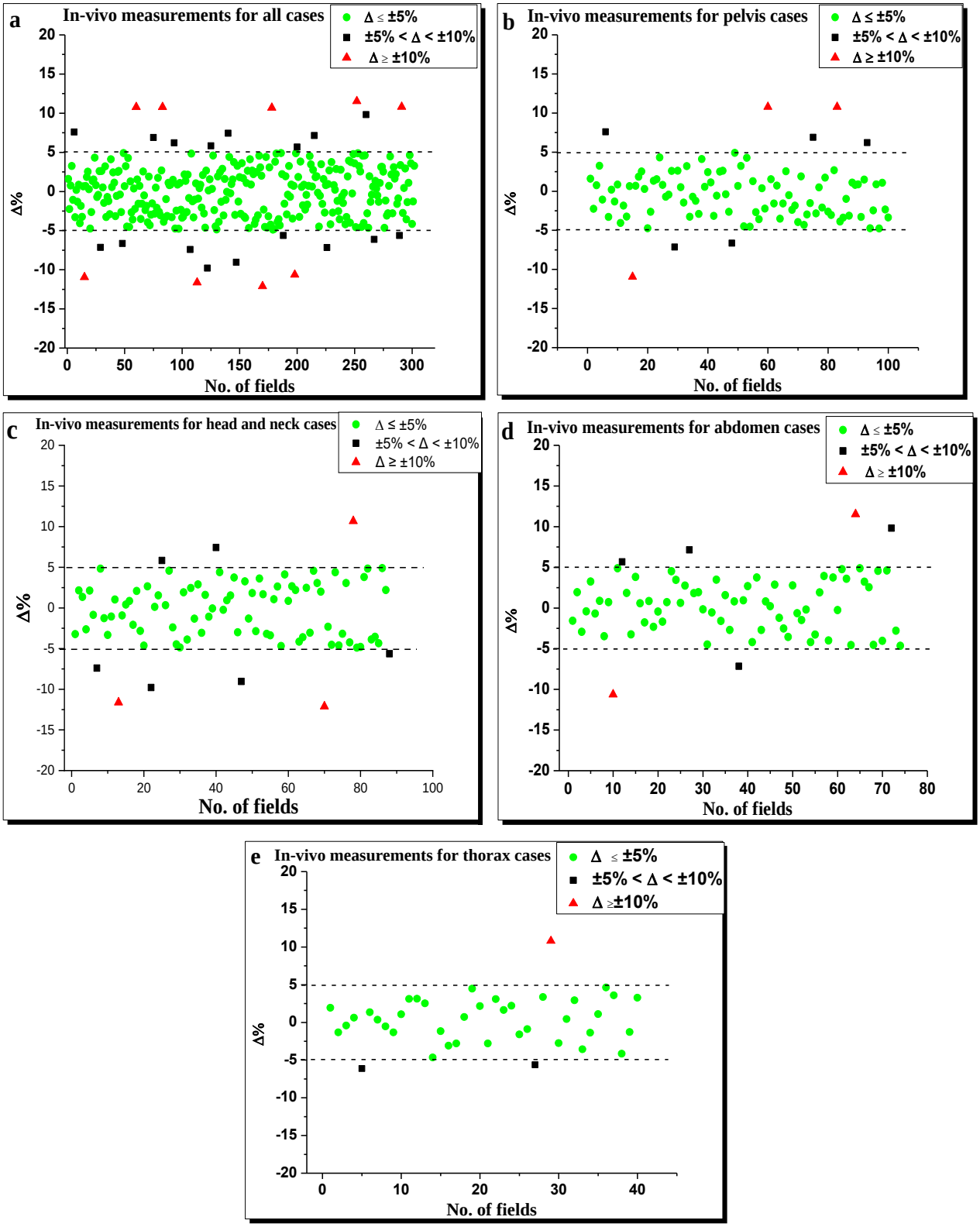

Fig. (4): Distribution of deviations Δ% for in-vivo patients' measurements for (a) all different cancer cases, (b) pelvis, (c) head and neck, (d) abdomen (e) and thorax cases. Δ%: the deviations between calculated and measured doses; the dashed lines indicate the ±5% dose deviation.

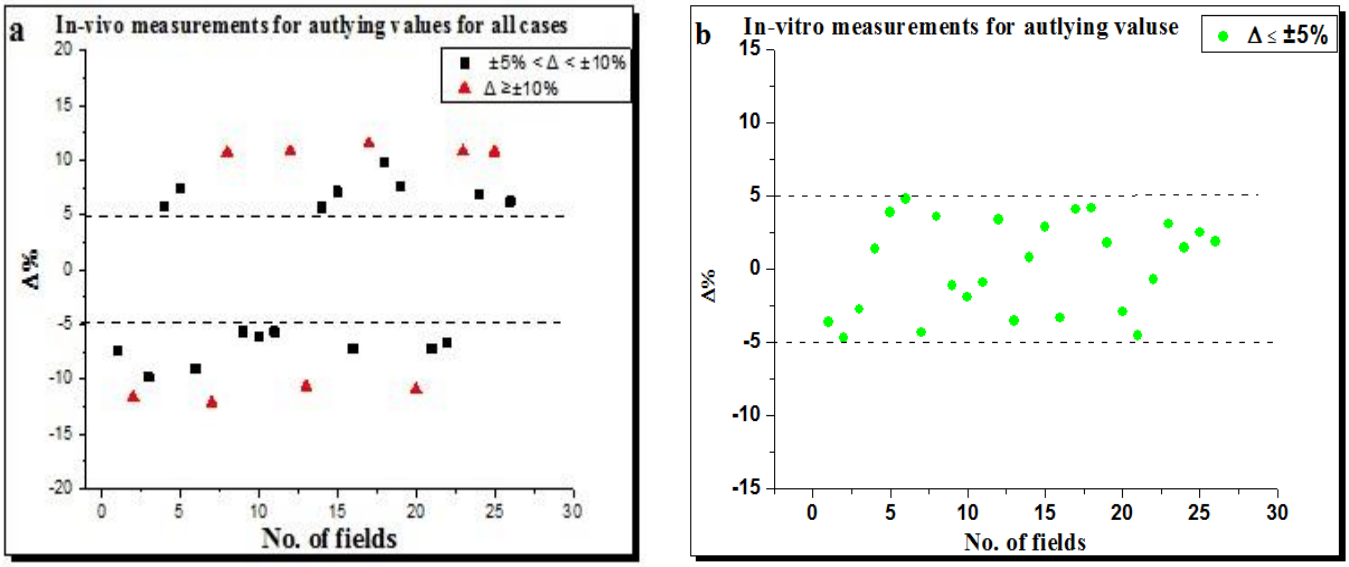

Fig. (5): The outlying values (a) for in-vivo measurements that were more than 5% between measured and planned doses before repeated as in-vitro measurements, (b) the outlying values after repeated as in-vitro measurements. Δ%: the deviations between calculated and measured doses; the dashed lines indicate the ±5% dose deviation.

4. DISCUSSION

There are challenges for medical physicists to measure the accurate delivered dose for patients during treatment using IVDD. Silicon diodes have many advantages in the clinical dosimetry field: fast reading, easy instrumentation, reliability, robustness, and high radiation sensitivity [3]. Accordingly, in this study, p-type diodes have been used instead of TLDs or OSLDs because they do not provide instantaneous reading and require a finite time to read out. During the measurements, diodes were fixed at the field's center. Otherwise, if the field's center is blocked, the diode positioning was determined along the Y-axis or X-axis.

Prior to the in-vivo measurements, IVDD was performed in vitro (at Alderson phantom). In vitro results were within ICRU recommendation (within 5% of the calculated dose) which indicated that IVDD is ready for clinical use.

On the other hand, For in vivo measurements, the total number of fields for measured dose achieved 91.4 % (276 fields out of 302) were within normal tolerance ±5%. Diode measurements detected that 5.6% (17 fields) of the dose measurements were more than 5% and less than 10% and only 3% (9 fields) were larger than 10% from the planned dose.

Interestingly, when the measurements were repeated (in vivo), the deviations of diode readings from the planned doses were improved. When the diode readings were again performed and outlying values have been exceeded 5%, it was repeated as in-vitro measurements on a phantom and the deviations were within ±5%. Results revealed that the standard deviation for H&N (SD 4.1%) was slightly higher than other cancer sites because of the irregular surfaces of the H&N region compared to easier measurements of the pelvis and abdomen. Furthermore, the light field is not distinguished when using mask. For the thorax, the lateral fields measurements were easier than the anterior field measurement because the hair on the thorax can make it difficult to attach the diode on the skin. In this case, the diode positioning was placed along either the Y-axis or X-axis where there is less hair to reduce diode positioning errors. The spread of the abdomen deviations (SD 3.8%) in comparison to pelvis (SD 3.4%) and thorax (SD 3.3%) were suspected to be due to variation of breathing movement of patients.

The outlying values that were more than 5% between measured and planned doses may be explained by either random or systematic. Major and common treatment errors involve the misuse of bolus, either inadvertently not using one or using the incorrect one (ex: 1 cm instead of 0.5 cm or vice versa) . However, the most

commonly used bolus is either 0.5 - 1 cm in thickness, which translates into an error in percentage depth dose (PDD), as a result, it is not likely to be detected by the technician. Thus, this error can be detected by IVDD. The linear accelerator's QA output is critical, so daily measurements using IVDD inform whether the machine requires QA based on the deviations between calculated and measured doses when all radiation beams are in the same pattern, whether positively or negatively. Other major deviations were observed in some diode readings because of several reasons, such as bad patient positioning, mechanical check such as an error in the alignment of lasers, and optical distance indicator (ODI), all of these resulting in the wrong SSD. Furthermore, when the mask was not suited to the skin and there was an air gap beneath the diode.

This results agree with study published by Bokulic *et al.* and Tunio *et al.* [13; 14]. According to our previous study [12] and other studies [15; 16] about use of diode for IVD in IMRT is possible for implementation, although facing some difficulties such as fluence which differs within each field and high gradient dose locations, this could lead to large uncertainty. In addition, positioning of the diode when the center of the field is partially or fully blocked. We believe that all of these variations could have an impact on treatment delivery, which further signifies the importance of IVDD in radiotherapy centers.

5. CONCLUSION

According to this study, IVD is one of the best approaches for 3D-CRT dose verification. Furthermore, diode readings provide an immediate readout during the treatment process. In addition, compared to the ion chamber, the diode is simpler and less expensive. The measures were also carried out in a comfortable and well-tolerated manner by the patients. This study concludes that IVDD may be implemented during actual treatment with a 5% normal range because the measured and calculated doses are in good agreement. However, when the difference between the measured and calculated doses is greater than 5% for some fields, in-vitro measurements of these fields are required. Moreover, IVDD is capable of detecting major and common treatment errors such as patient setup errors, incorrect SSD, misuse of bolus, the air gap in mask, and the linear accelerators QA output. This study was performed using the step-and-shoot technique on a 6-MV. Therefore, future work using dynamic IMRT as well as the investigation at higher energies more than 6-MV to determine the impact of electron contamination would be intriguing.

Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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