Performance characteristics and commissioning of MOSFET as an in-vivo dosimeter for high energy photon external beam radiation therapy

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SUMMARY

AIM: In vivo dosimetry is an essential tool of quality assurance programmes in radiotherapy. In fact, the assessment of the final uncertainty between the prescribed dose and the dose actually delivered to the patient is an effective way of checking the entire dosimetric procedure. Metal oxide semiconductor field effect transistors (MOSFETs) have recently been proposed for use in radiation therapy. The purpose of this work is to study the performance characteristics and to carry out the commissioning of MOSFET as an in-vivo dosimeter for high-energy photon external beam radiation therapy.

MATERIAL AND METHODS: Characterization and commissioning of low sensitivity TN502RD and high sensitivity TN1002RD MOSFETs for entrance and exit dosimetry respectively for application in in-vivo dosimetry in radiotherapy was carried out. The MOSFETs were characterized in terms of reproducibility, short-term constancy, long-term constancy, linearity, angular dependence, energy dependence, source to skin distance (SSD) dependence and field size dependence.

RESULTS: The reproducibility of standard sensitivity MOSFET is about 1.4% (1 SD) and 1.98% (1 SD) for high sensitivity detectors. The linearity of both MOSFETs was excellent (R2 = 0.996). The response of MOSFETs varies linearly for square fields from 3 x 3 cm^2 to 30 x 30 cm^2. For beam incidence ranging from ±45° the MOSFET response varies within ±3%. Commissioning of both MOSFETs was carried out in terms of entrance dose calibration factor, exit dose calibration factor, SSD correction factor, field size correction factor, wedge correction factor and shielding tray correction factor. The average calibration factor for low and high sensitivity MOSFET detectors is 0.9065 cGy/mV and 0.3412 cGy/mV respectively. The average SSD correction factors are quite small and vary between 0.968 and 1.027 for both types of detectors for the range of clinical SSDs from 80 cm to 120 cm. The field size correction factor varies from 1.00 to 1.02 for both types of detectors. The wedge and the shielding tray correction factors for both the detectors also show quite small variation. MOSFET characteristics are suitable for in vivo dosimetry of entrance and exit dose measurement relevant to 6 MV treatment.

CONCLUSION: It can be concluded that MOSFET dosimetry's low energy dependence, high sensitivity and immediate readout make it a good replacement for TLD in radiation therapy dosimetry.

KEY WORDS: MOSFET, in vivo dosimetry, entrance dose, exit dose

BACKGROUND

One of the essential tools in the quality assurance programme in radiotherapy, to measure the actual dose delivered to the target and in estimating the dose to the organs at risk, is in vivo dosimetry. This measurement effectively reveals the uncertainty between the prescribed dose and the delivered dose and acts as a quality assurance for the entire dosimetric procedure. In vivo dosimetry is particularly needed in total body irradiation (TBI) and in the estimation of doses to critical

structures due to the uncertainties in patient positioning or in the absence of accurate dose calculation systems. Thermoluminescent dosimeters (TLDs) and semiconductor detectors (diodes) are mostly used for in vivo dosimetry [1]. Nevertheless, each of them has its disadvantages: TLDs do not provide an immediate read-out and are time consuming, while diodes are online dosimeters that operate in continuous charge integrated mode, which requires a cable to measure the signal. Such kinds of setup are quite cumbersome during clinical setup where many diodes are used simultaneously as in the case of TBI. These disadvantages are overcome by the use of metal oxide semiconductor field effect transistors (MOSFETs). MOSFETs have recently been proposed for use in radiation therapy and they are a good alternative to TLD. The basic MOSFET structure, how it works, and its advantages are described elsewhere. On irradiation, electron-holes are generated within the silicon dioxide layer. The holes which do not undergo recombination undergo stochastic hopping transport through the oxide in response to the applied electric field. Some of these holes are trapped in long-term traps near the interface and cause a negative shift in the gate voltage. This shift is proportional to the absorbed dose. However, a temperature shift could also cause a shift in the voltage (up to 4 to 5 mV per degree Celsius), which would represent an overestimation of 15 cGy for a difference of 10 degrees Celsius between measurement and calibration. To remove the temperature correction factor, two MOSFETs are mounted on the same source substrate (dual MOSFET). These two MOSFETs operate at different gate voltages. The difference in the gate voltage shifts on the two MOSFETs is also proportional to the absorbed dose and is independent of temperature, if we assume that the two MOSFETs have the same temperature coefficient. MOSFET sensitivity depends on the applied bias. The dual MOSFET can operate at two bias voltages (dual bias) [2]. A higher positive bias during irradiation results in less recombination and therefore more holes are trapped on the SiO_2. Therefore the variation in the threshold voltage will be higher. The higher sensitivity mode will use two 9 V batteries, while the standard sensitivity mode will only use one 9 V battery. Besides everything else, the main advantage of MOSFETs is the instantaneous reading they provide while having a very thin active area (<2 μm) with physical size of < 4 mm^2. The post-irradiation signal is permanently stored and is dose rate dependent. The characteristics of MOSFETs such as portability, requirement of low power, detector irradiation without the need of cables, and negligible attenuation of the radiation make it suitable for in vivo dosimetry, dosimetry of small beams and of brachytherapy. Real time dose measurement using MOSFETs helps to detect and correct the delivered dose, before the end of treatment, if the predicted and measured dose differ by more than a fixed value defined as the "action level".

AIM

The purpose of this study is to describe the performance characteristics and commissioning of MOSFET as an in-vivo dosimeter for high-energy photon external beam radiation therapy.

MATERIALS AND METHODS

There are two types of MOSFET dosimeters currently available from Thomson and Nielsen Electronics, Ltd. Ottawa, Canada: the standard model TN-502RD and high-sensitivity model TN-1002RD. The high-sensitivity MOSFET dosimeters are about three times more sensitive than the standard MOSFET dosimeters. For this reason, the high-sensitivity MOSFET dosimeters are mostly used for low-dose applications, but they have a shorter lifetime than the standard dosimeters. There are also two bias settings for the MOSFET dosimeters: standard and high-sensitivity. Similar to the difference between the two types of dosimeters, the sensitivity and lifetime differ for each setting. With a combination of the aforementioned bias settings and dosimeter models, four different dosimeter sensitivities can be achieved. A standard setup was created so that measurements could be compared. Low sensitivity (TN502RD) and high sensitivity (TN1002RD) MOSFETs supplied by Thomson and Nielson, Canada were utilized for entrance and exit dose measurements in our study. The MOSFET dosimeter consists of three parts: (a) the MOSFET de-

tector bonded with an epoxy to the end of a 20 cm long, 2.5 mm wide, and 0.4 mm thick flexible cable, resulting in a flat surface on one side and a rounded, 1 mm thick epoxy coating on the other; (b) a 9 V dual bias supply box; (c) a reader with a liquid crystal display. For dose measurement, the MOSFET sensors are inserted into the bias box, which is connected to the reader through an interface cable. The zeroing function measures and stores the total threshold voltage required to allow conduction through the MOSFET prior to irradiation. The threshold voltage shift, which is proportional to the radiation dose, is obtained by the read function of the individual MOSFET detectors following irradiation. The readings show the total threshold voltage in millivolts, current threshold voltage difference in millivolts and the corresponding dose in centigray. Four MOSFETs were placed in grooves made in a slab of solid phantom (Blue water, standard imaging) with the flat side of it facing the beam as recommended by the manufacturer. A slab containing TN502RD dosimeters was placed in a solid phantom at 5 cm from the surface of the phantom and 20 cm from the posterior side (Fig. 1).

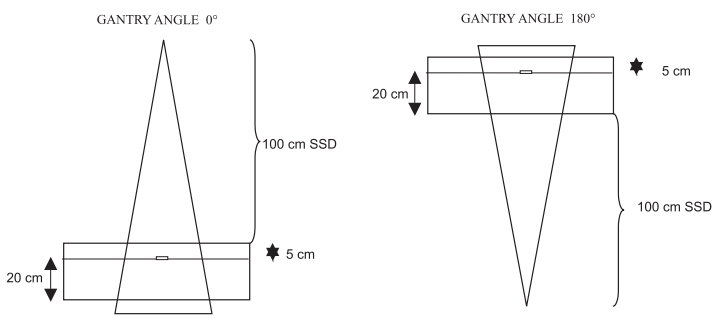

Fig. 1. Standard Entrance and Exit Dose Setup

Another slab containing TN1002RD dosimeters was placed in the same phantom with MOSFETs at 5 cm from the posterior side of the phantom and 20 cm from the anterior side of the phantom. From this point onwards this will be referred to as the standard setup. MOSFETs were irradiated with a 6 MV photon beam from a Siemens Primus Linac for a collimator size of 10 cm x 10 cm. The MOSFET were calibrated against a 0.6 cc Farmer ionization chamber type PTW TN30013 (PTW, Freiburg, Germany) connected to an electrometer, model PTW UNIDOS E. This ionization chamber has a calibration factor traceable to the PTW Freiburg calibration laboratory in Germany. The solid phantom (Blue water) has a special slab to accommodate the ionization chamber. All the measurements were performed with a Siemens Primus Linear Accelerator.

A. Characteristics:

1. Reproducibility:

The reproducibility of MOSFETs was evaluated by irradiating four MOSFETs in the standard setup and irradiating with 100 MU 15 times. The output of the linac was measured daily and was within 1.0%.

2. Constancy:

Short-term and long-term constancy tests were performed in the standard setup for all the MOSFETs with 100 MU. Measurements were made for the first six days of a month (first week) for short-term constancy and this was repeated for six consecutive weeks for long-term constancy.

3. Linearity:

MOSFET measurements were made for 20, 50, 100, 150, 200, 250 and 300 MU set in the linac unit in the standard setup.

4. Angular dependence:

Angular dependence measurements were performed in a cylindrically shaped solid phantom 10 cm in diameter (Fig. 2). The MOSFETs were placed at the isocentre at a source to axis (SAD) distance of 100 cm at the centre of the cylindrical phantom. Measurements were made from 315 to 45 degrees in 15-degree increments and the dose registered by the MOSFET was read from the reader for each beam.

5. Energy dependence:

Measurements of the dose response of the energy dependence were carried out for Co-60, 6 MV and 15 MV photon beams. For each energy a dose of 100 cGy and 30 cGy was delivered to the TN502RD and TN1002RD dosimeters respectively.

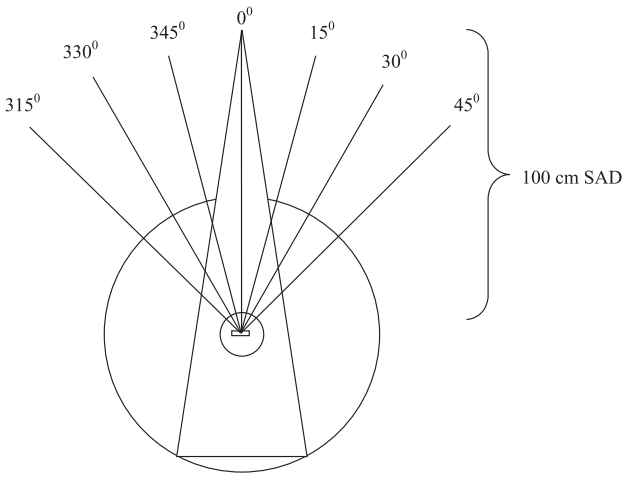

Fig. 2. Angular dependency setup for various gantry angles

6. SSD dependence:
SSD dependence was tested by placing an ion chamber at D_{max} in the solid phantom (Fig. 3). The SSD was varied and readings were taken with 100 MU. The MOSFETs were then placed at the surface of the solid phantom with the build-up cap and irradiated at the same SSDs. Measurements were carried out both for entrance and exit geometries.

7. Field size dependence:
MOSFET and ion chamber measurements were carried out for 100 MU with the standard setup and compared. Field sizes varied from 3 cm x 3 cm to 30 cm x 30 cm.

B. Commissioning:

1. MOSFET calibration factor
The first step in commissioning a new system or new MOSFETs for clinical use is to measure a calibration factor for each MOSFET. Calibration relates the MOSFET's readings under reference conditions of field size and SSD to the dose at a chosen point within a water phantom. The reference point and reference conditions for MOSFET dosimetry may differ from the beam calibration reference point and conditions. The MOSFET calibration factor is defined as the ratio of D_w (cal), the dose to water at the reference depth, to R(cal), the MOSFET reading, for the same MU and under the same reference conditions. D_w (cal) is determined from ion chamber measurements.

$$F_{cal} = D_w(cal) / R(cal)$$

It is recommended to calibrate the MOSFETs for each beam quality with which it is intended to be used.

2. CF_{ent} and CF_{ext} (entrance and exit dose correction factors):
The MOSFET is calibrated to measure the entrance dose, i.e. when positioned on the skin of the patient the measured dose should correspond to the dose to tissue at the depth of the maximum dose of the photon quality in use for a particular beam geometry. The ratio of the dose to MOSFET at D_{max} to the dose to the MOSFET with the build-up cap on the surface of the phantom on the entrance side was taken as CF_{ent}. Similarly, the ratio of the dose to MOSFET at D_{max} to the dose to the MOSFET with the build-up cap on the surface of the phantom on the exit side was taken as CF_{ext}.

$$CF_{ent} = R_{MOS,Dmax}/R_{mos,BUcap} \quad \text{(entrance side)}$$
$$CF_{ext} = R_{MOS,Dmax}/R_{mos,BUcap} \quad \text{(exit side)}$$

3. CF_{SSD} (SSD correction factor):
Three effects contribute to the SSD correction factor. One is the purely geometric effect of the different distances from source to ion chamber and source to MOSFET. The second effect is the instantaneous dose rate or dose-per pulse dependence of MOSFET response. The third effect is inadequate build-up, is dose from contaminant electrons. However, the clinical SSD correction factor includes all three effects and should be measured with the MOSFET exposed to the beam as it is for in vivo dosimetry.

It was determined as follows:

$$CF_{SSD} = (R_{IC,Dmax}/R_{MOS,BU})_{SSD} / (R_{IC,Dmax}/R_{MOS,BU})_{SSD = 100\ cm}$$

4. CF_{FS} (field size correction factor):
The field size correction factor relates the MOSFET readings to the total scatter factor, Sc, p.

It was determined as follows:

$$CF_{FS} = (R_{IC,Dmax}/R_{MOS,BU})_{FS}/(R_{IC,Dmax/RMOS,BU})_{FS = 10}$$

5. CF_{wedge} (wedge correction factor):
When wedges are placed, there is a change in the dose rate and also in the beam quality.

But MOSFET sensitivity does not depend on dose rate [3]. The wedge correction factor is expected due to the increased mean energy of the X-rays.

It was determined as follows:

$$CF_{wedge} = (R_{MOS,BU,10x10}/R_{IC,Dmax,10x10})/(R_{MOS,BU,wedge}/R_{IC,Dmax,wedge})$$

6. CF_{tray} (tray correction factor)

$$CF_{tray} = (R_{MOS,BU\ x\ ICDmax,Tray})/(R_{MOS,BU,Tray\ x\ ICDmax})$$

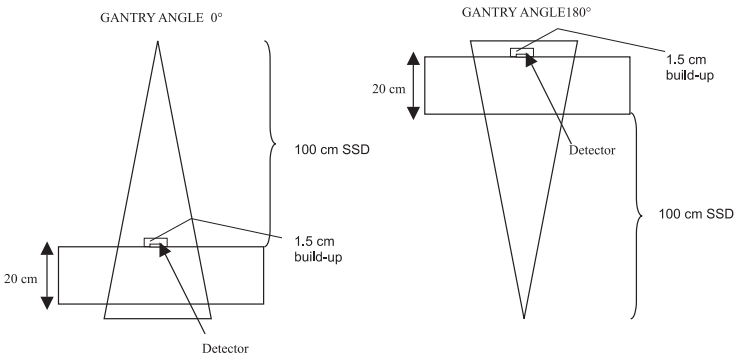

Fig. 3. Experimental setup for studying dependence on various factors

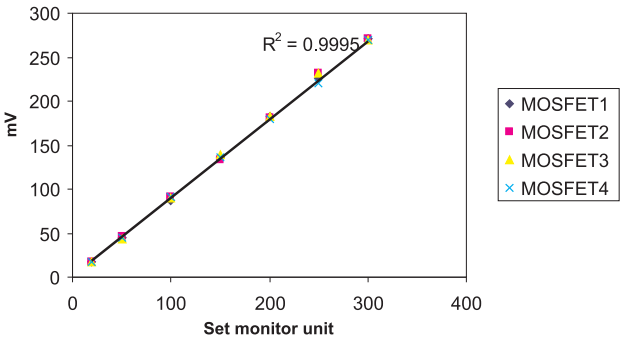

Fig. 4. Linearity for TN502RD dosimeters

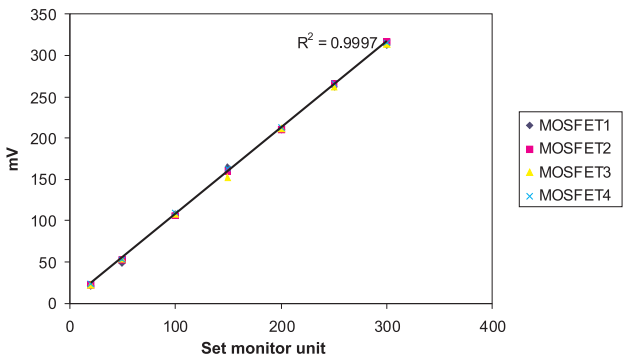

Fig. 5. Linearity for TN1002RD dosimeters

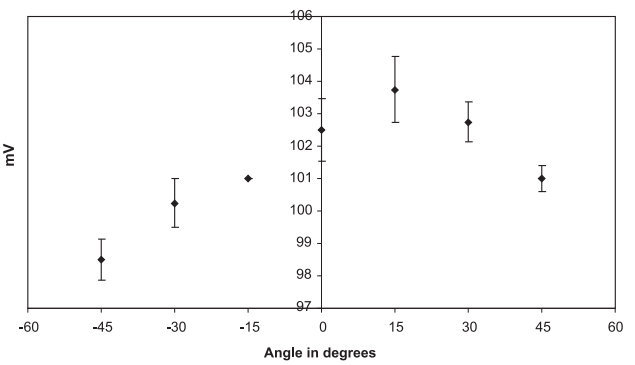

Fig. 6. Angular dependence of TN502RD dosimeters

RESULTS:

Readings of both the MOSFETs, TN502RD and TN1002RD, in mV for the reproducibility test are shown in Table I for four MOSFETs of each type. The reproducibility of the dosimeters was excellent, as indicated by the individual 15 readings, mean values for each dosimeter, their standard deviations, and overall mean of TN502RD and TN1002RD MOSFETs with standard deviations. Short- and long-term constancy test results for four dosimeters of each type are shown in Table II. Short-term constancy over a period of six days in the first week of a month and long-term constancy in terms of six weeks of six months were acceptable. Linearity of the TN502RD and TN1002RD MOSFET dosimeters is shown in Fig. 4 and 5 respectively and was excellent. Both the dosimeters indicated angular dependence in the range of angle from 315° to 45° as shown in Fig. 6 and 7 respectively. Results of energy dependence tests carried out for Co-60, 6 MV and 15 MV photon beams are shown in Table III. The response of the TN502RD and TN1002RD MOSFET dosimeters was higher for the 15 MV photon beam than for Co-60 and 6 MV photon beams for the same dose delivered to them. The dependence of the dosimeter response with SSD is shown in Fig. 8. The results indicated variation of MOSFET response over a SSD range of 80 to 120 cm. Field size dependence of both types of MOSFET dosimeters is shown in Fig. 9 and 10 in comparison to the ionization chamber. Both

Table 1. Reproducibility of the TN502RD and TN1002RD MOSFET dosimeters

S. No.	Readings in mV							
	TN502RD MOSFETs				TN1002RD MOSFETs			
	1	2	3	4	1	2	3	4
1	90	92	91	92	106	106	104	108
2	93	92	92	93	105	109	105	105
3	91	92	93	92	106	109	104	104
4	91	90	92	92	102	108	107	106
5	91	89	91	92	107	104	106	106
6	92	93	90	89	104	109	104	107
7	93	91	90	91	103	104	104	108
8	92	93	93	92	106	106	105	109
9	92	90	89	89	104	104	107	108
10	91	92	93	90	109	109	109	108
11	92	90	93	92	110	107	113	109
12	89	91	91	91	105	107	108	110
13	92	91	91	90	104	109	107	108
14	90	90	89	91	108	109	107	108
15	90	89	92	93	108	107	107	111
Mean	91.27	91.00	91.33	91.27	105.80	107.13	106.47	107.67
SD	1.16	1.31	1.40	1.28	2.27	1.96	2.42	1.84
Overall	Mean 91.22, SD 1.29				Mean 106.77, SD 2.12			

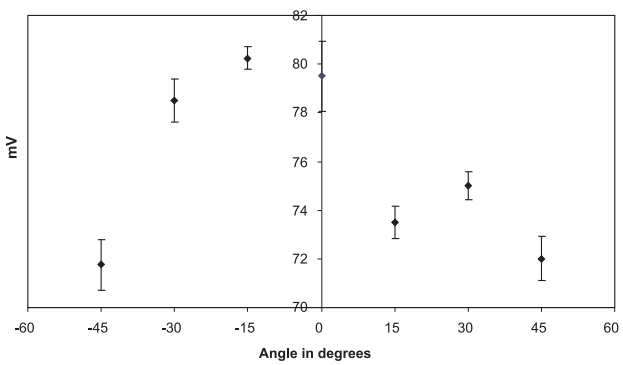

Fig. 7. Angular dependence of TN1002RD dosimeters

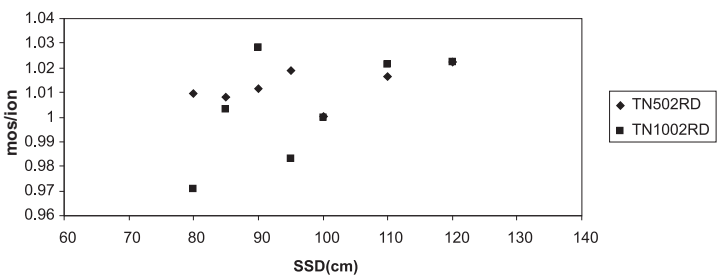

Fig. 8. SSD dependence of MOSFETs

types of dosimeters indicated similar field size dependence on ionization dosimeters.

The average dose measured by the ionization chamber at 5 cm depth and 20 cm depth in blue water was 82.77 cGy and 36.43 cGy respectively. The average MOSFET reading measured by the TN502RD entrance detector (5 cm) and TN1002RD exit detector (20 cm) was 91.3 mV and 106.77 mV. Hence the entrance and exit dose calibration factor for TN502RD detector and TN1002RD detector respectively is 0.9065mv/cGy and 0.3412mV/cGy. The SSD, field size and wedge correction factors for both TN502RD (entrance) and TN1002RD (exit) MOSFET dosimeters are shown in Fig. 11, 12 and 13 respectively. Shielding tray correction factors for TN502RD and TN1002RD MOSFETs are given in Table IV.

Table 2. Short term and long term constancy of the TN502RD and TN1002RD MOSFET dosimeters

Sr. No.	Readings in mV							
	TN502RD MOSFETs				TN1002RD MOSFETs			
	1	2	3	4	1	2	3	4
1	90	92	91	94	103	106	104	108
2	93	92	92	94	105	106	105	105
3	91	92	96	92	104	107	104	104
4	91	90	92	92	102	108	107	106
5	91	89	94	92	107	104	106	106
6	92	93	89	90	104	109	104	105
1	93	90	92	91	102	100	100	97
2	92	91	91	90	102	99	98	98
3	92	91	92	90	102	102	104	99
4	93	95	88	91	100	104	103	101
5	93	90	91	92	103	100	97	98
6	91	92	95	92	101	101	102	100
1	92	89	93	95	103	108	97	99
2	91	93	94	91	103	104	103	103
3	90	94	95	91	102	105	105	105
4	93	95	92	95	105	100	104	105
5	91	93	88	93	103	101	108	101
6	93	90	90	93	100	102	105	103
1	93	91	94	93	101	105	104	102
2	95	92	91	92	105	102	98	106
3	95	89	95	95	101	99	102	93
4	94	94	93	94	104	106	99	103
5	93	95	91	92	105	103	102	101
6	98	92	89	93	104	101	102	101
1	97	98	90	98	107	103	104	98
2	97	97	97	97	105	101	97	104
3	96	96	99	99	94	109	104	105
4	98	98	98	95	102	102	106	104
5	98	96	97	99	98	105	102	103
6	97	94	98	98	106	102	106	105
1	88	95	91	91	104	102	105	99
2	93	91	94	91	102	105	100	101
3	92	94	94	92	101	98	101	105
4	93	91	92	93	105	106	104	103
5	95	94	96	93	103	101	103	102
6	97	95	91	93	99	102	100	106
Mean	93.36	92.86	92.92	93.22	102.69	103.28	102.64	102.33
SD	2.55	2.50	2.86	2.47	2.56	2.93	2.92	3.23

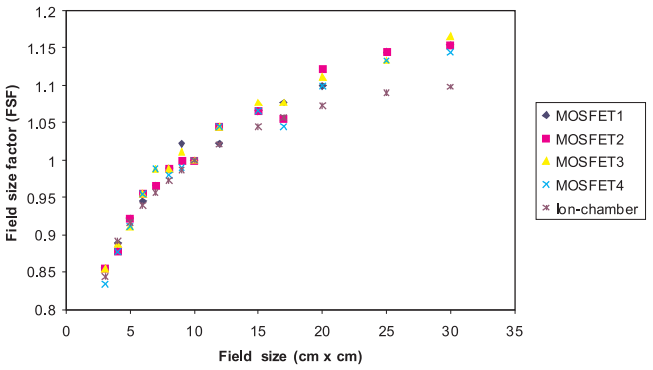

Fig. 9. Field size dependence of TN502RD MOSFETs

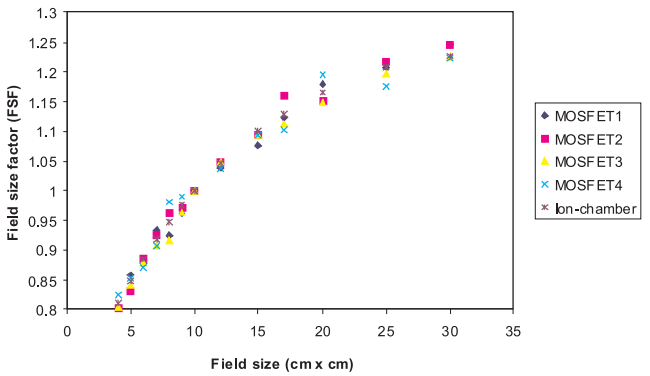

Fig. 10. Field size dependence of TN1002RD MOSFETs

Table 3. Energy dependence of the TN502RD and TN1002RD MOSFET dosimeters

S1. No.	Co-60 photons	6 MV X-ray photons	15 MV X-ray photons
	TN502RD MOSFETs (Readings in mV)		
M1	113	108	120
M2	113	107	124
M3	114	109	123
M4	116	110	121
	TN1002RD MOSFETs (Readings in mV)		
M1	93	90	95
M2	94	91	95
M3	93	90	97
M4	95	92	94

Table 4. Shielding tray correction factors for TN502RD and TN1002RD MOSFETs

Type of tray	Shielding tray correction factor (STCF)	
	TN502RD MOSFET	TN1002RD MOSFET
Solid	0.991	0.997
Slotted	0.993	1.000

DISCUSSION

Metal oxide semiconductor field effect transistor (MOSFET) dosimeters are increasingly used in radiation therapy and diagnostic radiology.

Ramani et al. [4] demonstrated the use of metal oxide silicon field effect transistors (MOSFETs) as clinical dosimeters for a number of patients with targets at different clinical sites. The doses determined both by thermoluminescence dosimetry (TLD) and MOSFETs in a clinical situation were evaluated and compared to expected doses determined by calculation. It was observed that a standard calibration of 0.01 Gy/mV gave MOSFET determined doses which agreed with expected doses to within 5% at the 95% confidence limit for photon beams. An energy-dependent variation in

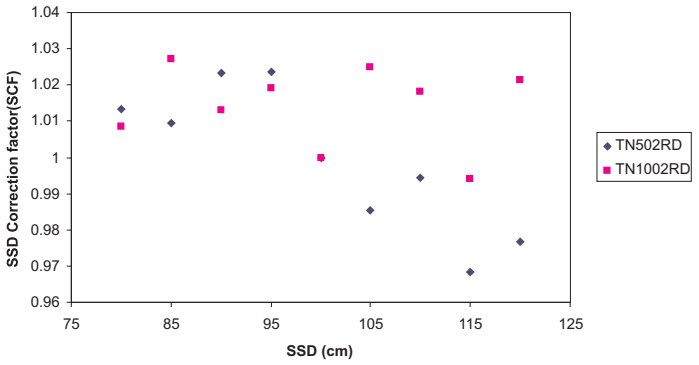

Fig. 11. SSD correction factors (SCF) forTN502RD and TN1002RD MOSFETs

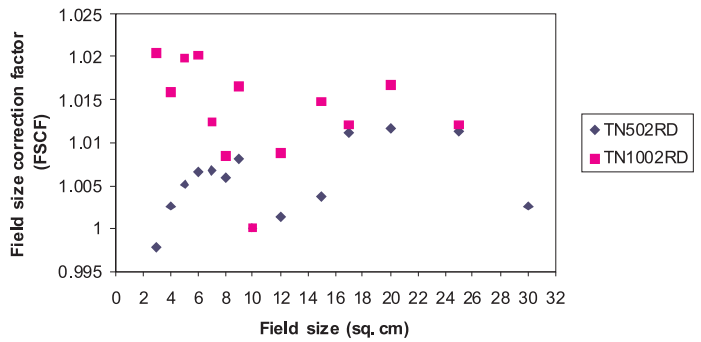

Fig. 12. Field size correction factors (FSCF) for TN502RD and TN1002RD MOSFETs

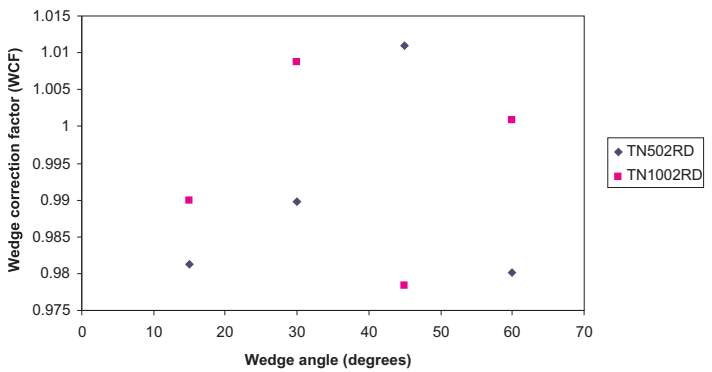

Fig. 13. Wedge correction factor (WCF) for TN502RD & TN1002RD MOSFETs

response of up to 28% was observed between two orientations of a MOSFET. It was concluded that MOSFETs can be used as clinical dosimeters and can be a good alternative to TLDs. However, they have limitations under certain clinical situations.

Scalchi et al. [1] calibrated metal oxide semiconductor field effect transistor (MOSFET) detectors to perform *in vivo* dosimetry during 6 MV treatments, both in normal setup and total body irradiation (TBI) conditions. MOSFET water-equivalent depth, dependence of the calibration factors (CFs) on the field sizes, MOSFET orientation, bias supply, accumulated dose, incidence angle, temperature, and spoiler-skin distance in TBI setup were investigated. MOSFET reproducibility was verified. The CFs varied linearly as a function of the square field side, for fields ranging from 5 x 5 to 30 x 30 cm^2. The MOSFET reproducibility was about 3% (2 SD) for the doses normally delivered to the patients. The effect of the accumulated dose on the sensor response was negligible. For beam incidence ranging from 0° to 90°, the MOSFET response varied within 7%. MOSFET characteristics were suitable for the *in vivo* dosimetry relevant to 6 MV treatments, both in normal and TBI setup.

With advanced conformal radiotherapy using intensity modulated beams, it is important to have radiation dose verification measurements prior to treatment. Metal oxide semiconductor field effect transistors (MOSFET) have the advantage of a faster and simpler reading procedure compared to thermoluminescent dosimeters (TLD), and with the commercial MOSFET system, multiple detectors can be used simultaneously. In addition, the small size of the detector could be advantageous, especially for point dose measurements in small homogeneous dose regions. To evaluate the feasibility of MOSFET for routine IMRT dosimetry, Cheung et al. [5] conducted a comprehensive set of experiments to investigate stability, linearity, energy, and angular dependence. For a period of two weeks, under a standard measurement setup, the measured dose standard deviation using the MOSFETs was ± 0.015 Gy with the mean dose being 1.00 Gy. For a measured dose range of 0.3 Gy to 4.2 Gy, the MOSFETs presented a linear response, with a linearity coefficient of 0.998.

Under a 10 x 10 cm^2 square field, the dose variations measured by the MOSFETs for every 10 degrees from 0 to 180 degrees was ± 2.5%. For IMRT dose verification, two special phantoms were designed. Preliminary results showed that the agreement between the dose measured by MOSFET and that calculated by Corvus was within 5% error, while the agreement between ionization chamber measurement and the calculation was within 3% error. They concluded that MOSFET detectors are suitable for routine IMRT dose verification.

Bulinski et al. [6] evaluated the metal oxide silicon field effect transistor (MOSFET) as an ionizing radiation dosimeter. Reproducibility as a function of dose and linearity were measured. The effects of energy, the direction of incident ionizing beam, field size and accumulated dose on the response of the detectors were investigated. A linear response as a function of the dose of the MOSFET detector was obtained. Reproducibility depended on the dose. For doses less than 20 cGy the reproducibility was about 6% (2 SD). For doses normally delivered to patients the reproducibility was about 3% (2 SD). The detector showed variation in sensitivity with energy of 3% over the energy range of 6-15 MV for X-rays and for cobalt 60 radiation. Similar variation in sensitivity with energy was obtained for high energy electrons in the range of 6-16 MeV. For a full angle the MOSFET detectors' sensitivity varied within 7%. Output factors measured with MOSFET agreed to within 1.5% of the output factors measured with an ion chamber. It was concluded by them that MOSFET detectors can be used as an ionizing dosimeter in radiotherapy and can be an alternative to TLDs and semiconductor detectors.

Dybek et al. [7] commented on the application of MOSFET detectors in photon beam dose measurements *in vivo* in radiotherapy. Before measuring doses *in vivo* parameters such as the dosimeter response to dose absorption, temperature, gantry angles and field side changes were determined using 6 MV and 15 MV photon beams. They concluded that MOSFET detectors are a useful tool for verifying the planned dose in external photon radiotherapy.

Jornet et al. [3] investigated the feasibility of dual bias dual metal oxide semiconductor field effect transistors (MOSFETs) for entrance *in vivo* dose measurements in high energy X-ray beams (18 MV). They were then calibrated for entrance in vivo dosimetry in an 18 MV X-ray beam. Calibration included determination of the calibration factor in standard reference conditions and of the correction factors (CF) when irradiation conditions differed from those of reference. Correction factors for field size, source surface distance, wedge, and temperature were determined. Intrinsic precision for MOSFETs for the high sensitivity mode was 0.7% (1 SD) as compared to 0.05% (1 SD) for the studied diodes. The linearity of the response with dose was excellent (R^2=1.000) for both *in vivo* dosimetry systems. The absolute values of the studied correction factors for the MOSFETs when covered by the different build-up caps were of the same order as those determined for the diodes. However, the uncertainties of the correction factors for MOSFETs were significantly higher than for diodes. They concluded that MOSFETs can be used for entrance *in vivo* dosimetry in high energy X-ray beams if covered by an appropriate build-up cap.

Rowbottom et al. [8] investigated the performance and characteristics of a miniature metal oxide semiconductor field effect transistor (micro-MOSFET) detector for its potential application to integral system tests for image-guided radiotherapy. In particular, the position of peak response to a slit of radiation was determined for the three principal axes to define the co-ordinates for the centre of the active volume of the detector. This was compared to the radiographically determined centre of the micro-MOSFET visible using cone-beam CT. Additionally, the angular sensitivity of the micro-MOSFET was measured. The micro-MOSFET response for 360° of rotation in the axial plane to the micro-MOSFET was ± 2%, consistent with values quoted by the manufacturer.

Ramani et al. [9] characterized the commercially available micro-MOSFET dosimeter for its dosimetric properties in radiotherapy treatments. The MOSFETs exhibited excellent correlation with the dose which was linear in the range of 5-500 cGy. No significant change in response was observed between 100 and 600 monitor units (MU) min^{-1} or change in

the dose per pulse. A uniform energy response was observed in the therapy range between 4 MV and 18 MV. However, below 0.6 MeV (Cs-137) the MOSFET response increased with the decrease in energy. At depth a single calibration factor obtained by averaging the MOSFET response over different field sizes, energies, orientation and depths reproduced the ion chamber measured dose to within 5%. The stereotactic and penumbral measurements demonstrated that the MOSFET could be used in a high gradient field such as IMRT. The study showed that the micro-MOSFET dosimeter could be used as an in-vivo dosimeter to verify the dose delivery to the patient to within ± 5%.

While it is difficult to characterize the dosimeter responses for monoenergetic sources by experiments, Wang et al. [10] reported a detailed Monte Carlo simulation model of the high-sensitivity MOSFET dosimeter using Monte Carlo N-Particle (MCNP) 4C. The angular dependence study showed that the MOSFET dosimeter has a higher response (about 8%) when photons come from the epoxy side compared with the Kapton side for a Cs-137 source.

Consorti et al. [11] investigated the use of metal oxide silicon field effect transistors (MOSFETs) as *in vivo* dosimetry detectors during electron beams in high dose-per-pulse intraoperative radiotherapy. The MOSFET system response in terms of reproducibility, energy, dose rate and temperature dependence, dose linearity from 1 to 25 Gy, angular response, and dose perturbation was analyzed in the 6–9 MeV electron beam energy range produced by an intraoperative radiotherapy-dedicated mobile accelerator. In experimental conditions, the overall uncertainty of the MOSFET response was within ± 3.5% (± SD). *In vivo* dosimetry results were in accordance with the predicted values within ± 5%. Metal oxide silicon field effect transistors are suitable for *in vivo* dosimetry during intraoperative radiotherapy because their overall uncertainty is comparable to the accuracy required in target dose delivery.

Wang et al. [12] presented a study to characterise a MOSFET dosimeter using the Monte Carlo simulation method. Monoenergetic photon beams ranging from 15 to 6 MeV were simulated to study the energy and angular dependences. The results were compared with published experimental data.

Ciocca et al. [13] reported the results of improvement of the effectiveness of in vivo dosimetry, based on a real-time check of the dose. Entrance dose was determined using micro-MOSFET detectors placed inside a thin, sterile, transparent catheter. The epoxy side of the detector was faced towards the beam to minimize the anisotropy. Each detector was plugged into a bias supply (standard sensitivity) and calibrated at 5 Gy using 6 MeV electrons produced by a conventional linac. Detectors were characterized in terms of linearity, precision and dose per pulse dependence. Excellent agreement between measured and expected doses was found. Real-time in vivo dosimetry appeared feasible, reliable and more effective than the method previously published.

We carried out the characterization and commissioning of low sensitivity TN502RD and high sensitivity TN1002RD MOSFETs for entrance and exit dosimetry for application in in-vivo dosimetry in radiotherapy. The MOSFETs were characterized in terms of reproducibility, short-term constancy, long-term constancy, linearity, angular dependence, energy dependence, SSD dependence and field size dependence. Both the MOSFETs showed excellent results. Commissioning of both MOSFETs was carried out in terms of entrance dose calibration factor, exit dose calibration factor, SSD correction factor, field size correction factor, wedge correction factor and shielding tray correction factor.

CONCLUSION

The use of MOSFET in in-vivo dosimetry has several advantages and unfortunately some disadvantages. The most important advantages are 1) simple calibration procedure, 2) immediate readout, 3) ease of maintenance, 4) very easy operation of the MOSFET system, 5) negligible dependence of the sensitivity on the temperature and accumulated dose, 6) small dependence of the sensitivity on the type and energy of radiation in the megavoltage range, 7) very small size of the detector which makes it especially useful for brachytherapy and for all measurements carried out in anthropomor-

phic phantoms, and 8) they do not have any dependency on impurities or environmental conditions and do not require packaging in comparison to TLDs. The disadvantages are 1) small reproducibility for small readings, 2) the relatively high angular dependence of the sensitivity, 3) use restricted by the length of the cable. In conclusion it can be said that MOSFET dosimetry is a cost-effective, easy to use technique and serves as a good alternative to TLD with certain limitations.

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