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NOTE

Effects of temperature variation on MOSFET dosimetry

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Abstract

This note investigates temperature effects on dosimetry using a metal oxide semiconductor field effect transistor (MOSFET) for radiotherapy x-ray treatment. This was performed by analysing the dose response and threshold voltage outputs for MOSFET dosimeters as a function of ambient temperature. Results have shown that the clinical semiconductor dosimetry system (CSDS) MOSFET provides stable dose measurements with temperatures varying from 15 °C up to 40 °C. Thus standard irradiations performed at room temperature can be directly compared to *in vivo* dose assessments performed at near body temperature without a temperature correction function. The MOSFET dosimeter threshold voltage varies with temperature and this level is dependent on the dose history of the MOSFET dosimeter. However, the variation can be accounted for in the measurement method. For accurate dosimetry, the detector should be placed for approximately 60 s on a patient to allow thermal equilibrium before measurements are taken with the final reading performed whilst still attached to the patient or conversely left for approximately 120 s after removal from the patient if initial readout was measured at room temperature to allow temperature equilibrium to be established.

1. Introduction

In vivo measurements of applied dose during radiotherapy treatment are important to ensure accurate dose delivery to patients. Assessment of dose for radiotherapy applications is performed with various types of detectors which are used in specific applications depending on the physical and radiation characteristics (Metcalfe *et al* 1997, Butson *et al* 2003). A MOSFET device has the feature of integrating dose measurements as well as allowing

immediate dose readout (Thomson *et al* 1984). Combining this with a very small sensing volume provides many advantages for a MOSFET dosimetry system in radiotherapy. As such, MOSFET detectors are finding applications in radiotherapy dosimetry (Butson *et al* 1996, Bloemen-van Gurp *et al* 2003, Kron *et al* 2002, Rosenfeld 2002, Chuang *et al* 2002, Quach *et al* 2000).

A MOSFET's dosimetric ability relies on the measurement of its threshold voltage. By applying a sufficiently large voltage to the MOSFET's silicon gate, a significant number of holes will be attracted to the oxide/silicon surface from the silicon substrate as well as the source and drain regions. When a sufficient concentration of holes has accumulated, a conduction channel is formed, allowing current to flow between the source and drain. The voltage necessary to initiate current flow is known as the threshold voltage. Further information is available in Rosenfeld *et al* (2001). When a MOSFET device is irradiated, three things occur within the detector's active volume: a build-up of trapped charge in the oxide; an increase in the number of interface traps; and an increase in the number of bulk oxide traps. These physical characteristics produce a change in the device's threshold voltage and, as such, a measurement for absorbed dose can be performed by comparison of threshold voltages, before and after irradiation. To be performed with a high degree of accuracy, the time of measurement before and after irradiation should be kept constant. One limiting factor in the use of MOSFETs for *in vivo* dosimetry is the inherent thermal error intrinsic to MOSFET devices (Savic *et al* 1995, Rosenfeld *et al* 2001), which can shift the threshold voltage of the device as a function of temperature. Work has been performed to incorporate a temperature measurement device and correction circuit; however, this can be limited by differences in temperature between the MOSFET and measuring probe (Rosenfeld 2002). This can limit the accuracy of the MOSFET detectors especially at low applied doses where the shift as a percentage of total measurement increases. We investigate the effects of temperature on dose measurement using the clinical semiconductor dosimetry system (CSDS).

2. Materials and methods

The CSDS evaluated for temperature effect is a commercially available system manufactured by the Centre for Medical Radiation Physics (CMRP), University of Wollongong, NSW Australia. It employs an integrating MOSFET with two p-MOSFET devices on the same chip, which are sourced from REM Oxford UK (Holmes-Siedle 2001). The system is capable of reading 10 MOSFETs on line with results sent directly to computer via an RS232 connection. A dual bias MOSFET probe can be used which employs k-type and r-type MOSFETs (Rosenfeld *et al* 2001) with gate bias voltage of +12 and +5 V respectively. Experiments were performed to analyse the effects of temperature variations on both the threshold voltage readout produced by the system as well as the dose response of the system. Temperature variations were performed with the use of 'cold' and 'heat' packs and experiments were performed with temperatures ranging from 15 °C up to 45 °C. Cold packs were water filled bags which were refrigerated to given temperatures. Heat packs were water filled rubber containers with water heated to varying temperatures. The MOSFETs were taped to the heat and cold packs during experimental procedures next to a small temperature probe to measure the temperature at the MOSFET device position. The effects of temperature were measured for variations in initial temperature, irradiation temperature and readout temperature. Doses were delivered using a 6 MV x-ray beam produced by a Varian 2100C linear accelerator. Heating and cooling times were analysed *in vivo* using a sample of patients and various sites of measurement. The MOSFETs were taped to the patients skin and on-line variations in threshold voltage measured as a function of time.

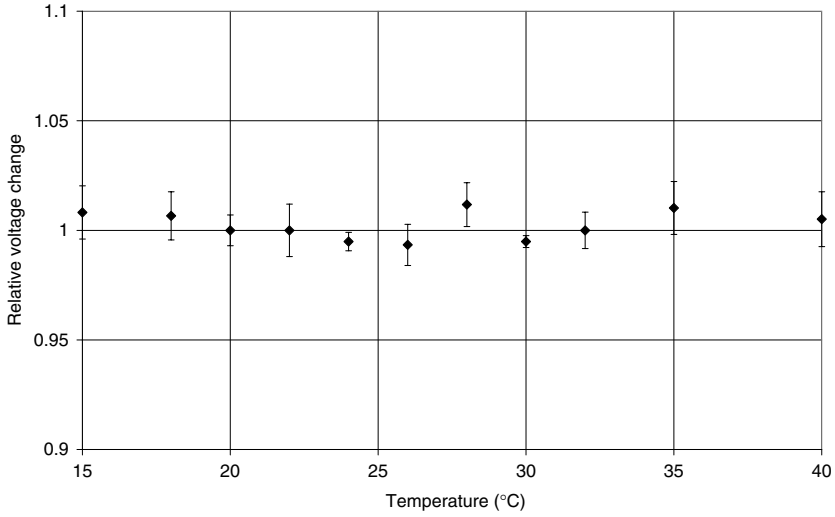

Figure 1. The relative threshold voltage change as a function of temperature when exposed to a dose of 100 cGy.

3. Results and discussion

Figure 1 shows results for relative dose measurement response for the CSDS MOSFETs as a function of ambient temperature. Results are normalized to 1 at 20 °C and range from 15 °C up to 40 °C which would cover all clinical treatment temperatures as well as *in vivo* body temperature assessments. A constant dose of 100 cGy was applied at all temperatures. As can be seen a negligible effect on dose response is seen for the CSDS with less than $\pm 1.5\%$ (1SD) variations seen for all temperatures with no trends in relative measurement output seen. Quoted errors are one standard deviation for 10 measurements made at each temperature. Both initial and final threshold voltage measurements were made with the MOSFET detector kept at the quoted temperature and the device had been kept in thermal equilibrium at the quoted temperature for the entire irradiation and readout process.

This is an important point, which is highlighted by figure 2 showing the measured threshold voltage for the MOSFET dosimeter as a function of temperature. Results are quoted for one typical MOSFET detector, with an applied dose history of approximately 100 Gy. The detector shows the inherent and intrinsic variation in threshold voltage as a function of temperature for MOSFET dosimeters. A variation of 50 mV is recorded for the dosimeter over the temperature range of 20–40 °C. This relates to a dose of approximately 8–10 cGy in high sensitivity mode.

If a MOSFET undergoes a large temperature change after its initial threshold voltage readout and before final readout, discrepancies in measured dose could be seen. Table 1 shows results for relative voltage change as initial, irradiation and readout temperatures are varied. If the initial voltage and readout voltage are the same, negligible differences in the relative voltage change are seen, which is also independent on irradiation temperature. However, if there is a variation in the initial readout temperature and final readout temperature, large differences in relative output are seen. The size of this variation or error is dependent on the magnitude of the temperature change. Thus any experimental and *in vivo* measurements should be made with the MOSFET detector at the same temperature and in thermal equilibrium for initial readout and final readout. Performing measurements in this manner will eliminate discrepancies due to large temperature shifts during the measurement period. As thermal

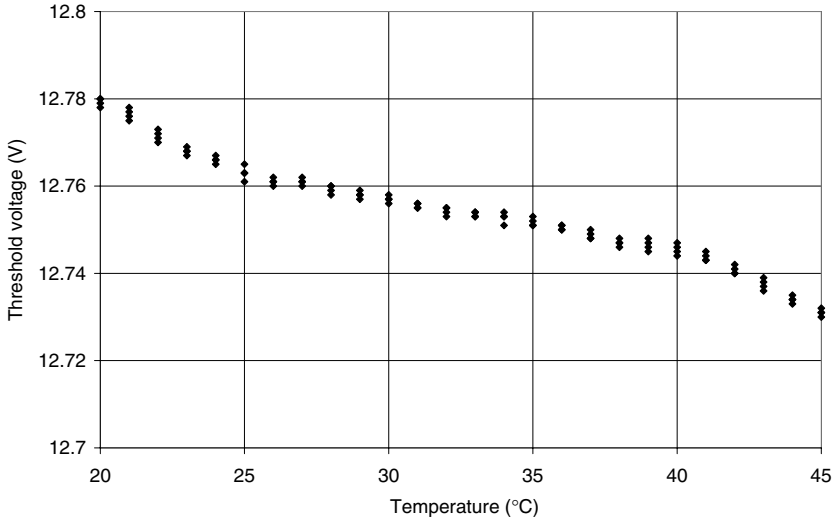

Figure 2. The variation in threshold voltage for a typical MOSFET detector as a function of temperature. Up to 50 mV variation is seen over a 25 °C temperature change. The use of multiple symbols at each temperature shows the variation in measured voltage at each given temperature.

Table 1. Temperature effects on relative MOSFET output for pre- and post-irradiation temperature changes.

Initial temperature (°C)	Irradiation temperature (°C)	Readout temperature (°C)	Relative voltage change
22	22	22	1
22	30	22	0.992
22	30	30	0.939
30	30	30	1.012
30	30	22	1.055
22	35	22	0.995
22	35	35	0.938
35	35	35	1.003
35	35	22	1.082
22	45	22	1.016
22	45	45	0.904
45	45	45	1.009
45	45	22	1.103

equilibrium is required for correct dosimetry, experiments were performed to analyse heating and cooling times for the CSDS MOSFET probes *in vivo*.

Figure 3 shows results for both 'heating' and 'cooling' of a CSDS MOSFET detector when it is placed directly on a patient's skin or removed after treatment. Time $t = 0$ represents the time when the detectors were either placed on the patient (heating) or removed from the patient (cooling). Results show that the threshold voltage in this case reduces when cooling takes place after removal from patient's skin and increases when placed on the skin surface. As can be seen, the degree of variation is dependent on the final equilibrium temperature of

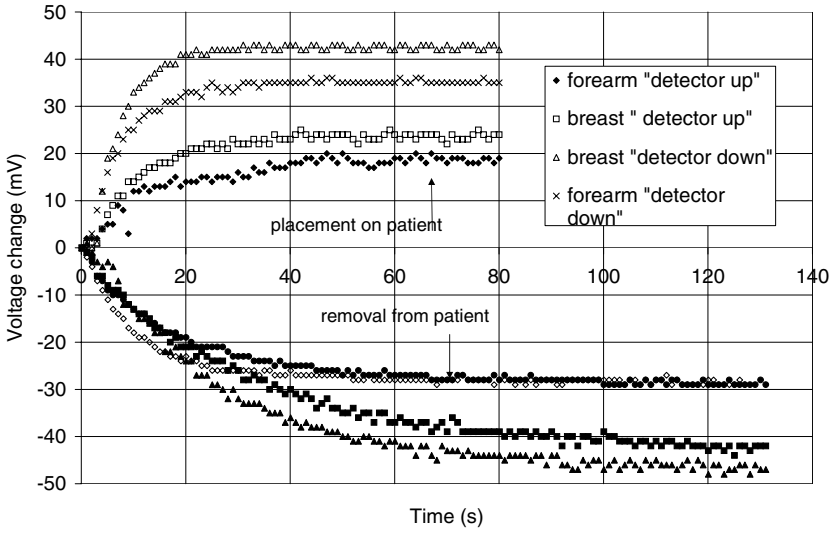

Figure 3. Variations in threshold voltage for a typical MOSFET probe as a function of time for heating and cooling effects produced by placement on and removal from patients.

the patient-specific contact site with larger variation seen for higher temperature change. The temperatures quoted in figure 3 (e.g. forearm 30 °C) represent the measured temperature at the site of detector placement as measured with a thermometer. Ambient room temperature was 21 °C during these experiments. Results also show that the required time for thermal equilibrium for heating, which occurs when the detectors are placed onto a patient, is approximately 30 s when the detector is taped detector down and approximately 60 s when taped detector up. When the detector is removed from the patient and allowed to cool down in ambient room conditions approximately 120 s is required to reach thermal equilibrium. Thus, if the threshold voltage is to be measured on the patient we would recommend leaving the CSDS MOSFET probes attached in place for approximately 1 min before an initial threshold voltage is measured and the final threshold voltage measured whilst the detector is still attached to the patient after the irradiation is finished. This, of course, should also be performed at a constant time interval after irradiation. Conversely, if the threshold voltage is measured before it is placed on the patient, the detector should be left for approximately 2 min after removal before the final threshold voltage readout is performed. As the dose response of these detectors seems to be temperature independent, either method could be used; however, we would recommend the latter procedure for dose analysis, thus minimizing any errors caused by fluctuations in MOSFET probe temperature caused by varying thermal contact with the patient. Using this method, no temperature corrections need to be applied to threshold voltage for dose analysis using the CSDS system.

Similar MOSFET systems are available for clinical use such as the Thomson and Neilson (Ramani *et al* 1997, Soubra *et al* 1994). As this system was not available for testing by the authors we are unable to comment whether these results are intrinsic to the CSDS MOSFET system or generic for other systems. Often in clinical practice, *in vivo* detectors are employed with the use of bolus material (Butson *et al* 2000, Kudchadker *et al* 2002). Bolus material may influence the heating and cooling characteristics of the MOSFET device and as such could vary the required time for thermal stabilization. Based on these variables we would recommend that if the MOSFET is used in conjunction with a bolus material further measurements be

performed to establish the appropriate thermal equilibrium time for the MOSFET for each specific bolus material.

4. Conclusion

When the same initial and final temperatures for the readout process are applied, the SCDS MOSFET has been shown to have a relatively temperature-independent output when the irradiation temperature is varied. Calibration measurements performed at room temperature can be used with sufficient accuracy with clinical measurement at higher body temperatures, given that the probe is in thermal equilibrium for each case. The MOSFET probes do require a length of time up to 2 min in some cases to reach thermal equilibrium when placed on or removed from areas of large temperature changes to minimize errors in measurement caused by intrinsic changes in the measured threshold voltage with temperature.

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