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TECHNICAL REPORT

# Evaluation of MOSFETs for entrance dose dosimetry for 6 and 10 MV photons with a custom made build up cap

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## Abstract

Commercially available MOSFETs, Thomson and Nielsen TN502-RD, were evaluated for suitability as an entrance dose in vivo dosimeter for 6MV and 10MV. Detector response was normally distributed around a mean (skewness=-0.01±0.24, kurtosis=-0.09±0.48) with a mean of 110.6 mV/Gy, with a standard deviation of 2.4% at 0.86 Gy. The standard deviation of readings increased with decreasing dose and increased at a rate greater than inverse square. The linearity coefficient was 0.9999. No significant dependence on angle, field size, dose rate, energy or time was observed. As such, they would be useful for entrance dose in vivo dosimetry. With a custom made build up cap corrections were required for field size, wedge, beam energy and tray factors, showing that build up cap design is an important consideration for entrance dose in vivo dosimetry using MOSFETs.

**Key words** MOSFET, in vivo dosimetry, radiotherapy, entrance dose

## Introduction

Entrance dose in vivo dosimetry has traditionally been performed with TLD's and diodes. As it is usually carried out at the start of treatment it is a useful tool for finding errors in the treatment chain which could be left undetected[1]. Diode entrance dose in vivo dosimetry has become more popular than TLD in vivo dosimetry due to the convenience of the instantaneous read out[2]. Results from large scale studies have been published for diodes showing the increased number of measurements that instant readings can make[1]. Implementing in vivo dosimetry with diodes is well established with ESTRO[3] and the AAPM[2] giving practical guidelines for the use of diode in vivo dosimetry. Both of these guides stress the importance of using build up caps on the detector to minimise influences brought about by the increased electron contamination near the surface with high energy photon beams. This contamination can lead to significant SSD and field size dependence for build up cap correction factors.

Typically, results from entrance dose in vivo dosimetry are spread around a mean with a standard deviation ranging from "1.2 % to 4.1 % (typically 1.5 – 3 %), depending on site and linac."[3].

MOSFETs have been used in a wide range of applications as their small collecting volume and size make them an excellent choice of detector for point dose measurements in regions where there is a high dose gradient. Due to these characteristics they have been shown to be useful in IMRT QA[4] as well as for penumbral dose checks[5]. They have also been employed as small field size detectors in radiotherapy[6].

More recently they have come under scrutiny as a useful entrance dose in vivo dosimetry tool[5,7]. The results have shown excellent linearity, directional dependence and dosimetric accuracy in the build-up region for high energy photons. They have no dose rate or temperature dependence[7,9], and can be read instantly[5]. They have been shown to be similar to diodes in terms of their absolute measurement error for an 18 MV beam, when placed beneath a build up cap[7].

MOSFETs have been shown to be useful as an implantable detector for testing in situ tumour dose during radiation therapy treatment[8].

For a small department a set of MOSFETs can be used for multiple purposes. This makes them a handy QA tool for evaluating plans or procedures. The thin cable also allows them to be placed in phantoms without creating large air gaps. They have small size and would therefore not pertubate dose near or around the MOSFET. Diodes used for entrance dose in vivo dosimetry are designed for a specialised use, wheras the same set of MOSFETs in a small department can be used from IMRT QA to entrance dose in vivo dosimetry by changing the phantoms they are

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placed in. This means that if entrance dose in vivo dosimetry is possible with MOSFETs in a department with small equipment overheads it is possible to meet the requirements for several QA practices with the same set of equipment.

In this study a custom made build up cap was investigated for entrance dose in vivo dosimetry for 6 and 10 MV using the Thomson and Nielsen TN-502RD isotropic MOSFETs set to the standard bias setting.

## Materials

### Thomson and Nielsen dosimetry

Thomson and Nielsen TN-502RD isotropic MOSFETs were used. The Patient Dosimetry Reader was the TN-RD-10. The bias supply was the NT-RD-22 dual sensitivity bias supply. The bias setting was set to normal (approximately 100mV/Gy).

Two separate bias options are available on the dual sensitivity bias supply, normal and high. The normal setting is useful for doses measured greater than 100cGy, while the high bias setting is useful for lower doses[10].

The voltage required to give a current from the MOSFET is called the threshold voltage. When the MOSFET is irradiated electron-hole pairs form. Some recombine, while the mobile electrons travel to the positive terminals. The remaining holes move slowly and become trapped at the Si-$SiO_2$ interface[9]. This causes a difference in threshold voltage as the trapped holes have a positive charge. The difference in threshold voltage as well as the absolute threshold voltage are given by the Patient Dosimetry Reader. The reader therefore needs to be zeroed between measurements.

### Ion chambers

Photon measurements were performed with a 0.6cc NE2571 Farmer type ion chamber in either water, CIRS Plastic Water® or RW3. A Wellhofer CC15 cylindrical ion chamber was used in water for field size, wedge and tray factors. Cylindrical ion chamber measurements were carried out with the effective point of measurement being 0.6r above the centre of the ion chamber[11].

### Phantoms

Specially milled RW3 was used to hold the MOSFETs during constancy and calibration measurements. The RW3 was milled from a 30 cm x 30 cm x 1 cm slab, with 5 grooves placed in the slab 0.5 mm deep leading to a central groove 2.0 mm deep and 7.0 mm long.

Two separate cylindrical angular dependence phantoms, one 2.6 cm and one 5.1 cm in radius respectively were used. Both were manufactured from clear acrylic. The 2.6 cm radius acrylic phantom was manufactured from a cylindrical acrylic rod with a 2.0 mm diameter hole drilled in the middle. The 5.1 cm radius phantom was milled in two halves with a groove down the middle leading to a rectangular hole. The hole was filled with wax to remove air spaces.

For both of these phantoms the MOSFET was placed in the central part of the cylinder. The angle of zero degrees was when the bulb of the MOSFET was facing the beam.

### Build up cap

The build up cap was made from aluminium. It consisted of a milled 8.00 mm hemisphere, with a 3.00 mm flat bottom below. The 3.00 mm bottom had a groove milled into it that fitted the MOSFET (Figure 1). As the density of Aluminium is 2.7 times that of water, the 8 mm depth corresponds to approximately 2.15 cm in water for high energy photons. This is slightly more than Dmax for 6 MV (1.50 cm), and slightly less than Dmax for 10 MV (2.50 cm). Aluminium is a good choice of material for a build up cap as MOSFETs have energy dependence for low energy photons, increasing in sensitivity by up to 3 times at around 50 keV[12], to 4.5 times at 75kV[5]. They are therefore more likely to be affected by characteristic radiation from higher Z materials.

Thomson and Nielsen offer a hemispherically milled high energy photon cap made of brass. The diameter of this cap is 6.35 mm. As the density of brass is 8.5 g/cm[3]. This corresponds to approximately 5.4 cm depth in water for high energy photons. As this is equivalent to quite a substantial depth the build up cap shadow would have a large underdose for 6 and 10 MV. Thomson and Nielsen also have water equivalent build up caps. These caps are hemispherical and come in sizes of 1.0, 1.5 and 2.0 cm. They would be larger, but would provide a similar water equivalent build up depth to the aluminium. Aluminium would therefore be a good choice as it would reduce size, while not increasing low energy scatter or characteristic radiation.

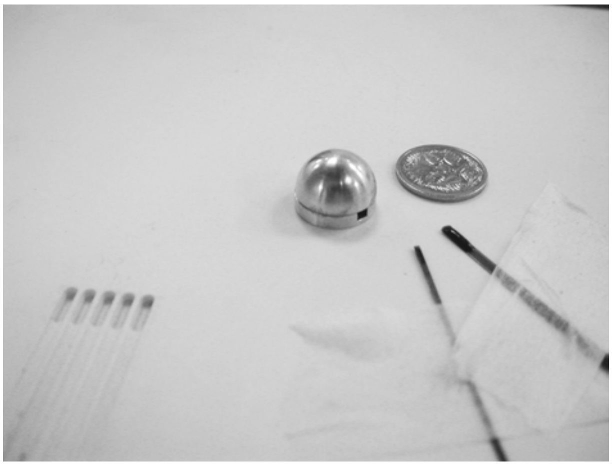

**Figure 1.** *Build up cap with TN-502RD (standard), TN-1002RDM (micro) MOSFETs and Milled RW3 slab.*

## Methods

### MOSFET measurements

TN-502RD MOSFETs were tested for linearity, constancy, reproducibility, angular dependence, and dose rate (SSD). For all MOSFET measurements the orientation was with the build up facing up.

Linearity, constancy and reproducibility measurements were carried out at 5.0 cm depth with a 10 cm x 10 cm field size, with 4 MOSFETs in a 6 MV beam. SSD and energy dependence were carried out at Dmax for 6 MV and 10 MV.

The dose, number of measurements, average reading (mV) and standard deviation of the linearity measurements is given in Table 1.

**Table 1.** *Linearity measurements.*

| Dose MU | N | Average reading mV | 3σ % |
|---|---|---|---|
| 20 | 28 | 18.3 | 21.9% |
| 50 | 20 | 48.3 | 8.8% |
| 100 | 52 | 95.4 | 7.3% |
| 200 | 8 | 189.0 | 6.3% |
| 400 | 4 | 391.5 | 2.4% |

Constancy and reproducibility measurements were performed before each use of the MOSFETs for the first six months of use. The MOSFETs were placed in a RW3 jig and irradiated with 100 MU. This corresponds to 0.861 Gy. The individual MOSFET reading, as well as the average reading of all four MOSFETs was taken (Figure 3).

SSD measurements were carried out by placing the MOSFETs in the RW3 jig and adjusting the SSD from 80 to 115 cm. The results were compared to ion chamber (ROOS) measurements at the same depth with the same SSD's in a RW3 jig.

Angular dependence was carried out with the MOSFET at the isocentre. Measurements were made in 15 degree increments in a 2.6 cm radius acrylic phantom from -90 degrees to + 90 degrees for 10 MV. For 6 MV angular dependence was carried out in 30 degree increments from -90 degrees to +90 degrees in the 2.6 cm radius phantom and in 15 degree increments from 0 to 90 degrees in the 5.1 cm radius phantom. The number of monitor units was kept constant in this range.

**Build up cap measurements**

Measurements were made with a MOSFET placed in the build up cap for 6 and 10 MV to determine whether correction factors were required with a build up cap.

The entrance dose calibration factor was the ratio of the dose measured at Dmax with a MOSFET to the dose measured in the build up cap with a MOSFET at 100 cm SSD.

The field size factor, wedge factor, SSD dependence and tray factors were compared to ion chamber measured factors. The ratio of the ion chamber factor to the MOSFET factor is the correction factor.

For SSD correction factor measurements the ROOS ion chamber was kept with the effective point of measurement at a depth of 1.5 cm for 6 MV and 2.5 cm for 10 MV. This is the depth of dose maximum for these energies at 100 cm. The SSD was then adjusted between 85 and 115 cm SSD. The ion chamber reading was taken. MOSFET readings were taken for 6 MV and 10 MV with the MOSFET in the build up cap with the bulb facing upwards for SSD ranges of 85 to 115 cm SSD. The MOSFET reading was divided by the ion chamber reading. The ratio of these readings was normalised by the average ratio of the MOSFET reading to ion chamber reading.

Field size correction factor measurements were performed for field sizes from 3x3 to 30x30 cm$^2$. Wedge correction factor measurements were measured for all hard wedges (15, 30, 45 and 60 degrees). These factors were measured with the bulb facing toward the outside of the build up cap surface at 100 cm SSD.

As the build up cap is symmetrical around the centre and the angle of incidence of the beam never greater than 90 degrees, the angular dependence was checked from 0 to 75 degrees in 15 degree increments. For all angles the number of MU was kept constant. The results were normalised by dividing the MOSFET readings by the average reading. The SSD was kept constant at 100 cm.

**Errors**

For MOSFET measurements and graphs the error was taken at the standard deviation (1σ).

## Results

### MOSFETs

***Angular, field size, energy, SSD, and linearity***

All 4 MOSFETs were linear, with r=0.9999 over the range of doses 17 cGy to 345 cGy. These doses are within the range of typical entrance dose in-vivo dosimetry measurements. There would therefore not be any need to correct for linearity with entrance dose measurements.

SSD dependence was less than 2% over the SSD range of 80 cm to 110 cm. As the SSD correction is over the clinical range of SSD's and there is no correction required for SSD there would not be a dose rate dependent factor for MOSFETs.

Angular dependence was less than 2% for both 6 MV and 10 MV. This would not be necessary for entrance dose in vivo dosimetry measurements as the build up cap would add an inherent angular dependence of its own. The build up cap could be modified so that the angular dependence was removed by custom shaping the cap. As no noticeable angular dependence was observed the build up cap shape was chosen as hemispherical.

No field size dependence was observed in the field size range of 3x3 cm to 25x25 cm.

Energy dependence was less than 2% between 6 MV and 10 MV. This shows that MOSFETs could be used for mixed-energy treatment checks in a phantom. As the build up cap would attenuate the different energy beams in different ways entrance dose measurements would require independent correction factors for different energies. Using the incorrect energy would therefore result in a different

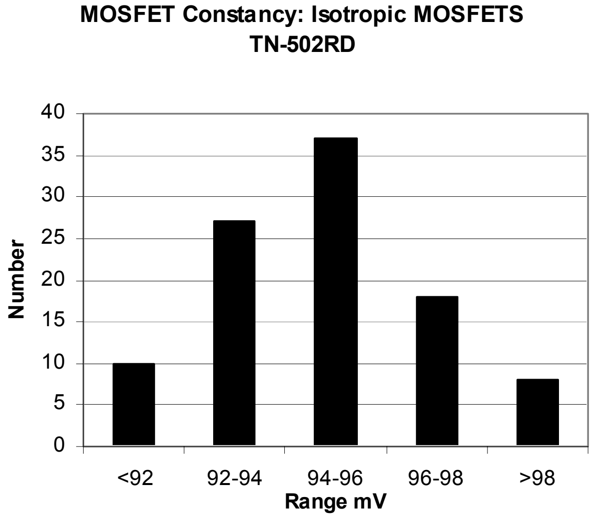

**Figure 2.** *Histogram of constancy results.*

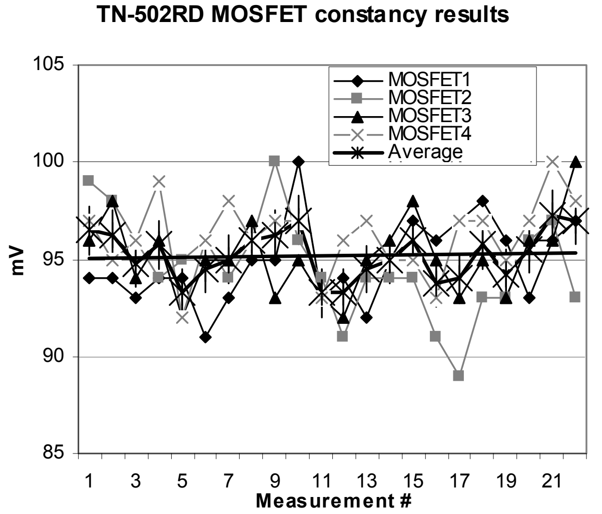

**Figure 3.** *Graph of constancy results from 4 TN-502RD MOSFETs.*

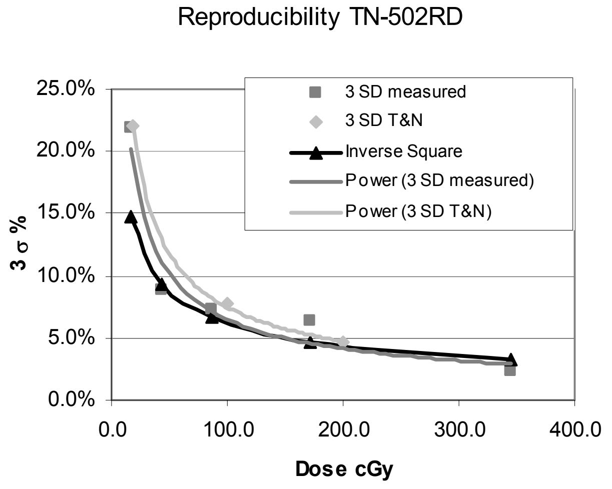

**Figure 4.** *Relationship between dose and a 3σ as a % for Thomson and Nielsen TN-502RD MOSFETs.*

entrance dose reading which can be picked up and traced to the incorrect energy.

### *Constancy*

MOSFET constancy measurements were made over a period of 6 months. Measurements were made on separate days to ensure that systematic errors were minimised.

Results of repeated measurements showed that the MOSFET readings did not decrease with accumulated dose over the lifetime of the MOSFET (Figure 3). They were also normally distributed around a mean, with a skewness and kurtosis of -0.01±0.24 and -0.09±0.48 respectively (Figure 2).

### *Dose-reproducibility relationship*

The standard deviation of measurements increased with decreasing dose. From Figure 4 the three lines going from lightest to darkest are estimates of the standard deviation based on a power law relationship. From these one can see that the measured standard deviation (grey) decreases faster than an inverse square (black) relationship with increasing dose.

This is observed for 3σ measurement standard deviations in the Thomson and Nielsen technical document[10] as well as measurements made on the TN-502RD isotropic MOSFET (Table 2, Table 3).

As a result of this relationship the standard deviation associated with a single measurement was taken as 1 standard deviation based on a power law relationship and not inverse square as the inverse square would fail if the ratio of doses was too large.

For multiple measurements the standard deviation of the group of measurements is taken.

**Table 2.** *Reproducibility Vs dose: users guide.*

| Dose | 3σ T&N[10] |
|---|---|
| 20 cGy | 22% |
| 100 cGy | 7.8% |
| 200 cGy | 4.1% |

**Table 3.** *Reproducibility Vs dose: measured.*

| Dose | 3σ Measured |
|---|---|
| 17 cGy | 21.9% |
| 43 cGy | 8.8% |
| 86 cGy | 7.2% |
| 172 cGy | 6.3% |
| 345 cGy | 2.4% |

## Results

### Build up cap

### *Entrance dose correction factor*

The entrance dose correction factor was 1.008 ± 0.8% for 6 MV and 1.088 ± 0.5% for 10MV. As these correction factors are approximately 8% different to each other an

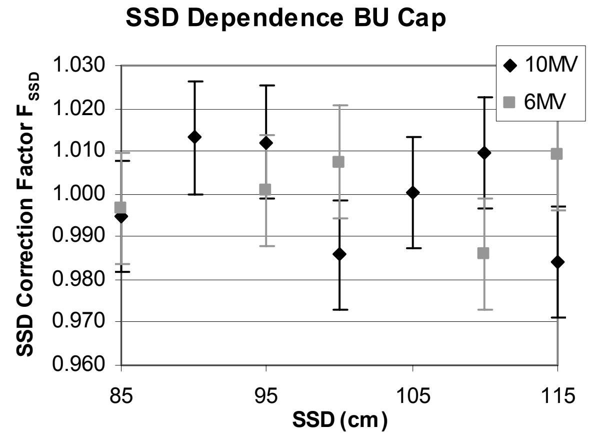

**Figure 5.** *SSD Dependence of MOSFET in Al Build Up Cap.*

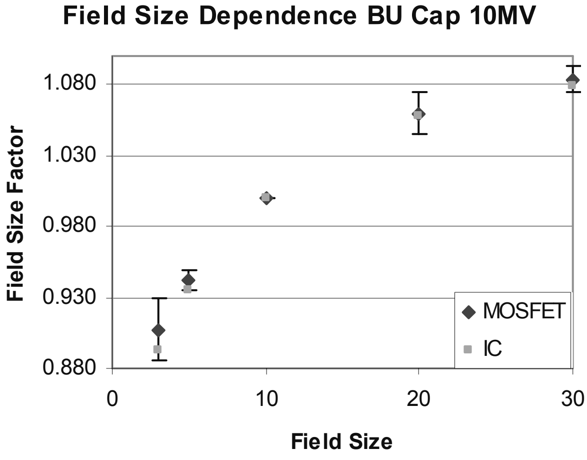

**Figure 6.** *Field size dependence for 10 MV in Al Build Up Cap.*

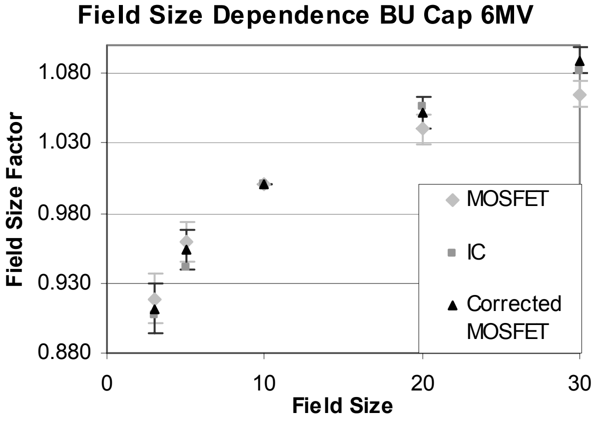

**Figure 7.** *Field size dependence for 6 MV in Al Build Up Cap.*

incorrect beam energy delivered or selected would be picked up during routine entrance dose in vivo dosimetry. If the build up cap was designed so that the entrance dose correction factor was similar for both these energies it would not be possible to distinguish between different energies and potential mistakes that would be picked up in in vivo dosimetry could get through.

***Build up cap shadow***

A large build up cap shadow would lead to an underdose immediately below the build up cap. For this reason, having a small build up cap would reduce the size of the shadow. Another factor would be the effective build up of the material above the shadow. A dense material would attenuate more of the beam than a less dense material. The AAPM[2] guidelines give an estimate of 5 to 6% as a minimum that should not be exceeded. The shadow of the build up cap was 4% for 10 MV and 6% for 6 MV. This is within the guidelines set by the AAPM[2].

***SSD correction***

The SSD correction was less than 2% from 85 cm to 115 cm SSD for both 6 MV and 10 MV (Figure 5). This is less than the typical SSD correction of 4 to 6% found for different build up caps in 18 MV beams[7], and similar to Isorad, EPD and QED diodes in 6 MV beams[2] over the same range of SSDs. As MOSFETs have no dose rate dependence there would not be a dose rate dependent contribution to SSD dependence. One would still expect the contribution from the SSD's of the actual measuring position to make a difference. The difference in position of the measuring points would be the difference between Dmax below the surface of the phantom and 3 mm above the surface for the MOSFET. If the SSD dependent factor was 1.00 with the surface for 100 cm SSD, the MOSFET, being closer to the source would increase its dose relative to Dmax below the surface at a faster rate than the ion chamber as it is closer to the source. This contribution is small in relation to the MOSFET uncertainty, contributing less than 1% difference in the range 85 to 100 cm SSD and less than 0.5% difference for the range 100 to 115 cm SSD for 6 and 10 MV. For the MOSFET SSD measurements the standard deviation of results was 1.6%. This effect could be present, but as the MOSFET has large uncertainty compared to this effect it could be hidden. Electron contamination is also a major contributing factor for SSD dependence. It would be hard to account for small differences in electron contamination as well as scatter contributions for the build up cap. As there was no noticeable SSD correction trend no SSD correction will be made.

***Field size correction***

No field size correction was necessary for 10 MV (figure 6), but a correction factor of 1.1% per 10 cm$^2$ field size was required for 6 MV (equation 1, figure 7). Over the clinical range of field sizes this amounts to about 4%. Typical diode field size correction factors range from 2 to 6% depending on diode type and energy[3]. The results from field size correction factor measurements with the build up cap show that field size correction measurements should be made prior to implementing in vivo dosimetry with a build up cap with MOSFETs even if no field size dependence is present without a cap.

$$CF_{FS} = 1 + (FS - 10) \times 0.00112 \tag{1}$$

**Table 4.** *Wedge correction factors.*

| Wedge angle | Wedge correction factor | | Uncertainty | |
|---|---|---|---|---|
| | 6 MV | 10 MV | 6 MV | 10 MV |
| 15 | 0.997 | 0.992 | 0.014 | 0.014 |
| 30 | 1.004 | 1.003 | 0.011 | 0.013 |
| 45 | 0.994 | 1.020 | 0.012 | 0.021 |
| 60 | 1.030 | 1.044 | 0.015 | 0.021 |

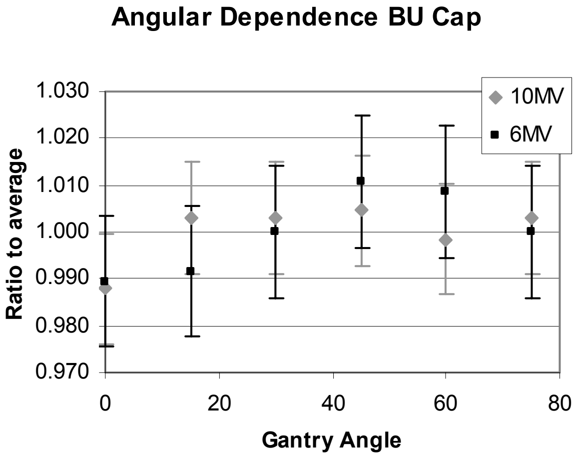

**Figure 8.** *Angular dependence of MOSFET in Al Build Up Cap.*

***Wedge correction factor***

Wedge correction factors were generally less than 2% for wedges' angles less than 45°, but the build up cap underestimated wedge factors for both 6 MV and 10 MV for wedges with high wedge angles (Table 4). For both 6 and 10 MV 60 degree wedges the correction factor was greater than the measurement uncertainty. Correction factors would therefore need to be included if one were to implement entrance dose measurements using this build up cap and high wedge angles.

***Angular dependence***

Angular dependence of the build up cap was less than 2% for both 6 MV and 10 MV over the range of 0 to 75 degrees (Figure 8). As there was no obvious angular dependence in this range angular dependence correction factors were not introduced.

***Tray correction factor***

Tray correction factors were 0.971 for 6 MV and 1.007 for 10 MV. As the 6 MV correction factor is greater than 2% it would be necessary to introduce it for entrance dose measurements with the build up cap.

## Discussion

As diodes give a larger signal per unit dose than any other detector their precision is high. The typical measurement uncertainty for relative measurements with diodes in phantoms is of the order of 0.2%[7]. This is far less than the typical measurement uncertainty for relative measurements with MOSFETs of 1.0%[7].

As MOSFETs have a large measurement uncertainty any trend that was not greater than 2% for MOSFETs was not included in the correction factors for the MOSFETs. For field size corrections for 6 MV the correction factor was no greater than 2%, but drifted from 0.985 to 1.020 that of the ion chamber for a 30x30 and 5x5 field size respectively. As this relationship was present and was approximately linear the field size correction factor was added based on a least square linear approximation. When the linear correction was made the maximum and minimum ratio of measured field size factors changed to 1.014 and 0.996 for 5x5 and 20x20 field sizes respectively. For 10 MV the field size correction factor was less than 1% different for all measurements but the 3x3 cm correction factor, which was less than 2% different. There was no linear trend present so field size correction factors were not included.

The depth of Dmax will change with SSD, but the SSD of a single depth (100 cm SSD Dmax) was chosen for all SSD's. Comparison of 6 MV commissioning PDDs taken at 85 and 100 cm SSD show that even though the Dmax position changes from 1.4 to 1.5 cm from 85 to 100 cm respectively the difference in PDDs between these two points is less than 0.2%. Over the range 1.2 to 1.7 cm on a smoothed PDD the maximum difference is only 0.3%. This is because around Dmax the PDD is flat and has a low slope. Small changes in depth will therefore make small changes to the dose measured. For 10 MV the peak is broader and the same argument can be used. Changing the depth of the Dmax position with change in SSD would therefore not be necessary as the minimum error that would be picked up by the MOSFET is of the order of 1%.

Correction factors could also change with SSD. This was not covered as part of this study.

## Conclusion

The average $\sigma$ for a 1.00 Gy measurement is 2.5%. This is the same range as a typical in vivo dosimetry results (1.5-3%). Thomson and Nielsen TN502 RD isotropic MOSFETs can be used with a build up cap for external beam entrance dose in vivo dosimetry with the bias set to normal, and would deliver results that are similar to current results with diodes.

Appropriate correction factors need to be measured for entrance dose in vivo dosimetry with high energy photon beams when a build up cap is used, even when these correction factors are not necessary when there is no build up cap. Correction factors for field size and hard wedges need to be measured. The uncertainty of a measurement depends on the dose received and decreases with increasing dose at a rate greater than $D^{-0.5}$, where D is the dose received in cGy. This can be important for fields receiving a small dose as the uncertainty in measurement can be large ($\sigma$=3.9% for 50 cGy). This large uncertainty could compromise measurement accuracy for low dose entrance dose measurements. Multiple measurements would therefore need to be made, or the bias increased to account for the large standard deviation.

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