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Practical issues regarding angular and energy response in in vivo intraoperative electron radiotherapy dosimetry

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ABSTRACT

Aim: To estimate angular response deviation of MOSFETs in the realm of intraoperative electron radiotherapy (IOERT), review their energy dependence, and propose unambiguous names for detector rotations.

Background: MOSFETs have been used in IOERT. Movement of the detector, namely rotations, can spoil results.

Materials and methods: We propose yaw, pitch, and roll to name the three possible rotations in space, as these unequivocally name aircraft rotations. Reinforced mobile MOSFETs (model TN-502RDM-H) and an Elekta Precise linear accelerator were used. Two detectors were placed in air for the angular response study and the whole set of five detectors was calibrated as usual to evaluate energy dependence.

Results: The maximum readout was obtained with a roll of 90° and 4 MeV. With regard to pitch movement, a substantial drop in readout was achieved at 90°. Significant overresponse was measured at 315° with 4 MeV and at 45° with 15 MeV. Energy response is not different for the following groups of energies: 4, 6, and 9 MeV; and 12 MeV, 15 MeV, and 18 MeV.

Conclusions: Our proposal to name MOSFET rotations solves the problem of defining sensor orientations. Angular response could explain lower than expected results when the tip of the detector is lifted due to inadvertent movements. MOSFETs energy response is independent of several energies and differs by a maximum of 3.4% when dependent. This can limit dosimetry errors and makes it possible to calibrate the detectors only once for each group of energies, which saves time and optimizes lifespan of MOSFETs.

Abbreviations: ANOVA, analysis of variance; CF, calibration factor; GH, Games–Howell test; IOERT, intraoperative electron radiotherapy; MOSFET, metal oxide semiconductor field effect transistor; T, Tukey's test.

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1. Background

Intraoperative electron radiotherapy (IOERT) is a highly selective technique. It is aimed at restricted anatomic volumes during surgical oncology treatment and consists of single fraction irradiation with a high delivered absorbed dose after direct visual examination of the tumour bed by means of an electron beam, taking care to separate adjacent normal tissue. IOERT can improve the therapeutic index because it permits direct visualization of the tumour and, thus, a more accurate definition of the target volume. At the same time, IOERT can exclude the dose-limiting normal tissues by means of separation or protection of organs and energy selection.[1] Currently, it is being revisited and reported on intensively.[2–8]

In vivo dosimetry is desirable for verification, recording, and eventual correction of treatment. This has led to recommendation of its use.[9,10] Detectors based on metal oxide semiconductor field effect transistors (MOSFETs) have been investigated for these purposes.[11–14] However, in vivo IOERT dosimetry is challenging because of tumour bed irregularities, flooding, and detector movement. In fact, large unexplained deviations in dosimetric assessment[12–14] arise and may be associated with the factors mentioned. Focusing on detector movement, a set of studies has evaluated MOSFET angular response with photons[15–25] and electrons.[11,12,26]

Consorti et al.[11] measured variation in detector response to within ±2% at different incident angles inside a cylindrical polystyrene buildup cover 6 mm thick. They used both TN-502RD and TN-502RDM MOSFETs (Best Medical Canada Ltd., Ontario, Canada). Ciocca et al.[12] placed TN-502RDM MOSFETs on a phantom surface and measured an up to 20% increase for oblique versus normal incidence at 30° when the beam was directed onto the flat side of the MOSFET, and an increase of always less than 4% corresponding to the epoxy side of the detector facing the beam. However, Bloemen-van Gurp et al.[26] studied TN-502RD MOSFETs and found a variation of up to 3.2% in a cylindrical phantom, whereas a variation of only within 3% was measured with the surface phantom setup.

Although Ciocca et al. measurements[12] are somewhat different than Bloemen-van Gurp et al. values,[26] all these results proved to be useful to characterize MOSFET response when it is tightly attached to an IOERT tumour bed. However, to date, no author has reported how this kind of detector could behave if surrounded by air. This situation may arise because of tumour bed relief and/or detector unintended lifting or detachment. In addition, as pointed out by Cygler and Scalchi,[27] there is no standardized way of defining sensor orientations, which could lead to a misunderstanding of published results.

With regard to energy dependence of MOSFETs, Consorti et al. affirmed that electron beam energy did not influence the detector response,[11] Ciocca et al. considered it when they reported absorbed dose to patients,[12] and Bloemen-van Gurp et al. also took it into account.[26] Therefore, in the opinion of the authors, MOSFETs energy dependence needs further investigation.

2. Aim

To report intrinsic angular response of the detector in the realm of IOERT in order to find out whether it could be a factor of dosimetry failure when the circumstances cited below are present and to show a close view of the energy dependence and its implications. Appropriate and unequivocal names for the three possible rotations of the detector in space are also presented.

3. Materials and methods

Seven reinforced mobile MOSFETs (model TN-502RDM-H; Best Medical Canada Ltd., Ontario, Canada) were used in the present study. Reinforced MOSFETs are made to enhance the mechanical endurance of the detector and named with the suffix H. The authors are unaware of whether this MOSFET submodel was actually used in the studies cited above as they did not report the submodel label.

3.1. *Proposal on the names of the rotations*

It is possible to use the expressions that describe the three possible rotations of an aircraft in the air if the detector has one dimension longer than the other two and this dimension is oriented like the body of the aircraft (Fig. 1). In this case, the roll motion is the rotation around the longitudinal axis of the detector; the pitch motion occurs when the detector moves up and down (analogously to the movement of the aircraft around the pitch axis, which is parallel to the plane of the wings); and the yaw motion is the remaining rotation movement, which does not cause a variation to the relative orientation of the beam and the sensitive element of the detector. Once this convention is established, we will not refer to the aircrafts' system of reference anymore and will set the sign of the axis and the angles according to our study.

3.2. *Angular response*

One naked MOSFET and one MOSFET sheathed by the tip of a bronchial catheter (Elekta AB, Stockholm, Sweden) were placed in air at the linac isocenter (Elekta Precise, Elekta AB, Stockholm, Sweden) under a 10 cm × 10 cm electron applicator. This linac is the machine used for IOERT procedures in our institution. Accordingly, the catheter used was the same unique model we always used in in vivo dosimetry to ensure

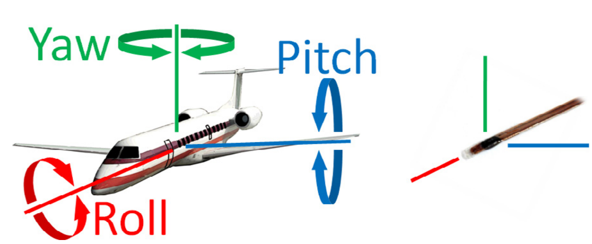

Fig. 1 – Sketch showing aircraft rotation movements (left), which can be used to describe MOSFET (right) rotations when aligned appropriately.

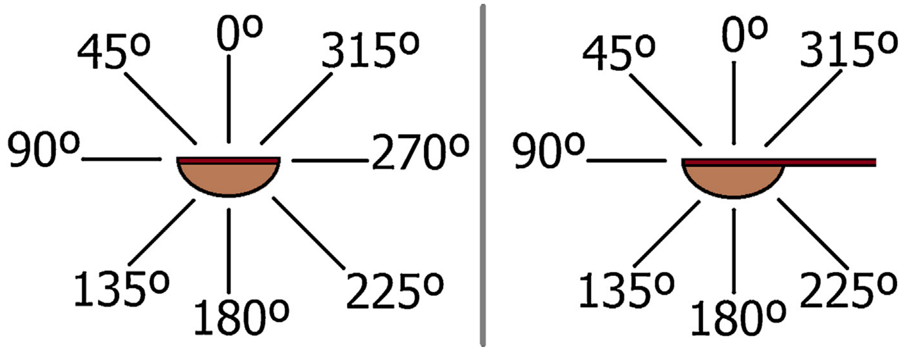

Fig. 2 – Angle convention used in our study: roll on the left and pitch on the right. In the case of roll, the observer faces the tip of the detector with the cable behind it.

sterility, independently of energy beam. Energies of 4 MeV, 9 MeV, and 15 MeV were used in order to achieve a reasonable sampling of detector response taking into account linac availability in our institution and MOSFETs depletion. The readout was recorded three times in voltage units. In all measurements 100 monitor units (MU) were delivered. All the readings were carried out with the standard bias setting (the lower of the two available biases). As minimum IOERT electron field used by us (40 mm in diameter) was several times wider than MOSFET (1.5 mm), there were no expected effects caused by small fields[28] and we did not include field size as a variable in our angular study. Moreover, the applicator diameter used in our in vivo procedure with patients was equal or greater than 60 mm 94% of the times.

Hereafter, an angle of 0° will be assumed to be the standard orientation stated by the manufacturer, that is, with the beam directed onto the flat side of the MOSFET and perpendicular to it. Angle convention is depicted in Fig. 2. In the case of roll, the observer faces the tip of the detector with the cable behind it. Between successive changes of the irradiation angle, the setup was verified not to experience inadvertent rotations of either the naked or the sheathed MOSFET. The uncertainty of type A associated with the reproducibility of the measurements was assessed with a coverage factor k equal to 2, which represents a generalization of a range of two standard deviations in the normal distribution as a confidence level whatever the distribution.[29]

3.3. *Energy response*

Firstly, linac output was determined according to the standard calibration protocol.[30] Secondly, 5 cm of plastic water—The Original (CIRS, VA, USA) was placed on the linac couch to achieve appropriate backscatter equilibrium. Then, five MOSFETs were placed on their calibration jig over the first block. Finally, the set was placed under the 10 cm × 10 cm electron applicator at a source-surface distance of 100 cm with the necessary slabs to place the detectors at the reference depths stated by the mentioned protocol.[30] They were 1, 1.5, 2.2, 2.9, 3.6, and 4.2 cm for 4, 6, 9, 12, 15, and 18 MeV, respectively. Consequently, we used the entire range of energies available in our linac to determine in vivo absorbed dose to patients with an accuracy higher than the one which would have been obtained with a *per-MOSFET* calibration only. The calibration factors (CF, in units of mV/Gy) were measured five times. Then, they were subjected to statistical analysis in terms of the energy and the specific MOSFET used. Type A uncertainty associated with CF determination was also estimated.

4. Results

4.1. *Angular response*

Initially we found a ratio of mean readouts coming from the two MOSFETs used in this section arranged as naked or sheathed at a roll of 0° and a pitch of 0° not greater than 1.01 and not statistically significant ($p \geq 0.555$). As a result, no correction for MOSFET was applied in this section. After that, one MOSFET was used naked and the other sheathed not to deplete any of them over the whole test.

Readouts at 0° roll and 0° pitch were 75.9 ± 2.2 mV, 81.0 ± 0.6 mV, and 86.8 ± 0.5 mV for 4 MeV, 9 MeV, and 15 MeV, respectively, with the naked MOSFET. We obtained readouts of 79.9 ± 0.7 mV, 86.1 ± 1.9 mV, and 92.9 ± 2.0 mV for 4 MeV, 9 MeV, and 15 MeV, respectively, with the sheathed MOSFET. When an analysis of variance (ANOVA) was carried out with the readouts obtained with roll angles, we found that the results were significantly affected by this rotation ($p \leq 0.002$). ANOVA for pitch results showed that this rotation affected readout significantly as well ($p = 0.000$). Then, Levene's test for equality of variances of the readouts led us to run multiple comparisons of readouts according to angle (28 combinations for roll and 21 for pitch) using Tukey's test (T) when assuming equal variances, or the Games–Howell test (GH) when assuming different variances.

Roll—naked MOSFET: With respect to findings significantly different from 0°, we found 45° for 4 MeV ($p = 0.000$ (T)) and 9 MeV ($p = 0.000$ (T)); and 45°, 225°, and 315° for 15 MeV ($p \leq 0.017$ (GH)).

Roll—sheathed MOSFET: In terms of findings significantly different from 0°, we found 90° in the case of 4 MeV ($p = 0.002$ (GH)).

Pitch—naked MOSFET: Moving from 0° to 45° or 315° caused a significant change except in the case of 15 MeV for 315° ($p = 0.541$ (T)).

Table 1 – Orientation angle value, (°); expanded uncertainty of the readouts with coverage factor, k, equal to 2, $u(\Delta V)$; readout differences with respect to the orientation of reference, diff. in ΔV; and level of significance obtained with post hoc tests with respect to 0°, p (in bold when significant, see Section 4 on type of test). T and GH stand for Tukey's test and Games–Howell test, respectively.

Angle (°)	4 MeV			9 MeV			15 MeV		
	$u(\Delta V)$ (mV) (k = 2)	Diff. in ΔV	Test, p	$u(\Delta V)$ (mV) (k = 2)	Diff. in ΔV	Test, p	$u(\Delta V)$ (mV) (k = 2)	Diff. in ΔV	Test, p
Naked MOSFET									
Roll			T			T			GH
45	1.8	23.2%	**0.000**	2.8	17.3%	**0.000**	1.8	13.7%	**0.017**
90	4.4	2.4%	0.930	3.3	3.6%	0.610	1.7	2.7%	0.417
135	1.9	0.5%	1.000	0.6	2.6%	0.880	1.7	3.2%	0.305
180	0.7	−1.3%	0.998	1.0	0.0%	1.000	4.1	2.5%	0.926
225	2.0	−3.3%	0.760	3.5	3.2%	0.738	0.3	3.2%	**0.008**
270	1.5	−0.6%	1.000	2.4	−0.1%	1.000	4.8	0.4%	1.000
315	1.3	−6.2%	0.122	1.8	3.9%	0.547	0.4	5.2%	**0.001**
Pitch			T			T			T
45	1.3	12.5%	**0.000**	0.5	7.4%	**0.000**	1.4	7.6%	**0.008**
90	0.5	−45.2%	**0.000**	1.7	−27.7%	**0.000**	2.9	−14.4%	**0.000**
135	1.7	4.5%	0.060	0.4	5.9%	**0.001**	1.7	5.8%	0.056
180	0.7	−1.3%	0.960	1.0	0.0%	1.000	4.1	2.5%	0.763
225	0.5	5.7%	**0.012**	1.1	4.3%	**0.011**	0.7	5.7%	0.059
315	2.1	−10.6%	**0.000**	1.9	−7.2%	**0.000**	0.6	−3.2%	0.541
Sheathed MOSFET									
Roll			GH			T			GH
45	1.6	−1.3%	0.903	3.0	−4.6%	0.365	3.8	−5.2%	0.486
90	0.2	13.3%	**0.002**	3.2	5.8%	0.153	1.5	1.4%	0.943
135	1.2	−1.0%	0.914	3.5	−1.9%	0.979	1.6	−0.7%	0.999
180	2.4	−2.0%	0.857	0.3	−4.5%	0.393	0.9	−1.2%	0.925
225	1.2	−4.9%	0.063	2.1	−5.4%	0.215	0.7	−4.6%	0.179
270	1.7	−3.6%	0.279	0.6	−3.2%	0.771	2.0	−4.2%	0.292
315	3.8	−8.1%	0.299	3.1	−5.4%	0.212	1.5	−4.7%	0.172
Pitch			GH			GH			T
45	0.7	0.2%	1.000	0.6	2.4%	0.515	1.5	7.7%	**0.000**
90	1.7	−48.8%	**0.000**	2.4	−38.8%	**0.000**	1.2	−26.9%	**0.000**
135	1.8	0.5%	0.998	1.2	−1.5%	0.860	1.2	0.0%	1.000
180	2.4	−2.0%	0.826	0.3	−4.5%	0.197	0.9	−1.2%	0.899
225	0.5	1.2%	0.444	0.4	1.2%	0.885	0.9	0.1%	1.000
315	0.8	10.9%	**0.001**	1.5	3.6%	0.322	1.8	1.5%	0.816

Pitch—sheathed MOSFET: With respect to findings significantly different from 0° we found 90° and 315° for 4 MeV ($p \leq 0.001$ (GH)), only 90° for 9 MeV ($p = 0.000$ (GH)); and 45° and 90° for 15 MeV ($p = 0.000$ (T)).

All details are presented in Table 1, whereas comparisons among other angles are summarized in Table 2. A graphical representation of all readouts is depicted in Fig. 3.

Different readouts of the naked MOSFET at a roll of 45° show the asymmetry of the intrinsic angular dependence. The setup with a sheath, used in IOERT to preserve sterility of the surgical bed, tends to smooth results. In this case, a maximum readout is obtained with a roll of 90° and 4 MeV (13.3% higher than the reference). Deviations of up to 5% appeared as insignificant due to detector readout uncertainty. A minimum readout around 8% lower than the reference was obtained at a roll of 315° with 4 MeV (not statistically significant). With regard to pitch movement, a substantial drop in readout was achieved at 90°. Significant overresponse was measured at 315° with 4 MeV and at 45° with 15 MeV.

4.2. *Energy response*

A two-way ANOVA showed a significant dependence of CFs on energy ($p = 0.000$) and not on the MOSFET used ($p = 0.131$) nor an interaction of both variables ($p = 0.970$). Focusing then on energy dependence, since the Levene's test resulted significant for different variances of CFs among energies ($p = 0.002$), we performed a Games–Howell test to identify the groups of energies which induced no significant changes in CFs. At a confidence level of 95% they were 4, 6, and 9 MeV; and 12, 15, and 18 MeV. A summary of the data is presented in Table 3, with the p-values and mean CF differences expressed in percentages concerning every energy pair. As can be seen, the maximum difference in mean CF within groups corresponds to −1.6% in the case where 4 MeV and 6 MeV are compared. 6 MeV and 18 MeV did not cause significant different CFs but they cannot be grouped with the other energies of any formed group.

The relative type A uncertainty associated with the reproducibility of the CFs ranged from 0.5% to 2.4% ($k = 2$), obtained both with MOSFET no. 1 and 12 MeV and 18 MeV, respectively.

Table 2 – MOSFET tested, energy in MeV, kind of movement and post hoc test, result of comparison for the majority of detector responses, and result of comparison for the rest of angles. T and GH stand for Tukey's test and Games–Howell test, respectively. Distinct responses are highlighted in bold.

MOSFET	Energy (MeV)	Movement and test	Majority of responses	Rest of responses and corresponding angles (°) in the comparison	
Naked	4	Roll, T	Equal $p \geq 0.079$	Different	45 among all, $p = 0.000$ 90 and 315, $p = 0.014$
		Pitch, T	**Different** $p \leq 0.012$	**Not Different**	0 and 135, $p = 0.060$ 0 and 180, $p = 0.960$ 135 and 225, $p = 0.972$
	9	Roll, T	Equal $p \geq 0.521$	Different	45 among all, $p = 0.000$
		Pitch, T	**Different** $p \leq 0.011$	**Not different**	0 and 180, $p = 1.000$ 45, 135, and 225, $p \geq 0.093$
	15	Roll, GH	Equal $p \geq 0.051$	Different	0 and 315, $p = 0.001$ 0, 45, and 225, $p \leq 0.034$ 45 and 90, $p = 0.012$ 45 and 135, $p = 0.014$ 225 and 315, $p = 0.020$
		Pitch, T	Equal $p \geq 0.056$	Different	90 among all, $p = 0.000$ 0 and 45, $p = 0.008$ 45 and 315, $p = 0.000$ 135 and 315, $p = 0.002$ 225 and 315, $p = 0.002$
Sheathed	4	Roll, T	Equal $p \geq 0.052$	Different	90 among all, $p \leq 0.034$ **Except 315, $p = 0.052$**
		Pitch, GH	Equal $p \geq 0.052$	Different	90 among all, $p \leq 0.001$ 315 among all, $p \leq 0.039$
	9	Roll, T	Equal $p \geq 0.153$	Different	90 among all, $p \leq 0.028$ **Except 0, $p = 0.153$**
		Pitch, GH	Equal $p \geq 0.069$	Different	90 among all, $p \leq 0.006$ 45 and 180, $p = 0.002$ 180 and 225, $p = 0.001$ 180 and 315, $p = 0.041$
	15	Roll, GH	Equal $p \geq 0.108$	Different	90 and 225, $p = 0.045$ 90 and 315, $p = 0.043$ 180 and 225, $p = 0.044$
		Pitch, T	Equal $p \geq 0.227$	Different	45 among all, $p \leq 0.001$ 90 among all, $p = 0.000$

Table 3 – Summary of the comparison among the mean CFs classified by energies: level of significance of the energy dependence for each pair, *p* (in bold when significant, Games–Howell test), on the left and difference in percentage of the average of every CF evaluation per energy on the right.

Compared energies (MeV)		*p*	Mean CF difference
4	6	0.065	−1.6%
	9	0.262	−1.2%
	12	**0.000**	−3.1%
	15	**0.000**	−3.4%
	18	**0.000**	−2.9%
6	9	0.979	0.4%
	12	**0.020**	−1.6%
	15	**0.006**	−1.9%
	18	0.138	−1.3%
9	12	**0.001**	−2.0%
	15	**0.000**	−2.3%
	18	**0.013**	−1.7%
12	15	0.923	−0.3%
	18	0.980	0.3%
15	18	0.726	0.6%

This last quantity is only 1% less than the maximum deviation between CFs in absolute value, which is 3.4%.

5. Discussion

5.1. *Technical considerations*

With respect to angular response, regardless of the inconsistencies cited above,[12,26] literature has shown correct performance of MOSFETs in the area of IOERT and in analogue situations. In addition, their response has been considered as equivalent for all detectors of the same model.[11,12,18,26,31,32] However, certain treatment sites and postures may induce displacement of MOSFETs.[13] To be more explicit, if the sheathed MOSFET is well attached to the tumour bed, one could expect little variation with an angle of incidence of the beam up to 45°, a range that covers the clinical scenarios, as tested on phantom by Consorti et al. and Bloemen-van Gurp et al.[11,26] However, our results do not support completely the decision by Ciocca et al.[12] on using the MOSFET with the epoxy side towards the beam (irradiation at 180°) because we found readouts significantly different at a pitch of 225° with 9 MeV ($p = 0.001$) and at a roll of 225° with 15 MeV ($p = 0.044$).

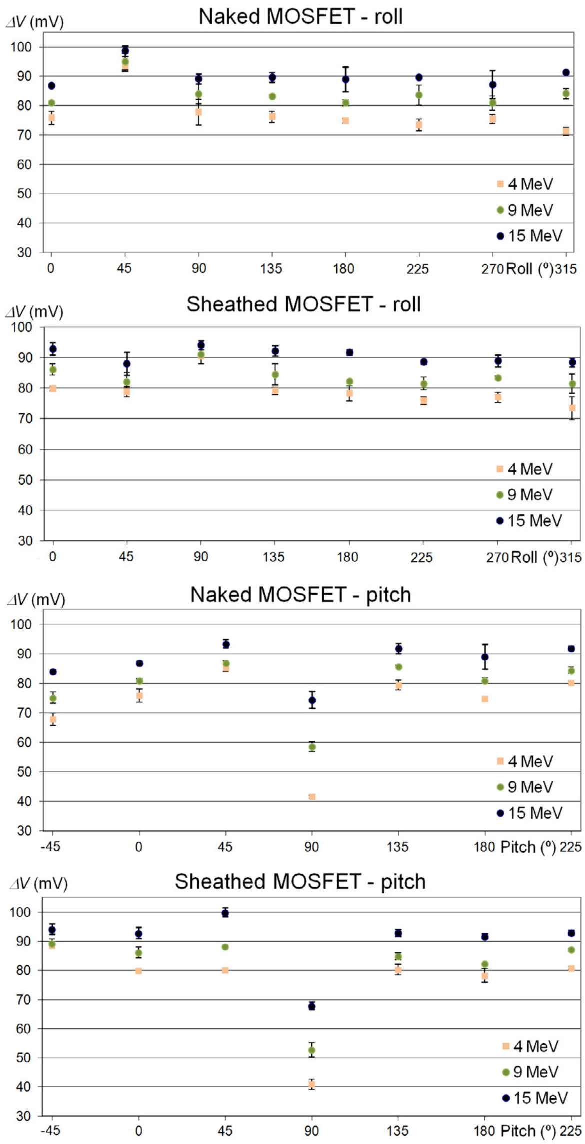

Fig. 3 – Mean readouts by angle with their associated uncertainty.

Moreover, MOSFET rolling, induced by cable torsion, or pitching that eventually causes a separation of the detector from the tumour bed has not previously been considered. Angular response could explain higher than expected results with a roll of 90° or a pitch of 315° and low energy, or a pitch of 45° and high energy. Dramatically lower than expected results were obtained with a pitch of 90°. Thus, physicians responsible for MOSFET attachment should be aware of these movements, which are usually forced by inadvertent cable torsion, especially an extreme pitch of nearly 90° which could lift the tip of the detector. Response rises with energy, consistently with the corresponding increase of electron initial depth dose in matter.[28] At the pitch of 90°, drop in response is greater and rise with energy is steeper because MOSFET active volume is further from the tip than from detector faces (indeed, with the naked MOSFET response rises faster because the extra distance added by the catheter is not present). Other substantial differences between the naked and the sheathed MOSFET may have been caused by changes introduced in the electron fluence by the catheter, although inter-MOSFET variation cannot be completely discarded at angles different than 0°.[26]

As mentioned in Section 3, pure yaw motions were neither expected to affect measurements because they do not change the relative orientation of the beam and the sensitive element of the detector nor studied by previous reports.[11,12,18,26] Taking all of this into account, IOERT researchers would appreciate more isotropic detectors from manufacturers, given that MOSFET setup within surgery is more difficult than in other settings.

With regard to energy dependence, the MOSFETs studied exhibit a response independent of several energies: 4, 6, and 9 MeV; and 12, 15, and 18 MeV. This behaviour may have affected Consorti et al. results who affirmed that the electron energy did not influence the MOSFET response, although there is a slight rising trend in their data which were only taken with 6, 7 and 9 MeV beams.[11] Furthermore, Bloemen-van Gurp et al. also reported a similar trend[26]; and a closer examination of their results with the corresponding uncertainties, taken with 4, 6, 8, 10, 12, and 15 MeV beams and presented in a graphical way, suggests the existence of the groups of energies that we study here. This behaviour presents two advantages. The first is that it can limit mistakes in dosimetry because the CFs have to be loaded manually in the software after the oral prescription right at the treatment unit and this action may be eventually forgotten. In fact, if the CF to be loaded is not significantly different from the CF to be used there will be no error. If it is different, the maximum magnitude of the net error (that is, the difference minus the extent of one tail of the possible distribution of the value) will only be up to 1% on average, corresponding to the confusion of 4 MeV and 15 MeV in this example, as a consequence of the differences and uncertainties reported in the previous section. This value is much lower than the proposed action level of 6–7% when performing in vivo dosimetry in IOERT.[11,12] The second advantage is that it could be possible to calibrate every detector once for each group of energy, saving time and optimizing MOSFETs lifetime. This feature was already observed by our team when the high bias setting of the reader was selected.[33]

Finally, our proposal for MOSFET rotations based on a natural language is easy to remember and solves the problem of defining sensor orientations[27] to ensure specific and unambiguous naming of the three possible rotations in three dimensional space when their shape is analogous to the shape of the detectors used here.

5.2. *Clinical considerations*

A real-time system of detection is necessary to perform a correction of irradiation. After delivery of a fraction of the total treatment, detector readout should be analyzed to find a substantial deviation from expected absorbed dose. If an action level is reached, irradiation setup should be checked to look for unintended movements. Then, if the setup remains the same, the rest of the treatment can be modified to achieve the intended absorbed dose. To the authors' knowledge, action levels have been proposed[11,12,34]; however, no experience with treatment compensation has been reported.

The angle definition used here considers applicator geometric axis, which is parallel to the main direction of incident electrons. With non-bevelled applicators geometric axis does not coincide with clinical axis,[35] that is, the axis chiefly taken as a reference for clinical assessment of depth dose and detector irradiation. This is a limitation when controlling optimal MOSFET irradiation, but if detector is properly attached and immobilized, in-patient measurements are assumed to be less affected by angle, as assessed with phantoms.[12,26] Moreover, this model of dosimeter has been assessed as a reliable in vivo detector for the current state of IOERT.[11–14]

In our procedure, the only professional authorized to manipulate patient's surgical bed is the oncologic surgeon (OS). Thus, he has to be instructed for proper detector handling and placement. Once detector is given to the OS, the rest of the team has to rely on his ability to attach it at the centre of the surgical bed surface (other groups reported detector placement inside the tissue[31]) as perpendicular to the beam as possible. For this reason, and after considering a typical reported detector relative uncertainty of 3.5% in response,[11] we decided not to increase the latter with another source of uncertainty caused by the angular response.

We obtained an acceptable roll range of ±45°, taking 0° as the reference. As the MOSFET can roll a little bit inside the catheter, this margin allows certain inaccuracy when the surgeon sets it up. On the contrary, pitch should be kept as close to 0° as possible. In this situation, the catheter prevents MOSFET from pitching but catheter lifting should be avoided for example with stitches.

To overcome the limitations regarding detector position and alignment assessment (for example, the presence of a roll and a pitch at a time) and obtain an increase in precision when evaluating this issues, it will be necessary to use the imaging and planning tools currently under investigation.[36–40]

The results of this study are expected to increase staff awareness on a careful placement of a detector to obtain accurate results and give the opportunity to achieve real-time dosimetry. As health professionals, we should keep in mind agencies' recommendations on this tool to ensure overall patient safety and to "maintain public confidence in radiotherapy as a safe form of treatment".[10]

6. Conclusions

Our proposal to name MOSFET rotations solves the problem of defining sensor orientations. Angular response could explain higher than expected results with a roll of 90° or a pitch of 315° and low energy, or a pitch of 45° and high energy. It also could explain lower than expected in vivo results when the tip of the detector is lifted to an extreme pitch of 90°. MOSFETs energy response is independent of several energies and differs between 1.6% and 3.4% in absolute value when dependent. This can limit dosimetry errors and makes it possible to calibrate the detectors only once for each group of energies, which saves time and optimizes the lifespan of the MOSFET.

Conflict of interest

None declared.

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