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MOSFET detectors as a tool for the verification of therapeutic doses of electron beams in radiotherapy

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Summary

Aim To examine the characteristics of MOSFET (Metal – Oxide Semiconductor Field Effect Transistor) detectors for the purpose of electron beam dose determination in *in vivo* radiotherapy.

Materials/Methods Indications of MOSFET detectors were recorded from phantom measurements, including: dose values of electron beams, the environmental temperature of the detectors, the incidence direction of an electron beam on the detector, the size of the irradiated field.

The change in sensitivity of the detectors when under the effects of accumulated doses was also tested.

Because of the very small dimensions of the detectors, they were placed in specially designed aluminium capsules - to ensure electron equilibrium (δ electrons) during the dose measurement. The detector indications were compared to those seen in a Markus type ionization chamber with a calibration certificate. The measurements were made for electron beams with energies of 6, 9, 12, 15, 18 and 21 MeV.

Results The following were established experimentally: There is a linear relationship between detector indications and the dose value. A drop in detector sensitivity is associated with increased environmental temperature (as much as 6% as temperatures rise from 22°C to 42°C). There is a non-linear drop in detector sensitivity with accumulated dose. Detector indications are not affected by changes in incident beam angles within the range of –70° to +70°. The dependency of detector indications on the size of the irradiated field conform with those recorded in the ionization chamber, with variations of up to 1.5%. The dependencies and correction coefficients determined in this study allow measurement of electron beam doses with an accuracy of 2.2%.

Conclusions MOSFET detectors are a useful tool for verification of the entrance doses in electron beam radiotherapy.

Key words **MOSFET detectors • *in vivo* dosimetry of electrons**

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Background

The agreement between planned dosage and those actually applied to patients is a significant element of effective radiotherapy [1–3]. Methods for the direct measurement of photon radiation doses, in cases of patients treated with radiotherapy (dosimetry *in vivo* – DIV), are very well developed and are applied in daily clinical practice [4–11]. Many radiotherapy centres make *in vivo* measurements as a routine procedure. However, the literature on dosimetry *in vivo* for electron beams is scant [12,13]. This has inclined us to use MOSFET type detectors as a tool for *in vivo* verification of therapeutic doses for electron beams.

Aim

The purpose of this report is to present the examined characteristics of MOSFET detectors, i.e. to investigate the relationships between their indications (responses) and the parameters associated with measurements of electron beam doses – so as to enable determination of the *in vivo* dose during radiotherapy.

The report is a continuation of the paper on the application of MOSFET detectors in the verification of *in vivo* doses of X radiation produced in linear accelerators.

Materials and Methods

A set of miniature MOSFET detectors, presented in a previous paper [6], was used. The active volume of the detector is less than 1 mm^3. The detector is mounted on a thin, semi-transparent strip of polyamide, under a layer of black epoxy resin 1 mm thick, providing a partial “build-up” effect during the measurement [14,15]. Hence, indications from a detector, placed on a phantom surface, should be dependent on the orientation of the detector’s flat surface relative to the incident radiation beam.

In order to apply MOSFET type detectors to the dose measurement for electron beam radiotherapy, we examined the relationships between detector indications and: the specified value of the electron beam dose, the detector’s environmental temperature, the incident direction of the electron beam incidence to the detector, the irradiated field dimension – when detectors were placed in the middle of the field.

Considering very small dimensions of detectors, to ensure electron equilibrium (of δ electrons [16]) during the dose measurement, the same aluminium caps were applied as those designed for photons [6]. Detectors were directed with the flat side towards the electron beam direction. The detectors irradiation was carried out for detectors alone as well as for detectors provided with the aluminium cap.

An essential element of the entrance dose measurement is the direction at which the radiation beam comes to the detector since it is not always possible to place the detector on the patient’s body in such a position that it is located on the central axis of the radiation beam and the angle between the axis and the detector basis is $\varphi=90^o$, which would correspond to calibration conditions.

The dependencies of the detectors indications on the provided dose value and the direction of incidence of the electron beam in relation to the detector were examined through placing detectors in the accelerator iso-centre (distance from the source 100 cm) in free air. The irradiation field at that distance was 10 cm × 10 cm.

To examine the dependencies of detectors indications on the irradiated field size, the detectors were placed on the surface of the PMMA phantom (SSD=100 cm). The indication dependencies were examined for detectors both with and without aluminium caps – while changing the square irradiation fields as regards the side length of 4 cm to 20 cm. The fields were formed with the use of the DEVA (Digital Electron Variable Applicator) type applicator.

A slightly different method of measurements was adopted for examining the dependencies of detectors indications on the detectors environment temperature. To this purpose, the detectors were placed in the water, on the axis of the beam, at the depth of the maximum dose, in the irradiation field of 10 cm × 10 cm at the SSD distance =100 cm. The temperature was changed in the range of 22°C – 42°C ±0.5°C.

Similarly to the photon beams, the dependence of sensitivity on a cumulated dose was examined, since this parameter can be a significant element during subsequent *in vivo* measurements made with the use of the same detectors. To examine this phenomenon also with photons, the detectors were irradiated with an electron beam with energy of

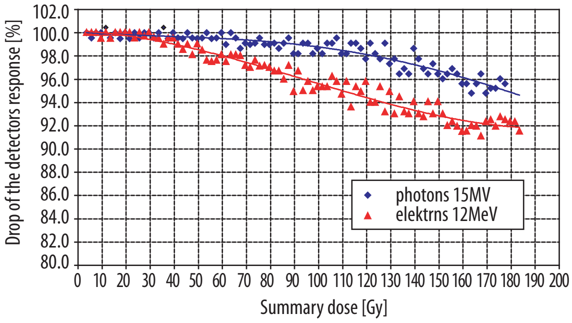

Figure 1. Dependence of MOSFET detector responses on the cumulated dose value for the electron beam with the energy of 12 MeV and X-ray radiation of 15 MV. The values read on the ordinate axis can be applied as an adjustment coefficient taking into consideration the dose cumulated by the detector.

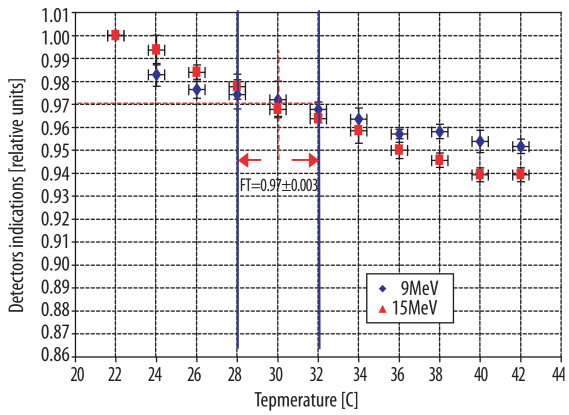

Figure 2. Dependence of MOSFET detectors indications on the environment temperature for electron energies 9 MeV and 15 MeV. In the range of temperatures limited with vertical lines (the scope of body temperatures on the surface), correction coefficient FT amounts to 0.97±0.003.

12 MeV as well as with an X-ray beam of 15 MV. At the same time, changes in the detectors sensitivity were controlled. Detectors were placed in water, at the depth of the maximum dose where previously the dose-rate value had been determined with the use of the Markus type and the Farmer 0.6 cm^3 ionization chamber – according to the radiation applied. Detectors indications were read each time after irradiating them with a subsequent dose of 2 Gy, till the total dose of 180 Gy was achieved.

Application of MOSFET detectors in the *in vivo* dose measurement in radiotherapy requires a previous calibration of the detectors. In the routine radiotherapy, the entrance dose, i.e. at the depth of the maximum dose, must be compared with the planned one, by means of electron beams. To this purpose, detectors calibration is carried out through determination of entrance dose ratio F_{Entr} as a quotient of the dose measured by the ionization chamber and the detector indication, with the chamber placed at the depth of the maximum dose, depending on the type of electrons energy, the SSD distance =100 cm from the source and the square field side 10 cm, whereas the MOSFET detector together with the aluminium cap is placed on the PMMA phantom.

It can be illustrated with the following formula:

$$F_{Entr} = \frac{D_C}{W_M},$$

where: D_C – dose determined by the chamber, W_M – indications of the MOSFET detector.

The *in vivo* verification consists of comparing the entrance dose as determined with the use of the Treatment Planning System (TPS) and measured with a calibrated MOSFET detector.

Results and Discussion

Dependence of the response of MOSFET detectors on the cumulated dose value

The measurements results for the dependence of the detectors sensitivity on the cumulated dose, for electron beams with energy of 12 MeV and, for comparison, for 15 MV photons, are presented in the form of diagrams on Figure 1. On analysing the results obtained, a continuous, non-linear drop in detectors sensitivity in the examined range of the summary dose was found. Above the cumulated dose of 40 Gy, a significant decrease in the detectors sensitivity can be observed – higher in case of electrons than photons.

In the course of routine measurements of an *in vivo* dose, an adjustment for the change in the detector sensitivity must be introduced – as suggested by the diagrams on Figure 1.

Dependence of detectors indications on temperature

The results of measurements of detectors indications on the environment temperature for electron beams with energy of 9 MeV and 15 MeV are presented in the form of a diagram on Figure 2.

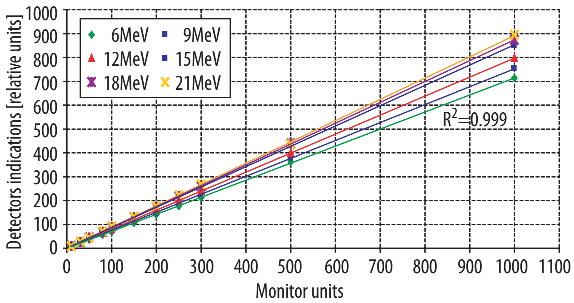

Figure 3A. Dependence of MOSFET detectors indications (relative units) without aluminium caps on the applied monitor units number. The detectors were placed in the free air, in the izocentre.

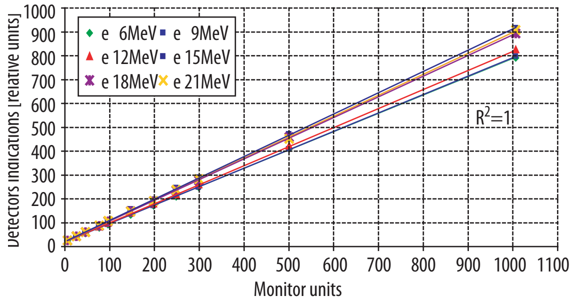

Figure 3B. Dependence of MOSFET detectors indications (relative units) with aluminium caps on the applied monitor units number. The detectors were placed in the free air, in the izocentre.

In the examined range of temperatures (22°C – 42°C), a drop of sensitivity was observed amounting to 6% at the borders of the range considered. For the temperature of 30°C being an equivalent of the patient's skin temperature [6], a decrease in detectors sensitivity was noted for both electron energies, amounting to 3% in relation to their calibration temperature.

Consequently, taking into consideration the range of temperatures where detectors calibration is carried out (22°C – 24°C) as well as the patient's skin temperature (28°C – 32°C) [6], it is reasonable to introduce a correction coefficient for detectors of 0.97 on the average.

Dependence of detectors indications on the delivered dose

The results of research on linearity of detectors indications on the delivered dose value as carried out for energies 6, 9, 12, 15, 18 and 21 MeV are presented in the form of diagrams on Figure 3A,B. In the examined geometry layout, the dose-rate in the water phantom, at the depth of the maximum dose amounted to 0.97 cGy/JM on the average.

The measurement results presented in the diagrams – including the regression line and the correlation coefficient – lead to the conclusion that there is a linear relation between the detectors indications and the dose absorbed in the examined range of 10 to 1000 monitor units (MU) considering the fact that the dose in the detector location site is directly proportional to the monitor units number. The repeatability of detectors indications of the examined electron beams in the range of 10 to 1000 MU did not exceed 0.2%.

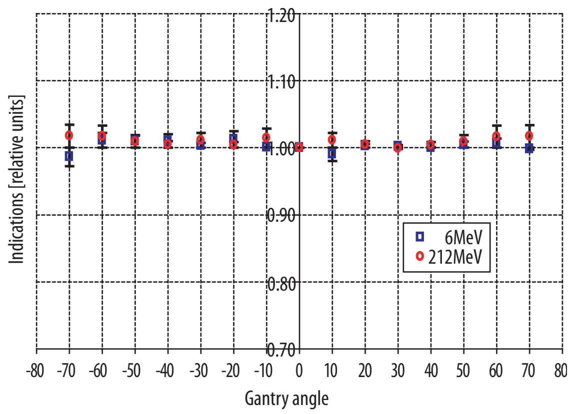

Figure 4. Dependence of MOSFET detectors indicators on the beam incidence direction for the following electron energies 6 MeV and 21 MeV.

Dependence of MOSFET detectors indications on the direction of the beam incident

It follows from the measurements results presented in Figure 4. that the impact of the direction of the beam incidence on the tested detectors indications in the examined range of angles of –70° to +70°, in relation to the perpendicular incidence of the beam axis to a flat detector surface does not exceed 1%. It seldom happens in the clinical practice that the surface is positioned at an angle higher than 60°. Therefore, it is not necessary to adjust detectors indications during measurements of *in vivo* doses due in to a skew detector irradiation.

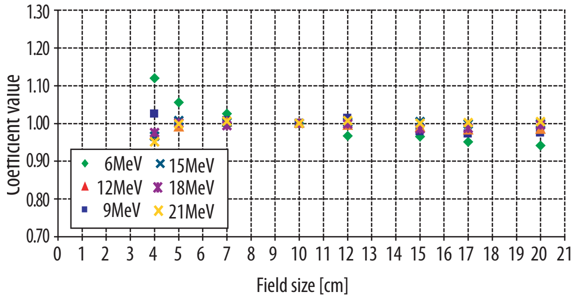

Figure 5A. Dependence of the quotation of the ionization chamber indications as placed at the depth of g_{max} in water and the MOSFET detector without an aluminium cap on the irradiation field size. The quotation was normalized to the field of 10 cm × 10 cm.

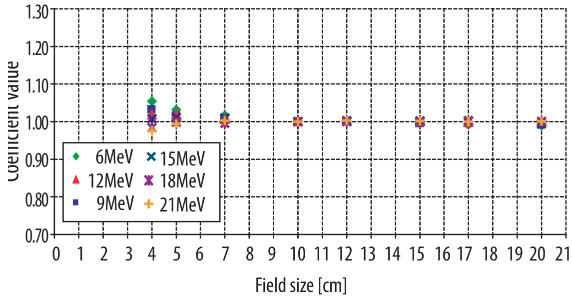

Figure 5B. Dependence of the quotation of the ionization chamber indications as placed at the depth of g_{max} in water and the MOSFET detector with an aluminium cap on the irradiation field size. The quotation was normalized to the field of 10 cm × 10 cm.

Table 1. Entrance dose F_{Entr} coefficients for applied electron energies.

	Electron energies [MeV]					
	6	9	12	15	18	21
F_{Entr}	1.16±0.001	1.13±0.002	1.08±0.009	1.08±0.007	1.08±0.003	1.08±0.005

Dependence of MOSFET detectors responses on the size of the irradiation field

The results of dependence of MOSFET detectors responses on the irradiation field is presented on Figure 5A,B, as a dependence of the quotient the Markus type ionization chamber as placed in water at the depth of the maximum dose and the MOSFET detector as placed on the phantom surface. The indications quotient was normalized for the field of 10 cm × 10 cm. On the basis of the result presented (Figure 5B), a conclusion can be drawn that the dependence of indications of MOSFET detectors (as provided with aluminium caps) on the field size in the range of 5 cm × 5 cm to 20 cm × 20 cm is identical, with the accuracy of 1.5%, to the one indicated by the Markus type ionization chamber. For smaller fields and for electron energy of 6 MeV and 9 MeV, a correction coefficient should be introduced: for the field of 4 cm × 4 cm amounting to 1.05 for energy of 6 MeV and 1.03 for energy of 9 MeV. Moreover, for the field of 5 cm × 5 cm and energy of 6 MeV – the correction coefficient is 1.03. When this dependence is compared with the similar one for detectors without aluminium caps (Figure 5A), it is evident that for the field of 4 cm × 4 cm, the discrepancies are larger in relation to the ionization chamber.

The decrease in detectors indications as compared with the Markus chamber for small fields can be caused by the insufficient thickness of the aluminium cap for low energies of electrons, since it can be observed that for low electron energies (e.g. 6 MeV), the drop in a dose on the phantom surface is higher and reaches 75% of the maximum dose, especially in case of small fields. For larger fields, the dose on the surface grows. Considering the fact that the ionization chamber was placed on the depth of the maximum dose, the MOSFET detector, as placed on the phantom surface, might have had a too thin aluminium cap. The effect is particularly visible in case of detectors without aluminium caps.

Results of entrance dose measurements

The experimentally set out values of coefficients of entrance dose F_{Entr} for the applied electron energies are presented in Table 1. The values of Table 1. refer to the mean of four detectors. They should be determined separately for each detector.

The detectors calibration error was 1.2% (1SD). The percentage difference (%Δ) of those dose was calculated by the following formula:

$$\%\Delta = 100\% \cdot \frac{D_M - D_{TPS}}{D_M},$$

where: D_{TPS} – dose determined on the basis of the treatment planning system, D_M – dose indicated by the detector.

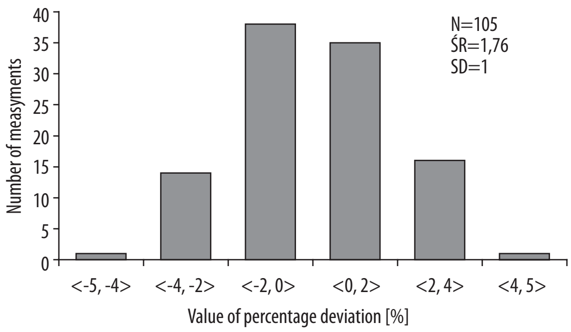

Figure 6. Histogram of percentage differences between the measured entrance dose and the planned one – for electron beams.

The value of 5% is adopted as the admissible deviation of the measured dose form the planned one.

Doses were verified for 105 measurements concerning 85 patients. The conformity of the planned dose and the measured one in the assumed range of 5% was observed in all patients subjected to *in vivo* measurements.

The largest percentage deviation of a verified dose amounted to 4.1% for a 9 MeV electron beam, for electron beams energies of 6 MeV and 12 MeV, it was respectively 4.0% and 3.6%. The results of verified doses are presented in the form of histogram on Figure 6.

Conclusions

The use of MOSFET type detectors in everyday electron dosimetry represents a number of benefits: easy calibration process, easy measurement and immediate readout. Measurements of parameters of detectors examined as the results obtained of the *in vivo* measurements lead to conclusion that MOSFET detectors are a good tool for verifying therapeutic doses also for electron beams.

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