Surface dosimetry in a CT scanner using MOSFET detectors
and Monte Carlo simulations

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Abstract. Diagnostic imaging with CT procedures is responsible for significant radiation doses
to patients. To enable individual patient dose estimates, a combination of MOSFET detectors
and Monte Carlo (MC) simulations was investigated for the determination of patient surface
dose. The behaviour of MOSFETs in kV x-rays from a CT scanner was investigated with
experiments and MC simulations with a CT scanner model. A dose reproducibility of 5% and a
mean loss of sensitivity with accumulated dose of about 10% was noted for the MOSFETs.
Beam energy increase from 80-140 kVp resulted in a response decrease of 10%. The MOSFET
detectors were calibrated in terms of absolute surface dose with the aid of MC simulations.
Good agreement was achieved between measured and calculated surface dose on a cylindrical
Lucite phantom. Experiments with a stationary x-ray tube and contiguous axial scanning led to
differences limited by 8%. Surface dose in helical scanning was investigated with
measurements with radiological film and an array of five MOSFET detectors, leading to good
agreement. It is concluded that an array of MOSFET detectors, calibrated in terms of surface
dose, is a valuable tool to assess individual patient surface dose. In combination with MC
simulations this may lead to estimations of effective dose.

1. Introduction
With the trend towards increasing number of CT scanning procedures for diagnostic examinations,
and the growing complexity of multi-slice scanning protocols, there is a need for a more accurate
individual patient dose assessment. Conventional dose indices used in CT dosimetry such as CTDI and
its variants are useful to compare the performance of different scanners but cannot be used directly to
monitor individual patient dose [1-2]. Monte Carlo (MC) dose calculation techniques offer the
possibility of individual patient dose calculation, in particular for the organ doses required for an
effective dose approach (for a recent review, see [3]). This procedure is still somewhat too time-
consuming for clinical routine use but could become the standard in the near future. In addition to the
detailed information from MC simulations, a quick and easy patient measurement of the skin dose (the
‘organ’ that receives the highest dose in kV imaging) would be desirable. A potential solution could be
the use of MOSFET dosimeters.

MOSFET dosimeters from Best Medical Canada (formerly Thomson Nielsen) offer a fast, simple
and inexpensive means to obtain a point dose measurement in radiation beams [4]. By combining
several MOSFETs in an array one- or two-dimensional measurements can easily be obtained. To
arrive at absolute dose a calibration protocol in the relevant beams is required. In this work, a
calibration protocol designed by Lemire [5], based on MC simulations, was used for kV CT scanner
beams. With the aid of a MC simulation model of a single-slice CT scanner the suitability and
accuracy of MOSFET detectors to determine surface dose in a phantom was investigated. The main
aim of the paper is to show the feasibility to determine absolute surface dose for various CT scanning conditions.

2. Monte Carlo model of a CT scanner
The BEAMnrc MC code [6] with its user code DOSXYZnrc was used to construct a model of a Picker PQ5000 single-slice CT scanner. Included in the model are the target, the primary electron beam, exit window/intrinsic filtration, beam limiter and collimator. The geometry of the compensators (beam shapers) was not known exactly and was therefore taken into account by modifying the statistical weight of photons such that measured and calculated beam exposure profiles were a match in the cone beam direction (perpendicular to couch translation direction). This was done by modifying the statistical weight of all particles in the phase space file by multiplying by the ratio: (measured profile with compensator / simulated open beam fluence profile). Therefore, it is implicitly assumed that the photon spectrum is invariant across the field. Stationary, single axial and contiguous axial scanning modes were modeled. The current version of DOSXYZnrc does not allow modeling of helical (spiral) scanning. Therefore, for that part of the study, MOSFET detectors were compared to measurements with radiographic film (Kodak X-Omat XV2) wrapped around a CTDI phantom. The dimensions of this cylindrical Lucite phantom are 15 cm length and 16 cm diameter.

The validation of the MC model of the CT scanner was done through determinations of half value layers (HVL) and exposure profiles in air. Measured and calculated first and second HVL in aluminium were within 1.6% and 2.2%, respectively, for the 80-140 kVp range of the scanner. Measured exposure profiles with film in the cone beam direction for open beams matched within a few percent, and for compensator fields they were forced to match by adjusting particle weights in the simulations, as explained above. Figure 1 shows measured and simulated relative exposure profiles in the direction along the couch translation. The agreement is very good except in the tails of the fields. This is because we made no attempt to correct for the non-linear dose response of the film at low doses, and possibly also because of the assumption of spectral invariance across the field.

Figure 1. Measured and simulated relative exposures in air for 140 kVp for different slice thicknesses. For the 10 mm slice a slight heel effect can be noted.
3. MOSFET detectors
The Patient Dose Verification System TN-RD-50 (Thomson-Nielsen, Best Medical Canada) with five high sensitivity TN-1002RD MOSFETs was used in this work to measure surface dose on phantoms. The MOSFETs have less than a 0.04 mm² active detection area which makes them ideally suited for point measurements. By repeated exposure in 140 kVp x-rays to doses in the range of 10-20 cGy an overall standard deviation of 4.5% on the readings (20 samples) was obtained (standard bias). MOSFETs exhibit radiation damage as they accumulate dose, leading to a decrease in sensitivity, as shown in figure 2. At the end of life an average 10.4% of sensitivity was lost. Ideally, MOSFETs need recalibration at mid-life. End of life corresponds to an accumulated dose of about 18 Gy (standard bias) or 7 Gy (high bias).

![Figure 2](image)

**Figure 2.** Normalized sensitivity as a function of accumulated dose for standard bias (in mV, to convert to cGy multiply by 0.09) over the lifetime of five MOSFETs.

A simple MC model of a MOSFET was built using DOSXYZnrc (figure 3). It consists of a Si chip with a SiO₂ active volume, mounted on a kapton carrier and encapsulated by epoxy. The thin connecting wires are omitted and the epoxy drop, which in reality is ellipsoid-like (but slightly different for individual MOSFETs), is approximated by a rectangular box.

![Figure 3](image)

**Figure 3.** Simplified MOSFET model for MC simulations. Not drawn to scale and no dimensions are given.

The MC model was used to study the angular and energy response of the detector. For a MOSFET oriented between a position where the SiO₂ sensitive element faces the radiation beam to a position perpendicular to it, no significant difference in angular response was obtained for 120 kVp x-rays. For larger angles, which wouldn't occur clinically, deviations from an isotropic behaviour were seen. More data on angular response can be found in the literature [e.g. 7].

By comparing measured energy response to a calibrated ion chamber measuring air kerma, a 10% loss of energy response was noted going from 80-140 kVp, as seen in figure 4 (effective energies range from 32-43 keV). The same result was obtained from simulations. Note that calibration factors would change over time, as suggested in figure 2.
4. Surface dose in CT scanning

The main aim of the study was to compare measured and calculated surface doses for a number of CT scanning techniques. To this end, MOSFET measurements were done on the surface of a cylindrical CTDI phantom (16 cm diameter, 15 cm length). A corresponding mathematical phantom was used in DOSXYZnrc simulations. The comparison was done in terms of absolute dose. The procedure to calibrate MOSFETs in absolute dose was elaborated in Lemire [5], and will be described here briefly.

The absorbed dose was determined using the “in-phantom” TG61 protocol [8] in a 30×30×15 cm³ solid water phantom. An A12 Exradin ion chamber was positioned at 1.5 cm depth. A CT slice thickness of 10 mm was used, and the chamber was aligned parallel to the fan direction of the scanner, ensuring complete coverage of the sensitive chamber volume. Static exposures of 120 and 140 kVp were used for the calibration. The absorbed dose to solid water at 1.5 cm depth was determined from:

\[ D_{SW,z=1.5\,cm} = M N_K P_{Q,\,cham} \left( \frac{\mu_{en}}{\rho} \right)_{SW}^{air} \]

where \( M \) is the chamber reading (corrected for reference pressure and temperature, and the recombination and polarity effects), \( N_K \) is the air kerma calibration factor for the beam quality used, \( P_{Q,\,cham} \) is the overall chamber correction factor that accounts for the change in the chamber response due to chamber perturbation, and the factor in square brackets is the ratio of the mass energy absorption coefficients, solid water-to-air, averaged over the photon spectrum at the reference point in the solid water phantom. The latter was calculated from a MC simulation.

DOSXYZnrc MC simulations which calculate absorbed dose in Gy/particle were then converted to the absolute unit of Gy/mAs by comparing a simulated calibration setup for reference conditions to an ion chamber measurement for the same set-up. By comparing calculated dose to the surface of a PMMA phantom to MOSFET readings in mV/mAs at the same position, MOSFETs can be calibrated in absolute absorbed dose in PMMA with a conversion factor in cGy/mV (all measurements presented in the remainder of the paper refer to the same PMMA CTDI phantom of 15 cm length and 16 cm diameter).

4.1. Static exposure

The first test was a static exposure of the cylindrical phantom with six MOSFETs positioned at different angles ranging from 0° (MOSFET right under x-ray source) to 130° (MOSFET in the shadow of the x-ray source). The simulated response is fit to a straight line.
of the phantom). Table 1 compares simulated to measured absolute dose for 140 kVp (effective energy 43 keV). Agreement within 3% was reached. For 120 kVp agreement was obtained within 2% (data not shown).

**Table 1.** Measured and simulated absolute dose on the surface of a CTDI phantom for a static exposure (140 kVp, 150 mAs). The percentage differences reported are with respect to the maximum dose at 0 degrees (75 mGy).

| Position (°) | Measured Dose (mGy) | Simulated Dose (mGy) | Difference (%) |
|-------------|---------------------|----------------------|----------------|
| 0           | 75±6                | 76±3                 | 1.0            |
| 30          | 73±5                | 73±3                 | -0.4           |
| 45          | 68±5                | 69±3                 | 0.8            |
| 60          | 62±5                | 61±3                 | -1.8           |
| 100         | 15±1                | 17.8±0.7             | 3.4            |
| 130         | 2.5±0.2             | 4.1±0.2              | 2.2            |

4.2. Contiguous axial scan

A linear array of 5 MOSFETs with a 2.5 mm spacing was used on the CTDI phantom, with the array oriented parallel to the couch translation. Figure 5 shows simulated surface dose profiles and table 2 gives minimum and maximum measured dose with the MOSFET array. In general the agreement is good, except for the minimum dose for 3 mm slices, where simulated dose overestimates measured dose by up to 12%. This is probably due to voxel volume averaging effects in the simulations where 1 mm voxels are used in the scan direction (the distance between maxima and minima for 3 mm slices is 1.5 mm). Collimation seems to have only a small effect on minimum and maximum doses; differences are limited to 8%. This confirms TLD measurements from an older study [9].

**Figure 5.** 140 kVp simulated surface dose for contiguous axial scans with 3 and 10 mm slices.

**Table 2.** Measured and simulated surface dose for contiguous axial scanning (175 mA, 1.5 s/rev). The percentage differences reported are local differences (\(D_{\text{sim}}/D_{\text{meas}}\)).

| kVp | Slice Thickness (mm) | Minimum Dose (mGy) | Difference (%) | Maximum Dose (mGy) | Difference (%) |
|-----|----------------------|--------------------|----------------|--------------------|----------------|
|     | measured             | simulated          |                | measured           | simulated      |
| 120 | 10                   | 22.9±2             | 23.8±1         | 3.4                | 27.2±2         | 28.2±1         | 3.6            |
|     | 5                    | 21.9±2             | 23.6±1         | 7.5                | 28.4±2         | 28.5±1         | 0.4            |
|     | 3                    | 22.2±2             | 25.4±1         | 12                 | 27.7±2         | 28.2±1         | 1.8            |
| 140 | 10                   | 30.8±2             | 32.5±1         | 5.2                | 36.3±3         | 39.0±2         | 6.9            |
|     | 5                    | 31.3±2             | 31.9±1         | 1.8                | 38.7±3         | 38.5±1         | -0.7           |
|     | 3                    | 31.6±2             | 34.2±1         | 7.8                | 36.9±3         | 37.9±1         | 2.4            |
4.3. Helical scan
The five MOSFET array was used to measure surface dose for helical scanning with 3, 5 and 10 mm slice thicknesses and pitch 0.5, 1, 1.25 and 2. Since helical scanning x-ray sources cannot be modeled with the current version of DOSXYZnrc we used radiographic film to obtain scanned surface dose profiles. Potential energy dependence effects of the XV2 film were ignored. Figure 6 demonstrates that relative mean surface dose was found to be roughly proportional to pitch\(^{-1}\). Table 3 shows that for 10 mm slices the difference between maximum and minimum surface dose, measured with a MOSFET array, are in general agreement. For slice thicknesses of 3 and 5 mm similar agreement was reached (results not shown). As for contiguous axial scanning, collimation has a minor effect on surface dose.

![Figure 6. Film measured surface dose profiles for helical scanning with different pitch and slice thickness.](image)

| Table 3. Minimum and maximum dose measured with MOSFETs for 10 mm slices, compared to film (last column). 175 mA, 1.5 s/rev. Good agreement is noted between maximum and minimum dose measured with film and MOSFETs. |
|---|---|---|---|---|---|
| kVp | Pitch | Minimum Dose (mGy) | Maximum Dose (mGy) | Difference (%) | Film Difference (%) |
| --- | --- | --- | --- | --- | --- |
| 120 | 0.5 | 46±3 | 51±4 | 10 | 7 |
| 1 | 23±2 | 28±2 | 17 | 16 |
| 1.25 | 13±1 | 24±2 | 44 | 41 |
| 2 | 5.8±0.4 | 16±1 | 63 | 60 |
| 140 | 0.5 | 63±5 | 70±5 | 10 | 7 |
| 1 | 30±2 | 38±3 | 20 | 16 |
| 1.25 | 18±1 | 32±2 | 43 | 41 |
| 2 | 8.0±0.6 | 27±2 | 70 | 60 |

5. Conclusions
In this work MOSFETs and MC simulations were used to determine surface dose for various CT scanning modes. Provided the MOSFETs are well calibrated, a measurement accuracy at the same level as TLDs can be achieved. The very small size and ease of use make them excellent candidates for clinical patient measurements. In this work, MC simulations were used to study the response of MOSFETs and to validate surface dose measurements in a CT scanner. We arrive at the following conclusions:
- Dosimetric reproducibility of the MOSFETs was 4.5% for CT doses; a 10% drop of sensitivity was seen over the MOSFET lifetime; from 80-140 kVp the response drops by 10%.
- For better accuracy, energy-dependent calibration factors are required for the MOSFETs; recalibration at mid-life is recommended.
Simulations and MOSFET measurements were within 3% for a fixed beam irradiation and generally within 8% for contiguous axial scanning.

- An array of 5 MOSFETs with 2.5 mm spacing suffices to capture at least one minimum and one maximum dose for axial and helical scanning, except for the pitch 2/slice 10 mm combination where more than 5 MOSFETs are needed.

- Slice thickness has a minor influence on dose, pitch has a major effect (dose~pitch^{-1}).

MC simulations are not essential clinically if surface dose is the only desired quantity, but in addition to using MC methods to study detector response and validate surface dose measurements, it can be used to assess organ dose in patients. MOSFET calibration factors to obtain absolute dose are required for surface dose measurements in kV CT scanner beams, possibly provided by the manufacturer, or determined using ion chamber measurements.

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