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Megavoltage cone beam CT near surface dose measurements: potential implications for breast radiotherapy

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Purpose: Cone beam computed tomography (CBCT) is fast becoming standard on modern linear accelerators. CBCT increases the dose to regions within and outside the treatment field, potentially increasing secondary cancer induction and toxicity. This study quantified megavoltage (MV) CBCT skin dose and compared it to skin dose delivered during standard tangential breast radiotherapy.
Method: Dosimetry was performed both in- and out-of-field using thermoluminescent dosimeters (TLDs) and a metal-oxide-semiconductor-field-effect-transistor (MOSFET) detector specifically designed for skin dosimetry; these were placed superficially on a female anthropomorphic phantom.
Results: The skin dose from a single treatment fraction ranged from 0.5 to 1.4 Gy on the ipsilateral breast, 0.031–0.18 Gy on the contralateral breast, and 0–0.02 Gy in the head and pelvic region. An 8 MU MV CBCT delivered a skin dose that ranged from 0.02 to 0.05 Gy in the chest region and was less than 0.01 Gy in the head and pelvis regions. One MV CBCT per fraction was found to increase the out-of-field skin dose from both the CBCT and the treatment fields by approximately 20%. The imaging dose as a percentage of treatment doses in the ipsilateral breast region was 3% for both dosimeters.
Conclusion: Imaging increases the skin dose to regions outside the treatment field particularly regions immediately adjacent the target volume. This small extra dose to the breasts should be considered when developing clinical protocols and assessing dose for clinical trials. © *2011 American Association of Physicists in Medicine*. [DOI: 10.1118/1.3641867]

Key words: MOSFET, MV cone-beam CT, surface dosimetry, TLD

I. INTRODUCTION

Image-guided radiotherapy (IGRT) utilizes advanced imaging technology in the treatment room to ensure correct patient setup. Megavoltage (MV) cone beam computed tomography (CBCT) (Ref. 1) is a technology used for IGRT that employs the medical linear accelerator treatment beam and an amorphous silicon flat panel detector to acquire projections of the patient. Cone beam reconstruction technology is then used to reconstruct a volumetric image of the patient.

In an era of increasing use of IGRT technologies where multiple images are taken during the treatment course, extra radiation dose to the patient from imaging should be considered. In particular, repeated imaging could potentially exacerbate radiation-induced skin toxicity by increasing the in-field skin dose. To the best of our knowledge, there have been no studies evaluating the influence of concomitant imaging on skin toxicity. In breast radiotherapy, total treatment doses of greater than 50 Gy and larger fraction sizes have been associated with greater skin toxicities.[2–4] If imaging were to increase the fraction dose or total treatment dose, to 60 Gy for example, the patient may experience worse skin reactions. Radiation-induced skin toxicity is a side effect most breast cancer radiotherapy patients (74%–100%) will experience during their treatment.[5–8] The dose to the skin can vary considerably inside and outside the treatment field. Knowledge of this dose is

important in order to identify areas where unwanted skin reactions may occur. The imaging dose may also contribute to a delivered dose that exceeds the prescribed dose.

Skin dose can vary considerably due to its dependence upon a number of factors such as treatment field dimensions, the use of beam modifying devices, and the obliquity of the beam. Additionally, skin thickness varies considerably over the entire body; breast skin thickness ranges from 0.6 to 2.7 mm.[9,10] Consequently, skin dose is difficult to assess and measure, particularly *in vivo*. *In vivo* skin dose measurements can be acquired by measuring the dose at various depths and extrapolating to the desired depth. This technique can be completed with multiple thermoluminescent dosimeters (TLDs) of different thickness[11] or multilayer Gafchromic film.[12] However, both methods can be time consuming due to multiple calibrations and both methods only provide retrospective dose information. Another option for *in vivo* skin dosimetry is to use a dosimeter with a small measurement depth (less than 1 mm) such as carbon-loaded TLDs,[13] radiochromic film,[14] or metal-oxide-semiconductor-field-effect-transistor (MOSFETs).[15] In the clinical environment, the most commonly used detectors for *in vivo* dosimetry are diodes and TLDs.[16]

The skin dose to various regions such as the contralateral breast from different breast radiotherapy techniques has been well reported.[17–19] Kilovoltage (kV) CBCT is the most common imaging modality provided by several vendors (XVI®, Elekta Oncology Systems; OBI, Varian Medical Systems; Artiste, Siemens); however, MV CBCT (Ref. 1) still makes up a substantial proportion of the imaging systems integrated with linear accelerators. In the literature, there is limited *in vivo* skin dose values available for MV CBCT, the image modality investigated in this study. A Monte Carlo study[20] provides a single value for the whole body skin dose from a head and neck MV CBCT (0.59 cGy for an 8 MU MV CBCT) and a pelvis MV CBCT (0.94 cGy for an 8 MU MV CBCT). In this study,[20] no region specific skin dose values were provided, such as the dose delivered in or out of the imaging field-of-view, and hence skin dose assessment to areas deemed at high risk of radiation skin damage, such as the eyes in head and neck radiotherapy, was not possible.

This report details a phantom study conducted for the purpose of investigating the additional skin dose a MV CBCT delivers to a female patient during a standard tangential breast radiotherapy fraction. Dosimetry was performed both in- and out-of-field using TLDs and a MOSFET detector specifically designed for skin dosimetry, the MO*Skin* MOSFET.

II. MATERIALS AND METHODS

II.A. Phantom, treatment plan, and megavoltage cone beam CT

A female anthropomorphic phantom (Radiology Support Devices, USA) was utilized for this study. Twenty-two point positions on the phantoms surface in the head and neck, chest, and pelvic region were chosen to measure the radiation skin dose from the breast radiotherapy treatment and MV CBCT image protocol described below. The measurement locations are shown in Fig. 1. The skin dose was measured with TLDs and MOSFETs, with specifications described in Secs. II B and II C, respectively.

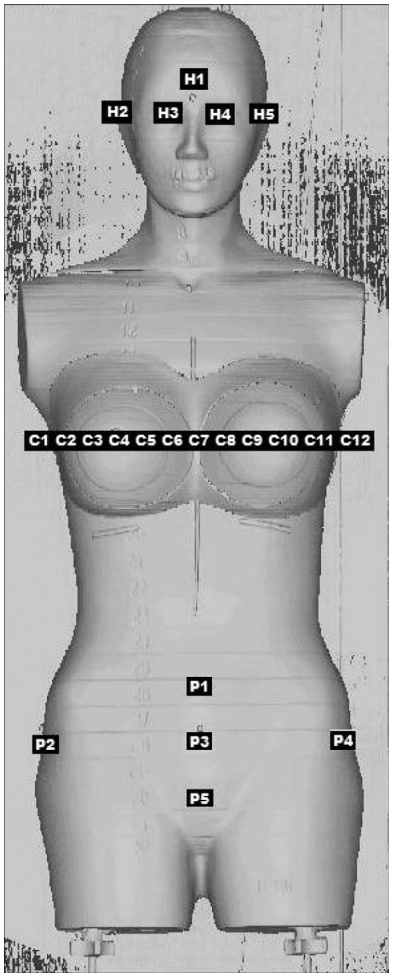

FIG. 1. Three-dimensional CT-render of female anthropomorphic phantom, illustrating the approximate radiation detector locations.

A standard breast radiotherapy treatment plan was developed for the left breast according to departmental protocol. The plan consisted of opposed tangential breast fields, at gantry angles 309° and 134°, with 15° virtual wedges, and a standard dose regimen of 50 Gy (designed to be delivered in 2 Gy fractions). Five fractions were delivered to the phantom in a single measurement, this ensured detectors at out-of-field treatment positions received a significant signal beyond the noise background threshold. Measured skin dose values were then extrapolated back to a single fraction dose.

A 60 MU MV CBCT imaging protocol was applied to the phantom. This high imaging dose assisted dosimetric response signal for both detectors and rendered background noise minimal. The image acquisition parameters included 6 MV photons, 200° rotation arc, 27.4×27.4 cm field-of-view, 256×256 reconstruction matrix, and 0.1 cm slice thickness. Measured dose values were scaled to Gy/MU and from this the dose for an 8 MU protocol was determined. The contralateral breast, points C1–C6, and ipsilateral breast, points C7–C12, are within the MV CBCT field-of-view.

A daily imaging schedule was investigated in this study, as this would deliver the highest skin dose to the patient and

thus a "worst case" scenario is presented. It is recognized that clinically for breast radiotherapy a weekly image schedule would be most likely.[21,22]

The breast treatment and MV CBCT protocol described above was delivered to the phantom using a Siemens Oncor linear accelerator (Siemens Medical Solutions, Erlangen, Germany) operating at 6 MV. Dose measurements were repeated twice to obtain statistical variation.

II.B. Thermoluminescent dosimetry

Standard $3 \times 3 \times 0.9$ mm lithium-fluoride TLD-100 chips (Harshaw, Erlangen, Germany) with a measurement water equivalent depth (WED) of approximately 1 mm (Ref. 23) were used. TLD chips were irradiated to known doses within the expected range of MV CBCT and breast radiotherapy energies (6 MV) and doses (0.1, 0.2, 0.5, 1, and 2 Gy) to establish TLD sensitivity and individual chip calibration factors. Only TLD chips with sensitivity ranging within $\pm 5\%$ were selected for measurements in this study. TLD chips were read within 24 h of irradiation with a Rialto NE TLD reader (NE Technology Ltd, UK). Two TLD chips were placed at each location to reduce statistical error in the dose measurements.

II.C. MOSFET dosimetry

The MOSFET detector utilized for this study was the MO*Skin*, a MOSFET designed specifically for skin dosimetry.[24] The MO*Skin* MOSFET has a uniform build-up layer with a measurement WED of 0.07 mm,[24] the International Commission on Radiological Protection (ICRP) defines this depth as radiosensitive basal layer of the skin.[25] The total detector size including packaging is $2 \times 5 \times 0.7$ mm. The MOSFETs surface dose response increases with increasing beam obliquity.[19] Previous studies have utilized this MOSFET for in-field skin and surface dosimetry.[19,26] Also for rectal wall interface dosimetry[27] and for brachytherapy applications.[24]

The accuracy of the MOSFET, utilized for this study, for out-of-field dosimetry was assessed. The MOSFET response for a 10×10 cm, 6 MV beam was measured at 2 and 15 mm depth (d_{max}) in solid water, at the following distances from the central axis 0, 6, 8, 10, 15, 20, and 25 cm. The 2 mm depth measurements were compared with an Attix ionization chamber (at 2 mm depth) in the exact same setup for comparison. The Attix chamber has a large guard ring and is optimized for build-up measurements.[28] The MOSFET dose measurements were then compared with a thimble chamber (at 15 mm depth) as the thimble chamber is not optimized for measurements in the build-up region.

MOSFET surface doses at each measurement location were obtained by multiplying the difference of the threshold voltage before and after irradiation by a calibration factor. The calibration factor was determined by irradiating the MOSFETs to a known dose in standard conditions in a 6 MV beam, before and after measurements. The average calibration factor was utilized for treatment and imaging measurements.

III. RESULTS

The out-of-field MOSFET response is illustrated in Fig. 2 for a 6 MV beam 10×10 cm field at distances 0, 6, 8, 10, 15, 20, and 25 cm from the central axis, and at depths 2 and 15 mm. Agreement within 0.1% was observed between the MOSFET and ionization chamber measurements, with the exception at depth 2 mm, 6 cm from the central axis, where 2% agreement was observed. Discrepancy between the Attix ionization chamber and the MOSFETs at a distance 6 cm from the central axis is attributable to the larger surface area of the chamber resulting in a section of the attix chamber sensitive volume residing in the radiation field.

The skin dose measured for a single treatment fraction and an 8 MU MV CBCT scan in the head, contralateral breast, ipsilateral breast and pelvic region is outlined in Table I. The skin dose from a single 8 MU MV CBCT was less than 0.01 Gy in the head and pelvis regions and ranged from 0.02 to 0.05 Gy in the chest region. The skin dose from a single treatment fraction was less than 0.02 Gy in the head and pelvic region and ranged from 0.5 to 1.4 Gy on the ipsilateral breast and 0.031–0.18 Gy on the contralateral breast.

Utilizing the measured values from Table I, the single 8 MU MV CBCT image skin dose is presented as a percentage of a single treatment fraction skin dose in Fig. 3. The imaging dose as a percentage of treatment dose is highest for the most lateral point of the contralateral breast.

IV. DISCUSSION

Skin dose measurements at a range of locations both in and out of a tangential breast treatment area for MV CBCT and treatment delivery have been presented. The MO*Skin* MOSFET was shown to be accurate for out-of-field dosimetry, with the MOSFET and ionization chamber measured out-of-field doses in agreement to within 0.1% (with the exception of one point) of the maximal dose in the beam. This agreed with a similar study[29] investigating the MOSFET peripheral dose accuracy. At 15 mm depth, 200 mm

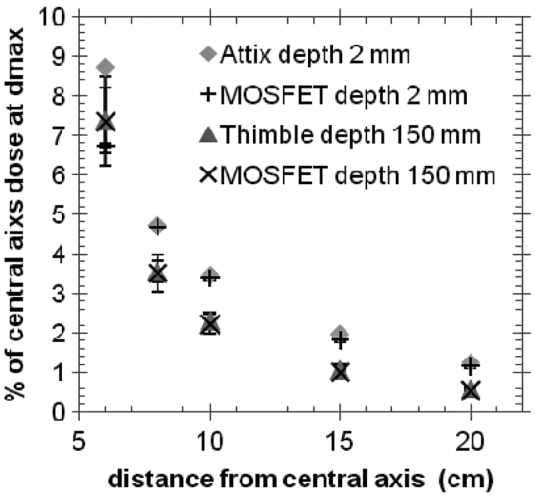

FIG. 2. MOSFET response measured out-of-field for a 6 MV 10×10 cm photon field. The error bars represent the 95% confidence interval of the mean of three measurements.

from the central axis, 4000 MU was delivered to the centre of the 10×10 cm field to ensure the MOSFETs received an adequate dose whereas 100 MU was delivered for the thimble chamber. However, the dose delivered to the MOSFETs out-of-field was significantly increased in comparison to the ionization chambers, to ensure sufficient signal to noise ratio. While using extra MU was practical in this phantom study, using MOSFETs with a higher sensitivity would be advantageous for patient dosimetry. The current study used the MO*Skin* MOSFETs at +12 V bias giving a sensitivity of 2.5 mV cGy^{-1}, there is potential to significantly increase the sensitivity by increasing the gate oxide thickness[30,31] and gate bias.[32]

The present study utilized two detectors to measure skin dose, both detectors illustrated that MV CBCT verification imaging increases the skin dose to areas that would not receive a significant skin dose from treatment alone. If MV CBCT was utilized for daily image verification during a standard tangential breast radiotherapy treatment fraction the skin dose at the lateral side of the contralateral breast would approximately double. This is attributable to the contralateral breast being within the MV CBCT field-of-view, as the MV CBCT acquires projection images in a 200° arc around the patient to reconstruct the 3D image. Reduced dose may be acquired by reducing the arc of imaging, however, image quality would be reduced due to the reduced projection angle.

The skin dose from an 8 MU MV CBCT ranged from 0.03 to 0.05 Gy and 0.02 to 0.03 Gy in the chest region for the TLDs and MOSFETs, respectively. In comparison, within the imaging field of a kV CBCT acquired for breast radiotherapy setup a previous study found the breast skin dose, measured with the same type of TLDs, received a lower dose of 0.01 Gy.[33] Limited organ and tissue dose measurements from a chest MV CBCT have been investigated previously with treatment planning systems.[34,35] These studies did not provide skin dose values; thus, a comparison with the present data could not be made.

The skin dose from a single 2 Gy treatment fraction ranged from 0.5 to 1.4 Gy on the ipsilateral breast, 0.031–0.18 Gy on the contralateral breast, and 0–0.02 Gy in the head and pelvic region. The contralateral breast skin dose values are in agreement with a similar study which reported doses of 0.022–0.13 Gy.[18] The higher doses measured in the present study are attributable to the phantom breasts utilized in this study not settling laterally as patients breasts tend to do. For this reason, the phantoms contralateral breast remains closer to the beam edge and hence may receive a higher dose.

The MOSFET uncertainty was large at positions outside the CBCT field-of-view and out-of-field of the treatment beams, see Table I. This is attributable to the MOSFETs lower detection limit of approximately 0.15 cGy.[36] For this reason, the MOSFETs utilized in this study would not be suitable for clinical skin dose measurements far from the treatment or imaging field-of-views unless, as mentioned above, the gate oxide thickness[30,31] and gate bias[32] is increased.

To the best of our knowledge, there have been no studies evaluating the influence of concomitant imaging on skin

TABLE I. Skin dose measured with TLDs and MO*Skin*s from a single treatment fraction and a single 8 MU MV CBCT to the head and neck region (H1–H6), the contralateral breast (lateral C1–medial C6), the ipsilateral breast (medial C7–lateral C12), and the pelvic region (P1–P5). The detector positions are detailed in Fig. 1.

	Single treatment fraction		Single 8 MU MV CBCT	
Position	TLD Dose (cGy) ±95% CI	MOSFET Dose (cGy) ±95% CI	TLD Dose (cGy) ±95% CI	MOSFET Dose (cGy) ±95% CI
H1	0.69 ± 0.01	0.57 ± 0.34	0.09 ± 0.05	0.02 ± 0.23
H2	1.37 ± 0.11	1.67 ± 0.13	0.20 ± 0.02	0.25 ± 0.29
H3	1.79 ± 0.12	2.36 ± 0.56	0.24 ± 0.08	0.16 ± 0.20
H4	1.82 ± 0.11	1.94 ± 0.41	0.22 ± 0.01	0.19 ± 0.53
H5	0.89 ± 0.03	0.94 ± 0.45	0.20 ± 0.04	0.21 ± 0.14
C1	3.10 ± 0.11	3.47 ± 0.67	3.68 ± 0.39	2.19 ± 0.27
C2	4.19 ± 0.13	4.43 ± 0.42	3.57 ± 0.45	2.10 ± 0.35
C3	7.40 ± 0.22	7.82 ± 0.51	2.97 ± 0.13	1.90 ± 0.17
C4	12.7 ± 0.09	12.8 ± 0.59	3.36 ± 0.45	2.08 ± 0.22
C5	17.9 ± 0.48	18.0 ± 0.63	3.80 ± 0.52	2.43 ± 0.24
C6	24.2 ± 2.69	26.7 ± 1.37	4.29 ± 0.73	2.77 ± 0.22
C7	57.8 ± 3.22	48.8 ± 1.43	4.47 ± 0.17	2.99 ± 0.26
C8	132 ± 2.32	88.1 ± 3.30	3.25 ± 0.27	2.16 ± 0.25
C9	130 ± 5.25	99.5 ± 3.25	2.90 ± 0.06	1.84 ± 0.08
C10	151 ± 1.27	120 ± 1.44	2.71 ± 0.31	1.83 ± 0.09
C11	128 ± 4.21	103 ± 2.64	3.17 ± 0.19	2.25 ± 0.23
C12	135 ± 2.86	96.8 ± 2.66	3.91 ± 0.37	2.74 ± 0.14
P1	2.25 ± 0.01	2.63 ± 0.26	0.62 ± 0.07	0.66 ± 0.26
P2	0.60 ± 0.04	1.10 ± 0.09	0.22 ± 0.10	0.20 ± 0.85
P3	1.13 ± 0.01	1.24 ± 0.32	0.28 ± 0.10	0.29 ± 0.50
P4	1.37 ± 0.25	1.31 ± 0.15	0.23 ± 0.01	0.24 ± 0.51
P5	0.51 ± 0.00	0.36 ± 0.23	0.12 ± 0.07	0.20 ± 0.86

toxicity. The impact of the MV CBCT imaging dose on skin toxicity was assessed according to studies which have investigated the deterministic and stochastic effects of skin irradiation.[2,37] This is not ideal, however, was deemed reasonable. Daily imaging was considered in this study, as this imaging schedule would deliver the highest imaging dose to the patient. This schedule would most likely not increase the possibility of contralateral breast skin reactions as it would not raise the total contralateral breast skin dose above the single fraction dose threshold (5 Gy) or total fractionated dose threshold (approximately 20 Gy) for mild deterministic effects.[2] However, the dose delivered to the contralateral breast during radiotherapy treatment is associated with an increased long-term risk of contralateral breast cancer,[38] the additional imaging dose may increase this risk. In the ipsilateral breast region (points C7–C12) the imaging dose as a percentage of treatment dose was as expected minimal (up to 3%), see Fig. 3. This is attributable to these measurement points being within both the treatment and CBCT field-of-view and the imaging dose being small in comparison to the treatment dose, see Table I. The imaging dose to the head and pelvic regions was up to 20% of the out-of-field skin dose delivered from the treatment at the same locations.

The contralateral breast (points C1–C6), head (points H1–H5) and pelvis (P1–P5) skin dose from the treatment alone consists of leakage, extra focal scatter and electron contamination. The contralateral breast is in the MV CBCT field-of-view and out-of-field of the treatment beams. Hence, the magnitude of the MV CBCT dose contribution to the total contralateral breast dose is significantly higher than that of the breast radiotherapy treatment. The delivered dose from an 8 MU MV CBCT is up to 118 and 62% of the dose delivered from treatment, for the TLDs and MOSFETs, respectively. An 8 MU MV CBCT increases the dose delivered to location C1 from 0.03 ± 0.01 Gy, for both detectors, for a single treatment fraction to 0.07 ± 0.02 Gy and 0.05 ± 0.02 Gy, for TLDs and MOSFETs, respectively. The large percentage difference between the TLD and MOSFETs is attributable to the detectors measuring similar skin dose values out-of-field of the treatment beams (at point C1 a difference of 0.5 cGy) and different skin dose values in the field-of-view of the CBCT scan (at point C1, a difference of 1.5 cGy). The dose discrepancy in-field of both the MV CBCT and treatment beams is attributable to differences in effective depth dose measurements. The MO*Skin* MOSFET WED of measurement is 0.07 mm whereas for the TLDs the WED is approximately 1 mm. Large charged-particle disequilibrium exists at these depths and thus a small change in depth will result in a large change in dose measured. Out-of-field the photon spectrum does not vary significantly[39,40] and hence the measurement WED of the detector has little effect on the dose measurement. Consequently, the TLD and MOSFET skin dose measurements in the head and pelvic region were within one standard deviation of each other.

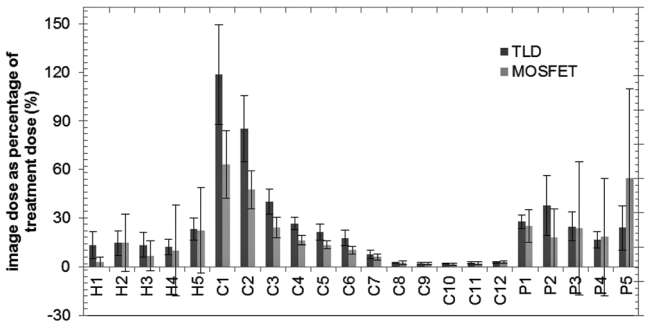

FIG. 3. The measured skin dose from a single 8 MU MV CBCT is presented as a percentage of the measured skin dose from a single treatment fraction. The error bars represent 95% confidence intervals.

Measurements in this study were completed under ideal conditions in that the phantom utilized was moderately inflexible and hence could be set up consistently. The single size and shape of the female anthropomorphic phantom limited the study as the interpatient variation seen in practice is not represented by these measurements. Additionally, the phantoms breasts sit upright on the chest wall and do not fall laterally with gravity, as a patient's breast might. Consequently, the phantoms contralateral breast remains closer to the edge of the treatment beam and hence may result in a higher measured dose in comparison to a typical patient.

Knowledge of the imaging skin dose separate from that of the treatment dose is necessary in order to assess its impact on side effects such as skin toxicity. This can be accomplished with the TLDs and MOSFETs utilized in this study. The MOSFETs allow real time skin dose measurements and hence may be more practical for future in-field *in vivo* measurements.

V. CONCLUSION

One MV CBCT per fraction was found to increase the out-of-field skin dose by approximately 20%. The contralateral breast skin dose from the treatment alone consists of leakage, extra focal scatter and electron contamination. The magnitude of the MV CBCT dose contribution is significantly higher than this. It is up to 118 and 62% of the dose delivered from treatment, for the TLDs and MOSFETs, respectively. In comparison, the imaging dose as a percentage of treatment doses in the ipsilateral breast region was 3% for both dosimeters. This extra dose will most likely not increase the skin toxicity in the treated breast. The skin dose to the contralateral breast is probably not enough to induce skin reactions but will add to the risk of second malignancy.[38] With the advent of new interface dosimeters accurate *in vivo* skin dose assessment is possible, linking this dose assessment to patient's reactions and secondary cancer risk remains the next challenge.

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