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Original paper

In vivo dosimetry with MOSFETs and GAFCHROMIC films during electron IORT for Accelerated Partial Breast Irradiation

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ABSTRACT

Purpose: The purpose of this study was to compare the delivered dose to the expected intraoperative radiation therapy (IORT) dose with *in vivo* dosimetry. For IORT using electrons in accelerated partial breast irradiation, this is especially relevant since a high dose is delivered in a single fraction.

Methods: For 47 of breast cancer patients, *in vivo* dosimetry was performed with MOSFETs and/or GAFCHROMIC EBT2 films. A total dose of 23.33 Gy at d_{max} was given directly after completing the lumpectomy procedure with electron beams generated with an IORT dedicated mobile accelerator. A protection disk was used to shield the thoracic wall.

Results: The results of *in vivo* MOSFET dosimetry for 27 patients and GAFROMIC film dosimetry for 20 patients were analysed. The entry dose for the breast tissue, measured with MOSFETs, (mean value 22.3 Gy, SD 3.4%) agreed within 1.7% with the expected dose (mean value 21.9 Gy). The dose in breast tissue, measured with GAFCHROMIC films (mean value 23.50 Gy) was on average within 0.7% (SD = 3.7%, range −5.5% to 5.6%) of the prescribed dose of 23.33 Gy.

Conclusions: The dose measured with MOSFETs and GAFROMIC EBT2 films agreed well with the expected dose. For both methods, the dose to the thoracic wall, lungs and heart for left sided patents was lower than 2.5 Gy even when 12 MeV was applied. The positioning time of GAFCHROMIC films is negligible and based on our results we recommend its use as a standard tool for patient quality assurance during breast cancer IORT.

1. Introduction

Since the publication of ASTRO [1] and ESTRO [2] guidelines, Accelerated Partial Breast Irradiation (APBI) to irradiate the tumour bed after lumpectomy is indicated as a standard of care for low risk breast cancer patients. According to the adapted ASTRO guidelines [3], APBI has been tested in a number of trials with several hundred patients over the last 10 years and shown, in properly selected breast cancer patients, similar outcomes as with whole breast radiotherapy.

Intraoperative radiotherapy, using electrons, as delivered by a single dose was introduced by U. Veronesi et al. (ELIOT) [4] and is one of the APBI techniques. ELIOT was delivered by mobile linear accelerators immediately after lumpectomy (and sentinel node procedure) with a single dose of 21 Gy (prescribed at the 90% isodose). To protect normal tissues during the ELIOT procedure, a protection disk was used [5].

In vivo dosimetry is an important tool to check whether the delivered dose conforms to the expected dose. Only a few *in vivo* dosimetry studies for electron IORT have been published until now [6–12]. For single fraction IORT treatments like ELIOT, this is especially relevant since a high dose is delivered in a single fraction. Ciocca et al. [6] described *in vivo* dosimetry with MD-55-2 radiochromic films (GAFCHROMIC, International Specialty Products, USA) to measure entrance dose during the ELIOT procedure with an estimated overall uncertainty of 4%. In their breast protocol, Consorti et al. [7] applied MOSFETs (metal-oxide semiconductor field-effect transistors) for real-time *in vivo* dosimetry and concluded that the measured dose between the protection disk and mammary tissue was within ± 5% of the predicted values.

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Ciocca et al. [8] achieved comparable results with micro-MOSFETs in measuring entrance doses during ELIOT procedures. Some disadvantages of MOSFETs were found, such as limited lifetime and the anisotropy with no build-up. Moreover, MOSFET dosimetry remains a single-point measurement while the use of radiochromic films gives detailed two-dimensional information on the dose distribution. López-Tarjuelo et al. [11] used MD-55-2 radiochromic films and MOSFETs simultaneously for *in vivo* measurements. They concluded that films are less stable and showed a higher uncertainty (SD = 9%) than MOSFETs (SD = 6.7%), but are useful and convenient if real-time treatment monitoring is not necessary. The introduction of radiochromic EBT (external beam therapy) films gave a new impetus to *in vivo* film dosimetry as two-dimensional detectors due to improved film sensitivity and uniformity. Robatjazi et al. [12] presented results of *in vivo* dosimetry with EBT2 films of the surface dose in ten patients with early stage of breast cancer.

The aim of this work was to measure *in vivo* simultaneously the breast tissue dose as well as the dose behind the protection disk with MOSFETs and GAFCHROMIC films during a single fraction IORT procedure. Such measurements are important to estimate the dose to organs at risk (OAR) such as ribs and lungs and, for patients with left sided breast cancers, the heart. The measurements of the dose behind the protection disk with MOSFETs and GAFCHROMIC films were not performed in Refs. [6–12]. Additionally, with *in vivo* GAFCHROMIC film dosimetry we monitor protection shield misalignment and display the isodose lines in front and behind the protection disk for Accelerated Partial Breast Irradiation.

2. Materials and methods

2.1. Patients

During the period May 2010–December 2015, 381 low-risk breast cancer patients ≥60 years were treated with a single fraction IORT in our institution. The following inclusion criteria were used: invasive breast cancer or ductal carcinoma in situ (DCIS) in female patients aged 60 years or older, tumour size less than 3 cm, tumour-free resection margins of at least 2 mm and absence of axillary lymph node metastases [13]. Electron IORT was given directly after completing the lumpectomy and the sentinel node procedure (and confirmed absence of axillary lymph node metastases). During the surgical procedure, the presence of a tumour-free resection margin of at least 2 mm was checked by visual inspection of the lumpectomy specimen by the pathologist in case of a palpable lesion, or was determined by specimen radiology in case of a nonpalpable lesion. Written informed consent was obtained in all cases.

After the breast resection, a protection disk (6 mm of Al + 3 mm of Cu) at least 2 cm larger than the applicator diameter was placed between the distal face of the residual breast and the pectoralis muscle. A needle controlled the position of the protection disk during the operation. The composition of the protection disk was chosen to attenuate the beam almost completely for both considered energies (0.3% and 0.6% of residual dose for 9 MeV for 12 MeV, respectively) causing as little as possible backscatter radiation according to Monte Carlo calculations [14]. The authors reported that the results of ionization measurements were higher, *i.e.* 1.2% for 9 MeV and 2.0% for 12 MeV.

IORT with a total dose of 23.33 Gy at 100% (21 Gy at 90%) was given during the operation according to the method described in the ELIOT study [4]. The Clinical Target Volume (CTV) was defined as the tumour diameter plus 1 cm margin (minus the minimum surgical tumour free margin). The applicator diameter (field border) was 2 cm larger than the CTV with the minimal applicator diameter of 4 cm. Complete skin sparing was verified in each case. Dose specification was determined at the 100% (d_{max}) according to ICRU 71 [15] with the requirement that the 90% isodose must enclose the target volume.

For 47 of these patients, *in vivo* dosimetry was performed with MOSFETs (metal-oxide semiconductor field-effect transistors, TN-502RD) or/and GAFCHROMIC EBT2 films. For each method, first fifteen patients were consecutively chosen while the rest was randomly selected.

2.2. IORT accelerator

All patients were irradiated with electron beams generated with an IORT dedicated mobile accelerator (Mobetron 1000, INTRAOP, USA). This accelerator delivers only electrons and possesses a set of cylindrical stainless steel applicators from 3 up to 10 cm in diameter, in increments of 0.5 cm. For each field size, bevelled applicators of 15° and 30° are also supplied. Commissioning measurements were performed according to Mills et al. [16]. All measurements were carried out in a Wellhöfer watertank and based on these measurements the dose in water could be calculated for each energy and applicator combination. Additionally a transmission through the protection disk was measured for each energy with different applicators and found to be 0.5%, 1.0% and 10.9% for 6, 9 and 12 MeV, respectively. The transmission values for 9 and 12 MeV are higher than reported by Martignano et al. [14], probably because of a higher beam quality of the Mobetron in comparison with the energies of a linac (Elekta Precise) used for the Monte Carlo dose calculation. Before patient treatments, a quality control check with a dedicated quality assurance applicator from IntraOp was performed for each energy, as described by Mills et al. and according to the AAPM TG72 Report [17] recommendations. In five and half years the output and energy (ΔR50) stability relative to reference conditions were within 1% and 2 mm, respectively.

Out of 381 patients, 52%, 45% and 3% were irradiated with 12, 9 and 6 MeV, respectively. R50 of these energies for a 10 cm in diameter applicator are, respectively, equal to 4.88, 3.61 and 2.47 cm. R100 (d_{max}) of 12, 9 and 6 MeV are, respectively, equal to 2.20, 1.83 and 1.24 cm. Source to surface distance using the Mobetron applicators is approximately 50 cm. A needle at three or more points measured the tissue thickness from the surface till the protection disk. The maximum thickness was used to determine the energy used. A 0.5 cm or 1.0 cm water equivalent acrylic bolus supplied by IntraOp was used to increase the entrance dose to at least 90% and to create a more homogeneous thickness of breast tissue. The most used (41%) applicator diameter was 5 cm (range: 4–6.5 cm). The angle of the applicator was equal to 0° in most cases (76%), or bevelled (15° and 30° in 11% and 13%, respectively).

The Mobetron has a soft-docking system to align the treatment head to the applicator.

Formal beam calibration was performed on the treatment day for quality control purposes. We applied the output factor measured with the Roos chamber in a homemade acrylic plastic phantom to the patient measurements because the measurements with the IntraOp quality assurance (QA) tool are relative.

2.3. MOSFET measurements

The MOSFET system in our institution consists of an online wireless read-out system (for up to 5 detectors) and several MOSFET detectors (Thomson Nielsen TN-502RD) based on a dual-MOSFET dual-bias design [18]. The dual-bias design uses the difference between the two differently biased MOSFET readings as a measure for absorbed dose, resulting in better characteristics for e.g. temperature dependence [19]. The lifespan of the MOSFET detectors is limited to ~20,000 mV, corresponding to a dose range of 20,000 cGy for a standard bias setting. The basic evaluation of the MOSFETs consisted of measurement of linearity with dose, reproducibility in time, dose rate and energy dependence for electron beams of a conventional linear accelerator (Synergy, Elekta). The measurements of dose linearity, dependency on field size, dose rate, energy and angular response for electron beams in the range of 4–12 MeV were also performed at the Mobetron in a

homemade acrylic plastic (PMMA) phantom at the depth of dose maximum.

2.4. MOSFET in vivo dosimetry

The *in vivo* dose measurements were executed by attaching the first MOSFET detector under the bolus at the end of the applicator approximately in correspondence with the beam axis and the second detector behind the protection disk, which was used to shield the thoracic wall. Each MOSFET detector was packed in a sterile and transparent plastic bag. The MOSFET detectors were oriented with their epoxy side towards the radiation beam.

The field perturbation by the MOSFET was assessed using by film dosimetry (KODAK X-Omat V) with a 6 cm applicator at the dose maximum in the custom made PMMA phantom. Additionally, the influence of the sterile bag as a difference in MOSFET readings with and without this bag was measured.

Calibration of the MOSFET detectors was done by measuring the absolute dose with a Roos plane-parallel ionization chamber on the same day. The calibration measurements were performed with the electron beams of the Mobetron in a homemade PMMA phantom ($30 \times 30 \times 20\,cm^3$) at the depth of dose maximum for each energy. This calibration of the MOSFETs in the PMMA phantom was cross-correlated to the absolute dosimetry in a water phantom.

The expected dose was calculated under the water equivalent bolus and behind the protection disk based on the thickness of the breast tissue and the transmission of this disk. These calculations were made on basis of water measurements and taking the geometry of the beam into account.

2.5. GAFCHROMIC EBT2 film, scanning procedure

The structure of the EBT2 GAFCHROMIC (International Specialty Products, USA) film model is made by combining clear polyester overlaminate with the active film coating. The substrate of the active film is clear (175 μm) polyester coated with an active layer film (nominally 30 μm thick) over which a topcoat (nominally 5 μm) is applied. The over-laminate (50 μm) polyester with approximately 25 μm of pressure-sensitive adhesive is bound to the coated side of the active film. The EBT2 films (8 × 10 inch sheets, from one batch) used in this study were handled according to manufacturer recommendations [20] and those outlined in the American Association of Physicists in Medicine (AAPM) Task Group Report 55 [21]. According to these recommendations all colour corrections and image enhancement options were disabled to get the raw data without pre-processing. The EBT2 films were scanned with EPSON V750 PRO colour scanner 24 h after irradiation to reduce time-after-exposure differences in 48-bit RGB mode. The images were acquired in transmission mode. The spatial resolution of the scans was 72 dots per inch. For calibration purposes, a film was cut in strips of $10 \times 8\,cm^2$. For *in vivo* dosimetry, the strips of 8 cm in diameter were used to be of the same size as the most used protection disk. During the cutting of the films, all strips of the films were scanned in the same direction according to labelling in respect to the original sheet. Moreover, each piece of the film was placed in the centre of the available scan area to reduce the lateral artefacts [22,23]. The optical density is greater at the lateral edges of the scanner's field of view and this effect is also dose-dependent, being smaller at low doses, but becoming more substantial at higher doses. An unexposed film representative for this batch was scanned as well.

2.6. GAFCHROMIC EBT2 film in vivo dosimetry

During the dose measurements with GAFROMIC films, the first and the second films were placed before and after the protection disk, respectively. For sterilization purposes, the protection disk together with the GAFCHROMIC films was packed in a sterile foil (OpSite Flexifix).

According to Baghani et al. [24], the EBT2 film response is independent of physical parameters of intraoperative electron beam including energy, field size, dose rate, and incidence angle. Our calibration measurements of the GAFCHROMIC films were performed with the electron beams of the Mobetron with an applicator of 6 cm in diameter in the same custom made PMMA phantom at the depth of approximate dose maximum for each energy (9 and 12 MeV). Cross-calibration of the GAFCHROMIC films was performed by measuring the absolute dose with a Roos plane-parallel ionization chamber in the same PMMA phantom. Additionally, the calibration measurements were performed for each film placed at the depth of approximate dose maximum on the aluminium part of the protection disk in the same PMMA phantom. This was done to determine the degree of backscattering due to the protection disk (6 mm of Al + 3 mm of Cu) and to be able to account for this.

2.7. Image processing and dose response curve

According to the manufacturer, in principle any of the colour channels of GAFCHROMIC films could be used for measurements. However, it is preferable to use the colour channel that has the greatest response gradient, i.e. the highest change in response per unit change in dose. Using this criterion it is clear that for doses > 10 Gy the response gradient is the greatest in the green colour channel. At doses in the range 5–10 Gy the response gradients are similar in the red and green channels. The response in the blue channel has a substantially lower response gradient because of the influence of the marker dye.

A MATLAB 7.5.0 program (Math Works, US) was written to standardize processing of GAFCHROMIC film images based on the workaround proposed by A. Micke [22] and Lewis [23] for single channel dosimetry. The main steps of this workaround are:

1. Scan all films in the RGB (red, green and blue) mode on a colour scanner.
2. Convert the red, green and blue response from raw scanner values to transmittance (T):
3. T = scanner value/65535
4. Measure the average transmittance in the centre (1.5 cm in diameter) of the calibration films to get responses in the red, green and blue colour channels and fit it to the function:

$$T(D) = (A \cdot D + B)/(D + C)$$

where D is the dose and A, B, C are constants.

5. Plot each channel optical density ($-\log_{10}(T)$) versus dose.
6. Use the function in Step 3 to convert the measurement films, from transmittance values to dose values for green and red channels for the energy used.

Based on measurements with 6 MV photons, Devic et al. [25] recommended using the red channel of EBT (external beam therapy) GAFCHROMIC films in the dose range from 0 to 4 Gy, the green channel from 4 to 50 Gy and the blue channel for doses above 50 Gy to get both precision and accuracy below 1.5%. For electron IORT, Robatjazi et al. [12] used a calibration of the EBT2 film at 0–8 Gy for machine quality assurance by analysis of the red channel and 8–24 Gy for patient-specific QA by an analysis of the green channel. According to [12,22,25,26] the green and red colour channel were used in this work for the dose evaluation in front of and behind the protection disk, respectively.

3. Results

3.1. Basic evaluation of MOSFETs

Basic evaluation of MOSFETs at a conventional linear accelerator

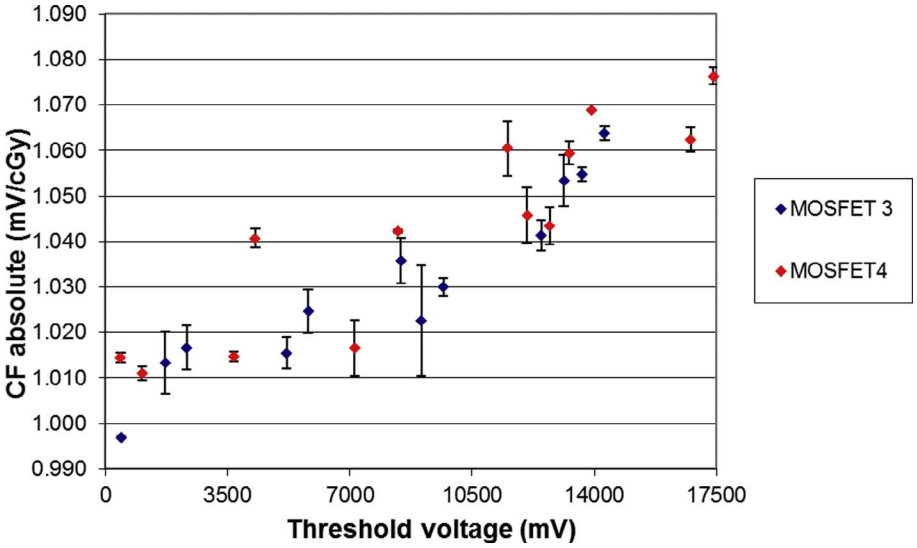

Fig. 1. Calibration factor (CF) for MOSFET readings (mV/cGy) versus threshold voltage for two out of six MOSFET detectors used. All measurements were done on the Mobetron accelerator, using an applicator of 10 cm in diameter. The error bars indicate the standard deviation of 3 or 4 measurements.

led to the following results: good dose linearity in the range of 0.1–10 Gy, with variations less than 3% in successive measurements; no dose rate dependence (100–400 MU/min); and small (within 3%) energy dependence. The results of basic evaluation of the IORT dedicated mobile accelerator were: good dose linearity in the range 2–20 Gy; no or only small (within 3%) energy dependence (4, 6, 9 and 12 MeV); no or only small (within 3%) field size dependence (3, 6 and 10 cm in diameter); no temperature dependence (21–41 °C); no or only small (within 3%) angular dependence (0–180°). The calibration factors depend on threshold voltage (see Fig. 1).

For the IORT dedicated mobile accelerator, the inherent uncertainty of MOSFETs in the measurement under reference conditions was 2.5%.

3.2. MOSFET in vivo dosimetry

The results of *in vivo* MOSFET dosimetry for 27 patients are shown in Fig. 2. The dose measured with MOSFETs under the bolus at the breast tissue surface (mean value 22.3 Gy, position 1, see Fig. 3) agrees within 1.7% (1 SD = 3.4%, range: from −9.1% to 5.9%) with the expected dose (mean value 21.9 Gy). For a single patient measurement with MOSFETs, the inherent uncertainty was 3.5% for position 1 and about 5% for position 2, even for bevelled applicators. In 3 and 8 of 27 patients the applicators of 15° and 30° were used, respectively, and the results were also very good even for these applicators. The maximum deviation of -9.1% from the expected dose was registered because of a displacement in the position of the MOSFET.

The influence of the sterile bag on the MOSFET was measured with 6 MeV electrons and resulted in a difference of MOSFET readings of 0.8%, i.e. within the uncertainty of the MOSFET measurements. The dose perturbation by the MOSFET resulted in the maximum decrease in dose in the underlying tissue of 2%.

The dose measured with MOSFETs under the protection disk was less than 2.1 Gy (mean dose 0.2 Gy, range: 0.05 Gy to 2.05 Gy) even for 12 MeV. For 6 and 9 MeV the measured dose was less than 0.2 Gy. The expected dose averaged over 27 patients was 0.6 Gy (range: 0.1 Gy to 2.33 Gy).

3.3. GAFCHROMIC EBT2 film in vivo dosimetry

The calibration curves for the red, green and blue colour channels are presented in Fig. 4 for EBT2 GAFCHROMIC films placed at the same depth in the PMMA phantom (a, b) and on top of the aluminium part of the protection disk (c, d) in the same PMMA phantom for 9 and 12 MeV. In the case of measurements on the protection disk, the dose was taken without correction for backscattering. For each colour channel and each energy, a difference was clearly seen. Afterwards, this difference was minimized by correcting for a backscatter effect of 9% for 9 MeV and 12 MeV (see Fig. 4).

For a measurement under reference conditions and a single patient measurement with GAFCHROMIC films, the inherent uncertainty was approximately 2% and 3% for position 1 (approximately 4% for position 2), respectively. The dose measured with GAFCHROMIC films at

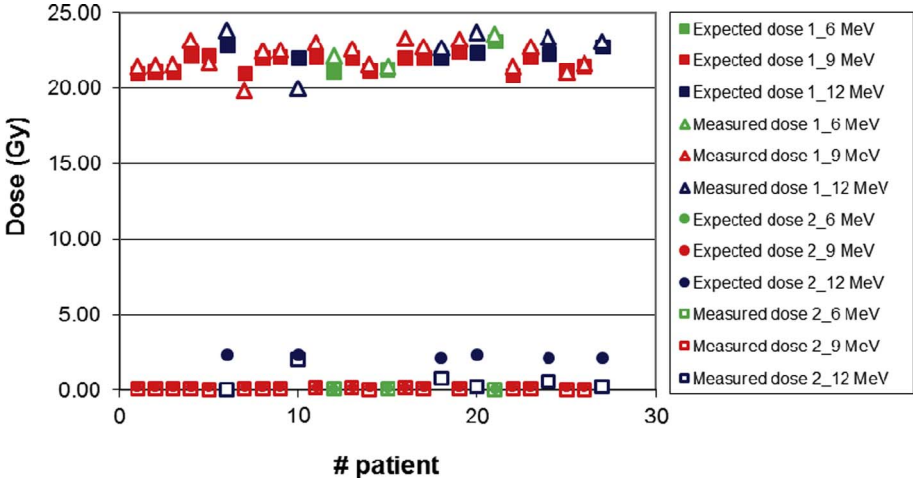

Fig. 2. Results of MOSFET *in vivo* measurements for 27 patients under the water equivalent bolus at the breast tissue surface (position 1) and behind the protection disk (position 2) in comparison with the expected dose for 6 (green), 9 (red) and 12 MeV (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

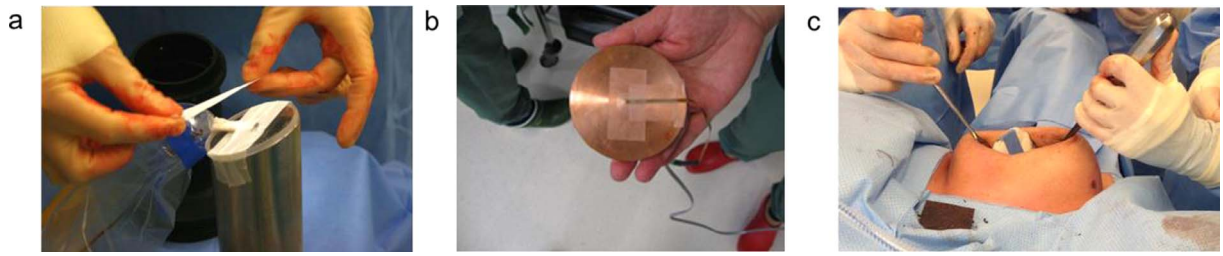

Fig. 3. The first MOSFET detector was taped under the bolus at the end of the applicator, and then the bolus with the detector was packed in a sterile bag (position 1, a). The second detector was attached behind the protection disk and then the disk with the detector packed in a sterile bag (position 2, b). The placement of the protection disk with EBT2 GAFCHROMIC films packed in a sterile bag in the breast tissue (c).

the centre of the irradiated area in depth of breast tissue (in front of the protection disk, green channel, without backscattering correction) (mean value 23.61 Gy) was on average for 15 patients within 1.2% (SD = 3.6%, range −4.7% to 5.8%) of the prescribed dose of 23.33 Gy (see Fig. 5). The average breast tissue depth for these measurements was 1.87 cm (range: 1.1 to 3.0 cm). The results of GAFCHROMIC film *in vivo* dosimetry using the calibration in PMMA are, after correction for backscattering, also in a good agreement (mean value 23.50 Gy, mean value difference = 0.7%, SD = 3.7%, range −5.5% to 5.6%) with the prescribed dose. In 2 and 4 of the 15 patients bevelled applicators of 15° and 30° were, respectively, used and the deviations of the results were larger for these applicators than for the applicators of 0°.

The dose measured at the highest dose area behind the protection disk averaged over 20 patients was 0.62 Gy, 0.21 Gy for 9 MeV and 1.38 Gy for 12 MeV (see Fig. 5). For three out of 20 patients, the dose behind the protection disk was also measured with MOSFETs and these results were in a good agreement with GAFCHROMIC film measurements: MOSFETS dose 0.04, 0.23, 0.05 Gy and GAFCHROMIC dose 0.2,

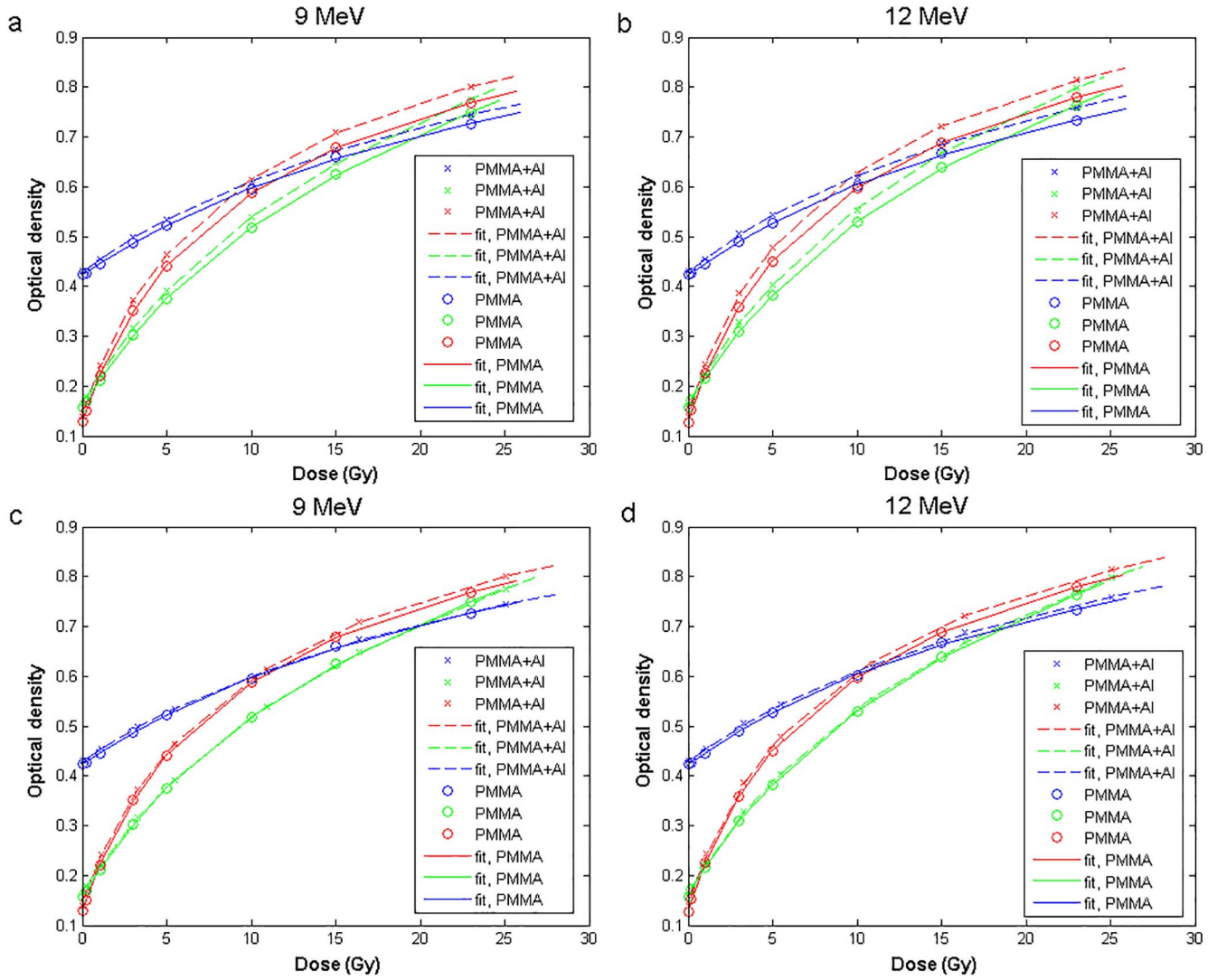

Fig. 4. Calibration curves for the red, green and blue colour channels for EBT2 GAFCHROMIC films placed at the same depth in the PMMA phantom and on top of the aluminium part of the protection disk in the same PMMA phantom for 9 MeV (a) and 12 MeV (b). Calibration curves for the red, green and blue colour channels after correction for a backscatter effect of 9% for 9 MeV (c) and for 12 MeV (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

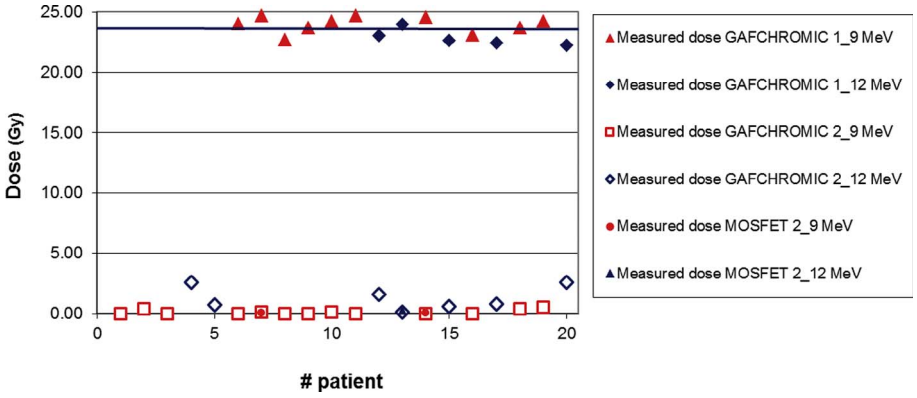

Fig. 5. Results of GAFCHROMIC EBT2 film *in vivo* measurements for 20 patients in breast tissue in front of the protection disk (position 1) and behind the protection disk (position 2) for 9 (red) and 12 MeV (blue). The prescribed dose is given as a dark blue line. In the first five patients, the measurements with GAFCHROMIC films were not performed in position 1. For three of the 20 patients, the dose behind the protection disk was also measured with MOSFETs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

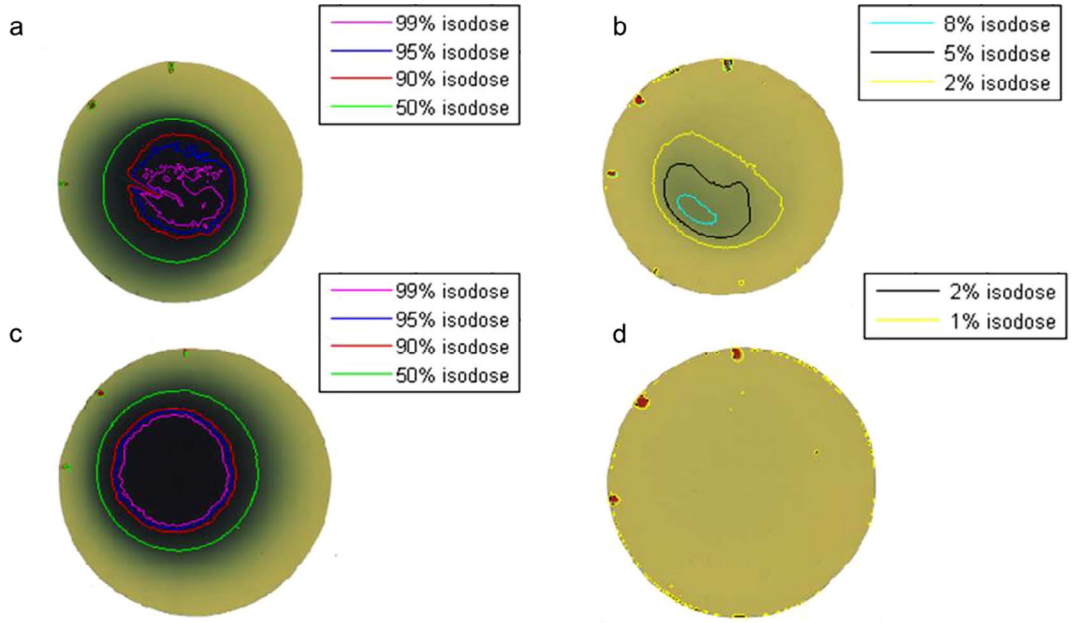

Fig. 6. Two representative examples of GAFCHROMIC EBT2 films with the isodose distribution in front of the protection disk (a, c) and behind the protection disk (b, d). For patient 12 who was treated with 12 MeV, an applicator of 4 cm with a bevel angle of 30° and a protection disk of 7 cm was used (a, b). For patient 14 who was treated with 9 MeV, an applicator of 4.5 cm with a bevel angle of 15° and a protection disk of 8 cm was used (a, b).

0.2, 0.1 Gy, respectively.

Some examples of the GAFCHROMIC EBT2 films are presented in Figs. 6 and 7, showing the isodose lines. In these examples, the dose behind the protection disk is about 8% of the prescribed dose for 12 MeV and less than 1% for 9 MeV, which is representative for all other patients. In two cases with an applicator with a bevel angle of 30° and 15°, presented in Fig. 6, there was no misalignment of the protection disk relative to the applicator. It can also be seen that isodose lines before the protection disk are quite symmetrical, which confirms our hypothesis that the applied bolus homogenizes tissue thickness, leading to a uniformly applied dose in the glandular breast tissue.

In 2 out of 4 patients with a protection disk of 7 cm in diameter, a misalignment of the protection disk relative to the applicator occurred whereas this occurred in only 1 of 11 patients with a larger protection disk of 8 cm. Two examples of such misalignment are given in Fig. 7.

4. Discussion

A high accuracy in dose delivery during single fraction IORT is required to observe any effect of dose on local control of the tumour or normal tissue complications. Unfortunately, there is no reliable image-based treatment planning system for IORT until now. Therefore, *in vivo* dosimetry is an important tool to check whether the delivered dose conforms to the expected dose. For IORT in accelerated partial breast irradiation, this is especially relevant since the high dose is delivered in a single fraction. The aim of this work was to measure simultaneously *in vivo* the breast tissue dose and the dose behind the protection disk with MOSFETs and GAFCHROMIC films during single fraction IORT procedures. Such measurements are important to estimate the dose to organs at risk (OAR) such as ribs, lungs and, for patients with left sided breast cancer, heart, during a single dose treatment of 23.33 Gy at d_{max} (21 Gy at 90%) to the target.

The results of our *in vivo* MOSFET measurements for 27 breast cancer patients are in good agreement with the results by Consorti et al. [7] and Ciocca et al. [8] for entrance dose measurements. The deviation from the expected dose of our patient measurements of ± 3.7% under the bolus at the breast tissue is comparable to their results. The results were even very good for the applicators of 15° and 30°. This result is in accordance with our angular dependence within 3% and comparable with the angular dependence of Ciocca et al. (less than 4%), corresponding to the epoxy side facing the beam. For the same model of MOSFET detectors, a larger angular dependence (5% or 8.8%) was reported by Bharanidharan et al. [27] for photon beams and by Phurailatpam et al. [28] for Ir-192 HDR brachytherapy. The slightly lower average dose measured by MOSFETs than the expected dose can probably be explained by the influence of the sterile bag of the MOSFET

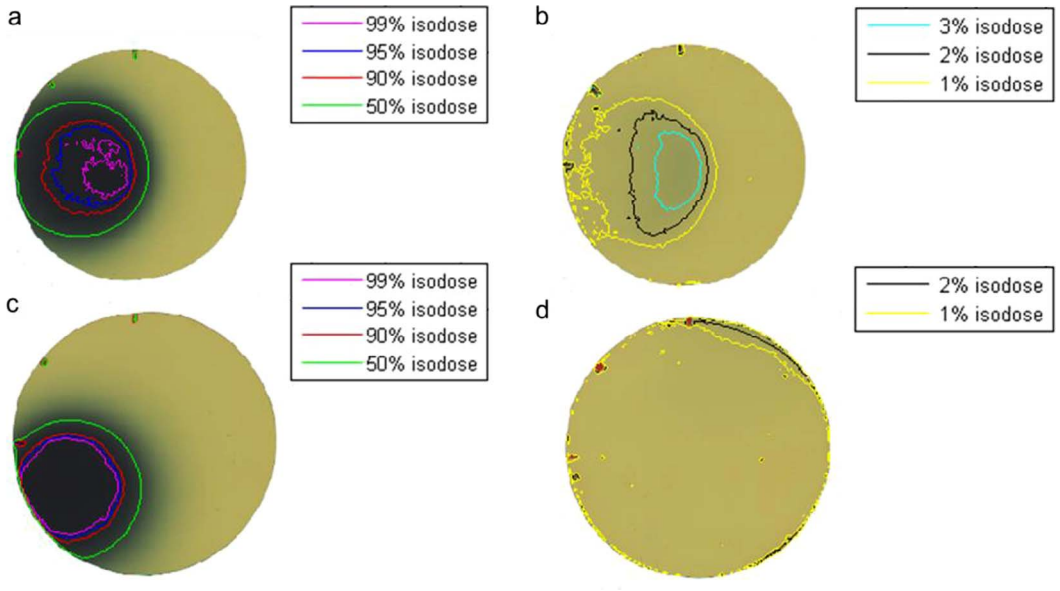

Fig. 7. Two examples of GAFCHROMIC EBT2 films with the isodose distribution in front of the protection disk (a, c) and behind the protection disk (b, d). For patient 17 who was treated with 12 MeV, an applicator of 4 cm and a bevel angle of 0°, a protection disk of 7 cm was used (a, b). For patient 7 who was treated with 9 MeV, an applicator of 4 cm and a bevel angle of 0°, a protection disk of 8 cm was used (a, b).

of about 0.8%, i.e. within the uncertainty of the MOSFET measurements. A dose perturbation by the MOSFET of less than 2% was found for 6 MeV. Consorti, describing this effect for the same type of MOSFETs in a plastic catheter as negligible, observed that the perturbation ranged from 1.5% to 20% at the lowest electron energies (4 MeV). Our results showed that the accuracy of *in vivo* MOSFET dosimetry for electron IORT is according to 1.5–5% uncertainties which Hensley described in his review [29].

We attempted to define a real-time action level as ± 6% proposed by Ciocca however all our measurements were inside this action level except the one caused by a displacement in the position of the MOSFET.

Additionally, we measured the dose under the protection disk with MOSFETs and found values up to 0.2 Gy for 6 and 9 MeV and up to 2.1 Gy for 12 MeV.

A backscatter effect of 9% for 9 MeV and for 12 MeV due to a protection disk of 6 mm of aluminium and 3 mm of copper was measured with GAFCHROMIC films. These backscattering values are slightly higher than the backscatter factors of 7% and 8% for 9 and 12 MeV, respectively, calculated by Martignano et al. [14]. The reason for this difference could be a slightly higher beam quality of the Mobetron in comparison with the energies of a linac (Elekta Precise) used for the Monte Carlo dose calculations by Martignano. This factor can also be a reason of higher attenuation factors measured with ionization chamber and *in vivo* film dosimetry relative to the Monte Carlo dose calculations by Martignano.

The results of *in vivo* dosimetry with GAFCHROMIC EBT2 films presented in this work are in good agreement with the results of Ciocca et al. [6] and Robatjazi et al. [12] although they measured the surface dose whereas in this work the dose measured behind the glandular breast tissue, before the protection disk (exit dose) is reported. Severnigni et al. [30] reported that in 95% of the cases of *in vivo* dosimetry with EBT3 films a good agreement of the exit dose with the prescribed dose has been obtained with an average difference of less than 4%. Our results of 0.7% ± 3.7% deviation from the prescribed dose showed that the accuracy of *in vivo* dosimetry with GAFCHROMIC EBT2 films for electron IORT is comparable or better than standard deviations for electron beam measurements from conventional units. Hensley [24] has shown these deviations range between 3.5% and 9.9% with the mean deviations typically shifted by a few per cent from expected dose.

As stated by Ciocca et al. [31], the most critical failure mode in IORT consisted of internal shield misalignment and it can be monitored by *in vivo* GAFCHROMIC film dosimetry. As we showed in this study, using a larger protection disk results in a smaller chance of misalignment than for smaller protection disks. As a result of this work, we improved our IORT procedure for APBI by using a protection disk of 8 cm as a standard and our surgeons became better aware of a possible protection shield displacement. Unfortunately, it is not possible to use a protection disk of 8 cm for all patients, for example patients with smaller breast. Dries et al. [32] proposed a fixed alignment of the protection disk using a spacer to reduce accidental radiation dose to the thoracic wall. The fixed alignment of the disk allows a reduction of the diameter of the disk and, consequently, reduces the incision length. They concluded that disk backscatter, tissue density variations and air gaps can influence dose uniformity significantly.

5. Conclusions

Results of *in vivo* MOSFET and GAFROMIC EBT2 film dosimetry during electron IORT were assessed. The results of both methods are in a good agreement. The dose measured with MOSFETs under the water equivalent bolus at the breast tissue agreed within 1.7% ± 3.7% with the expected dose. The exit breast dose of *in vivo* dosimetry with GAFCHROMIC EBT2 films for electron IORT was found within 0.7% ± 3.7% relative to the prescribed dose, which is comparable or better than described in literature. For both methods, the dose to the thoracic wall, lungs and heart in patients with breast cancer was lower than 2.5 Gy even when 12 MeV was applied. Additionally, *in vivo* GAFCHROMIC film dosimetry can monitor protection shield misalignment and display the isodose lines in front and behind the protection disk as has been demonstrated in this work. As a result, we improved our IORT procedure for APBI by using as a standard a protection disk of 8 cm and our surgeons became better aware of a possible protection shield displacement. Although using GAFCHROMIC film as a QA tool has the disadvantage of producing results after the treatment and not in real time, we still prefer the film to MOSFET because of at least four reasons: one measures the dose at the distal region to test the adequacy of the penetration; one can look at isodoses to confirm uniformity; one can see if the shield was well placed and the calibration factors of MOSFETs depend on threshold voltage. Moreover, the positioning time

of GAFCHROMIC films is negligible and based on our results we recommend to use it as standard tool for patient quality assurance during breast cancer IORT.

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