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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