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Fetal dose estimation for Virtual Tangential-fields Arc Therapy whole breast irradiation by optically stimulated luminescence dosimeters

F. Dusi [a,*], F. Guida [a], E.N. Villegas Garcia [b], M.A. Rossato [a], A. Germani [a], S. Sapignoli [a], A. Scaggion [a], A. Scott [c], A. Zorz [a], M. Paiusco [a]

[a] Medical Physics Department, Veneto Institute of Oncology IOV – IRCCS, Padua, Italy
[b] The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy
[c] National Cancer Treatment Centre, Cornwall Regional Hospital, Montego Bay, Jamaica

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ABSTRACT

Breast cancer is the most frequently diagnosed tumor in pregnant women and radiation therapy should carefully be weighted up because of the dose to the fetus. The aim of this study was to investigate fetal dose in a patient treated with Virtual Tangential-fields Arc Therapy (ViTAT), an innovative technique for whole breast irradiation. Optically stimulated luminescence detectors (OSLDs) were calibrated on a Varian TrueBeam linac, with both a 6X and 6XFFF beam quality, and used for out-of-field measurements. Fetal dose related with ViTAT technique was compared to the standard 3D conformal radiation therapy technique (3DCRT). The fetal dose delivered with a ViTAT technique planned with 6XFFF beam was also investigated. Measurements were taken on a phantom composed of Rando Alderson Phantom slices and solid water slabs. OSLDs were placed in a region identified by the height of the fundus from conception to the twentieth week using a custom made PMMA grid. Due to the higher number of monitor units, the peripheral dose of ViTAT delivered with 6X beams is higher than that of 3DCRT. However, nanoDots measurements prove that ViTAT can be used in place of 3DCRT while maintaining similar fetal dose levels if 6XFFF beams are used.

Introduction

Breast cancer is the most common type of cancer in women [1], as well as the most frequently diagnosed tumor in pregnant women [2]. Although it is desirable not to treat pregnant patients with radiation, at times it may be unavoidable. In these cases, the absorbed dose to the fetus has to be carefully estimated, as the fetus is very sensitive to even low levels of radiation, and adverse effects include malformation, severe intellectual disability and risk of cancer [3–5].

Out-of-field dose, and consequently the fetus dose, is strongly dependent on treatment technique [6]. It has already been demonstrated that advanced radiotherapy techniques such as IMRT, VMAT and tomotherapy present high peripheral doses because field modulation increases head leakage and collimator scatter [7–11].

Recently, an innovative technique for whole breast irradiation has been introduced: Virtual Tangential-fields Arc Therapy (ViTAT) [12]. This technique mimics the performance of the still largely used tangential field irradiation (TF) with improved PTV homogeneity and slightly better sparing of contralateral OARs, while allowing for automatic knowledge-based planning [13].

Nothing has been reported about fetal dose evaluation with Virtual Tangential-fields Arc Therapy for breast cancer irradiation. In this context, this work aims to estimate the radiation dose delivered to the fetus when ViTAT modality is applied and compare it to that obtained by the still largely used three-dimensional conformal radiation therapy (3DCRT).

Since it has been largely shown that use of FFF (flattening filter free) beams reduces the low dose spread during VMAT [14–18], due to its lower scatter and leakage dose, the work introduces a ViTAT plan solution with FFF beams and the related fetal doses are investigated.

Fetal dose estimation for radiotherapy requires particular attention on the part of the medical physicist [19,20]. It is known that treatment planning systems (TPS) used for radiotherapy are not completely reliable and do not provide an accurate dose estimation far from the treatment field [21,22]. Fetal dose has been estimated through in vivo measurements or dosimeters inserted in phantoms [7,19,23–26].

* Corresponding author.
E-mail address: francesca.dusi@iov.veneto.it (F. Dusi).

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Measurements are challenging: out-of-field dose is a lot smaller than in-field dose, which requires a more sensitive detector, and the energy spectrum becomes softer with increased distance from the field edges [27], which requires that the energy response of the detector should be taken into account.

In this study OSLDs were selected for dose measurement because of their high sensitivity and small size [28,29]. In addition, OSLDs offer several advantages over the most frequently used thermo-luminescence dosimeters (TLDs): they can be read almost immediately without additional thermal processing and they can be read multiple times without a significant loss of signal [30].

To the best of our knowledge this study presents the first investigation of fetal doses delivered during ViTAT plans in breast cancer irradiation.

Materials and methods

Treatment plans

A combination of anthropomorphic Rando Alderson phantom slices and solid water slabs (Fig. 1) was scanned using GE Optima CT580 with a 2.5 mm slice thickness and the CT images were sent to the Eclipse TPS; breast target and ipsilateral lung were contoured. Three right breast treatments were planned with different modality: a 6X ViTAT, a 6XFFF ViTAT and, for comparison, a 6X 3DCRT plan with field in field technique (Table 1). ViTAT plans include 4 short lateral arcs and 4 short medial arcs in the range [220°, 240°] and [50°,70°], respectively. Arcs are optimized as sectors of 4 partial arcs [220°,70°] setting to zero the dose rate in the range [240°,50°]. ViTAT technique is quite similar to the delivery technique introduced by Munshi A. at al. [31] but it improves the coverage of the target and potentially the dose out of range since the suggested length of the arcs is reduced from 30° to 20°. As suggested by Esposito et al [12] a virtual bolus with a thickness of 1.5 cm and a density of −500 HU was added to account for breathing. This strategy forces the optimizer to create a flash margin for off-target irradiation. The bolus was removed for final dose calculation. The 6X and 6XFFF ViTAT treatments were planned on Eclipse optimized with PO algorithm v.15.6.04 and computed with Acuros XB v.15.6.04 having the Aperture Shape Controller (ASC) priority set to Very High in order to limit plan complexity [32]. The rates of 600 and 1400 MU/min were set for 6X ViTAT and 6XFFF ViTAT, respectively. The dose prescription was 42.4 Gy (2.65 Gy/fraction, 16 fraction in total). All the plans were optimized to satisfy the following clinical criteria: V95% > 95 % (the fraction of PTV receiving more than 95 % of the prescribed dose higher than 95 %) and maximum dose <108 % for PTV, V50% < 20 % and V5% < 40 % for the ipsilateral lung.

Table 1
Parameters for right breast treatment planning for different techniques. Abbreviations: ViTAT - Virtual Tangential-fields Arc Therapy, FFF - flattening filter free.

Techniques	Energy	Treatment Fields		MU
		Lateral arc	Medial arc	
ViTAT	6X	[220°–240°]	[50°–70°]	406
	6XFFF	[220°–240°]	[50°–70°]	411
3D Field in Field	6X	64°, 235°		295

OSLD calibration

OSLD out of field measurements are challenging because they are very sensitive to the beam quality especially with a high component of photons with energies below 100 keV [28,30]: therefore, the calibration procedure offered by the Vendor (using a Cs-137 spectrum), through

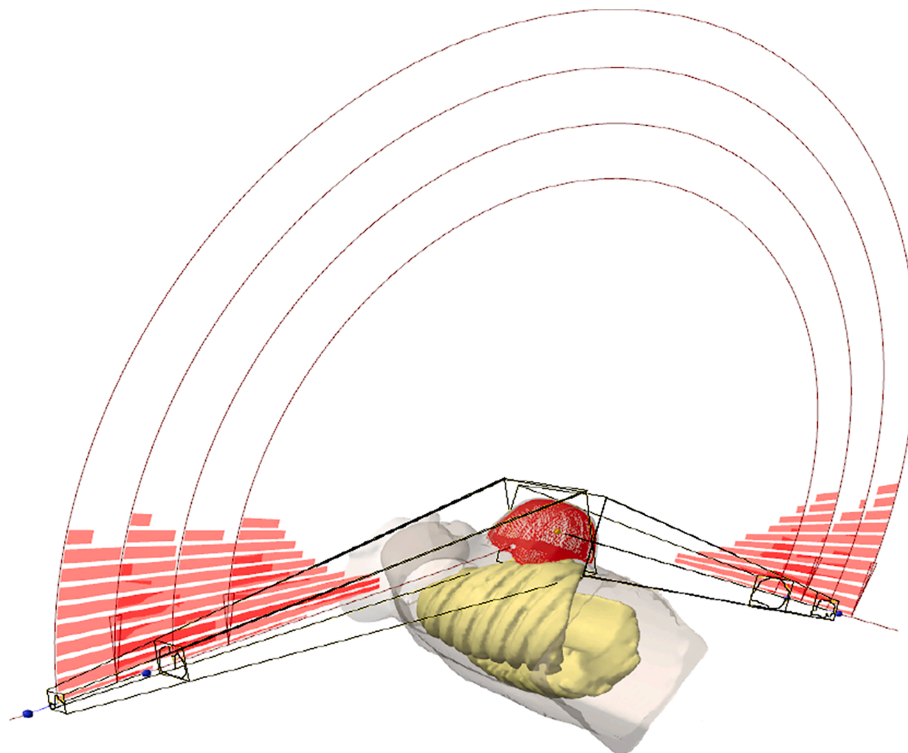


Fig. 1. 3D view of a right side ViTAT plan showing the geometry used: 4 partial arcs (two clockwise and two counterclockwise) completely blocked apart the first and last 20°. The bars along the arcs show the partial sectors where the beam is on and the relative intensity of the beam at each control point.

pre-irradiated dosimeters which are provided with the OSLD reader, is not the ideal calibration. In order to minimize the difference between the calibration condition and the experimental condition, as recommended in AAPM TG-191 [30], we investigated the out-of-field OSLD calibration factor changes in the whole volume identified as the fetal region for the first twenty weeks of pregnancy. Therefore, in line with the fetus position spanned by Bradley et al. [24] we estimated the calibration factor from a distance of approximately 20 cm to 40 cm from the isocenter of the fields; for each position depth 5 cm, 10 cm and 15 cm were also considered. A phantom of dimensions 60 cm × 30 cm × 20 cm was built from two stacks of 30 cm × 30 cm × 20 cm solid water slabs of different thicknesses. Custom made PMMA slabs of 2 mm thickness were cut to allow precise positioning of nanoDots in order to build a grid pattern without air gaps (Fig. 2(a)). The distance between each OSLD in the grid was 5 cm, both in the latero-lateral and cranio-caudal direction.

For calibration measurements, a 10x10 cm^2 field was set at 30 cm from the central OSLD of the grid at SSD = 100 cm (Fig. 2(b)). A Farmer chamber with a PTW UNIDOS electrometer (PTW-Freiburg, Freiburg, Germany) was used as the reference detector for calibration because of its negligible energy response [33]. At each location in the grid, the calibration factors were calculated as the ratio of the average dose measured by the Farmer chamber in that point and the average OSLD reading. The calibration factors for the two beam quality, 6X and 6XFFF, were found. The two sets of measurements, for 6X and 6XFFF beams, were repeated three times.

For completeness the nanoDots were also calibrated in-field for 6X and 6XFFF photon beams to find the calibration factor for the OSLDs in reference conditions (SSD = 100 cm, on the central axis of the beam, 10 cm × 10 cm field, 100 MU). These measurements were performed in a phantom (30 cm × 30 cm × 20 cm), with the Farmer chamber set at a depth of 10 cm in the center of the field.

The OSLD system used consisted of nanoDots from Landauer (Landauer, Inc., Glenwood, IL), paired with the microSTARii reader, and handled following AAPM TG-191 recommendations [30]. The reader is designed to operate at two different LED levels depending on the range of doses being measured. The reader was set to read in automatic configuration, so it automatically switches between the strong beam LED (appropriate for low doses) and weak beam LED (appropriate for high doses) when reading dosimeters based on the pretest counts obtained prior to initiating a normal photomultiplier tube (PMT) count reading. Before each irradiation the OSLDs were kept for optical bleaching to get the signal almost equal to the background [34] after which dosimeter verification and pre-assignment was performed in order to automatically correct the reading for individual sensitivity and individual background.

Fetal dose measurements with OSLDs

Measurements were performed at our department on a TrueBeam STX machine equipped with HD Millenium MLC (Varian Medical Systems, Palo Alto, CA). For each of the three treatment plans, measurements were performed with the same setup as for OSLD calibration (Fig. 2). The dose measurement points were selected to reflect the dose range in the fetus at different age periods: the position of the fundus from the conception to the twentieth week of gestation [19] delineates the measurement range. Dose measurements with OSLDs were repeated three times for each energy for each location in the grid.

Results

OSLD calibration

All OSLDs for the out-of-field calibration were read using the strong LED setting. At the depth of 10 cm and a distance of 30 cm from the isocenter in the cranio-caudal direction, the calibration factor for the nanoDots was found to be 3.2×10^{-4} ($\pm 0.1 \times 10^{-4}$) cGy/count and 2.9×10^{-4} ($\pm 0.1 \times 10^{-4}$) cGy/count for 6X beam and 6XFFF beam respectively. For both 6X and 6XFFF beams, regardless of the depth and the distance from the isocenter, the coefficient of variation (COV) of calibration factors was below the maximum COV associated with a single calibration factor, that is 3.61 %. Therefore, for each point of measurements, we applied the calibration factor found at 10 cm depth and 30 cm far from the isocenter for 6X and 6XFFF beams.

All OSLDs for in-field calibration were read using the strong LED setting. The calibration factor for the nanoDots was found to be 3.8×10^{-4} ($\pm 0.1 \times 10^{-4}$) cGy/count and 3.7×10^{-4} ($\pm 0.1 \times 10^{-4}$) cGy/count for 6X beam and 6XFFF beam respectively.

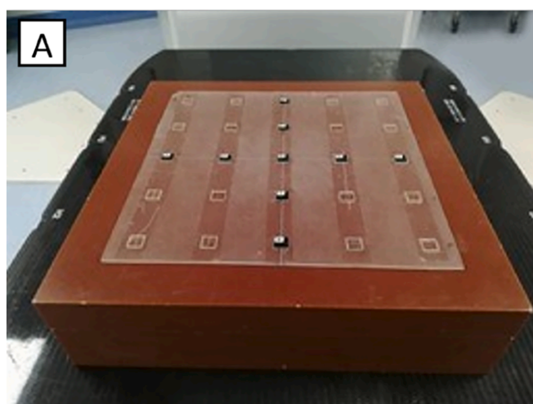
Fetus dose measurements

Doses normalized to prescribed dose (4240 cGy) are shown as a function of distance from the isocenter, for each technique used and at the three different depths (Fig. 3). The dose calculated by the Acuros algorithm is also shown. It must be noted that the algorithm stops the dose calculation at a distance of around 20 cm from the isocenter.

In Table 2 an overall of all measurements is reported, both in absolute dose and in percentage with respect to the prescribed dose, at different depth, CAX distance and delivery techniques.

Discussion

The fetus can be considered as a peripheral organ at risk throughout



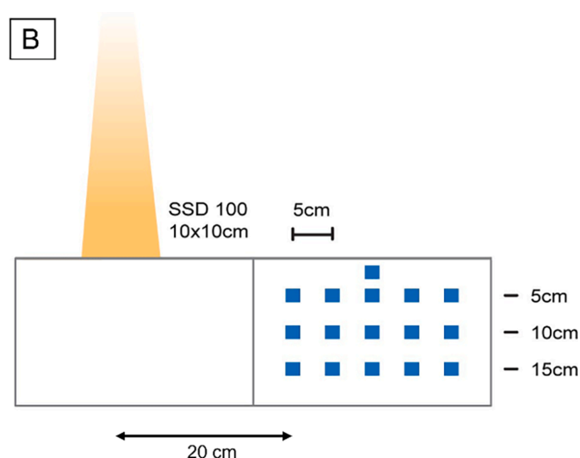


Fig. 2. Coronal view of the custom PMMA grid at a depth of 10 cm with OSLDs inserted in (A) and the OSLDs set up in a solid water phantom for out-of-field measurement (B).

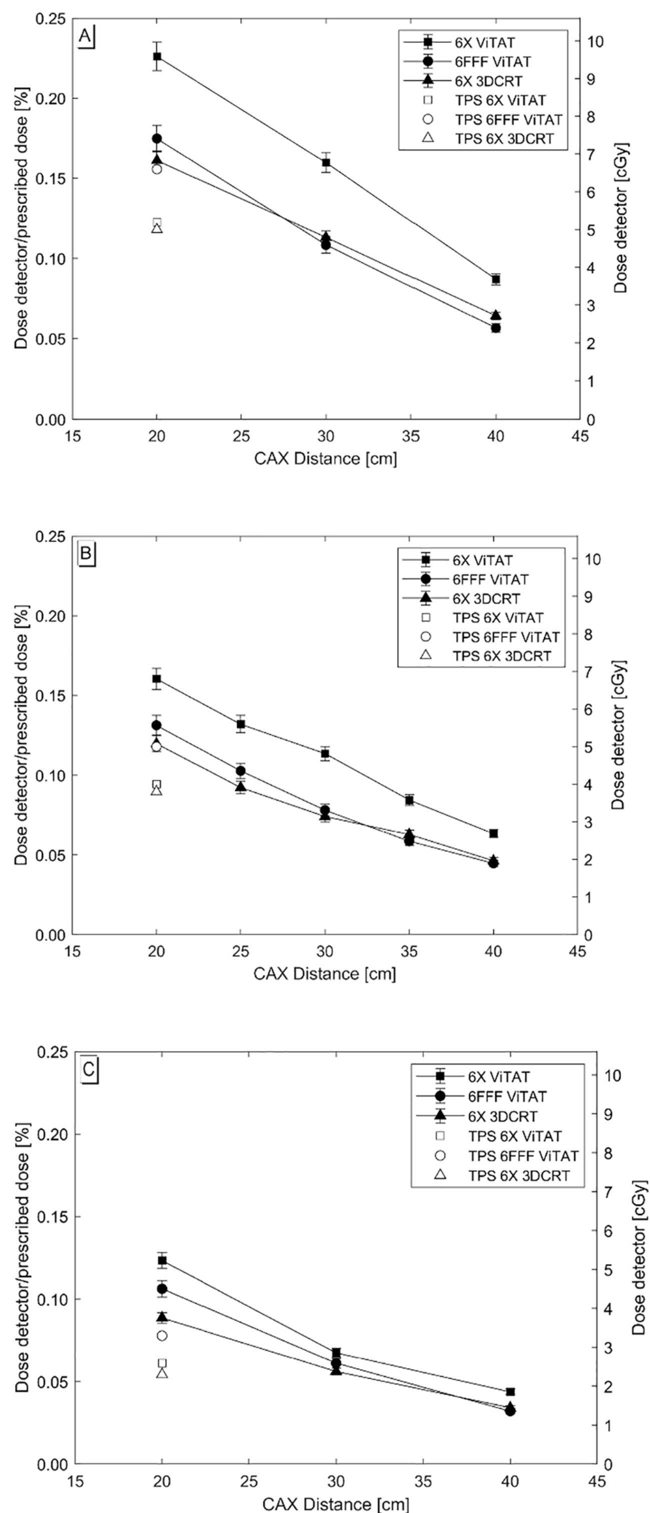


Fig. 3. Normalized fetal dose as a percentage of prescribed dose from different techniques for whole breast irradiation and TPS as a function of the distance from the isocenter at 5 cm depth (A), 10 cm depth (B) and 15 cm depth (C). The error bar indicates the standard deviation (SD) with appropriate uncertainty propagation of OSLD data. Filled squares, circle and triangle refer to 6X ViTAT, 6FFF ViTAT, 6X 3DCRT, respectively. For the same energies, TPS values are indicated by hollow symbols.

breast cancer radiotherapy. Unintentional dose outside of the radiotherapy treatment field arises from radiation scattered within the irradiated volume in the patient, collimator scatter and leakage radiation from the head of the Linac [11,19] as well as from couch and room backscatter or additional shielding [35]. Commercial TPSs do not appropriately model all these components outside the treatment field, therefore proving to be unreliable for out-of-field dose calculations. This necessitates measurements for an accurate dose estimation. Our goal was to estimate fetal doses using OSLDs for the ViTAT breast irradiation technique, with 6X and 6XFFF photon beams, and compare these doses to peripheral doses from 3DCRT, given that it is the clinical standard for breast irradiation.

Results confirmed the importance of calibrating the OSLDs as close as possible to experimental conditions to account for differences in the out-of-field energy spectrum. In fact, we found that in-field calibration factor was 19 % and 28 % higher than out-of-field calibration factor for 6X and 6XFFF beam respectively.

For in-field measurements no differences were found in calibration factors between the FF and FFF beams while for out-of-field measurements a mean difference of 10 % was found. Results are justified by the energy response of the OSLD [28,36–38].

For in-field location the mean energy is higher than 1.0 MeV both for 6X and 6XFFF [17]; the soft component impacts the OSLDs response less than 1 %, so the nanoDots response is almost energy independent [39].

For the CAX distance under consideration, the photon mean energy is 250 keV for 6X [37] and 200 keV for 6XFFF [17]. As above stated, the keV range is challenging for OSLD [30]. Indeed, the energy correction factor shows a variability up to 31 % [37]. In particular, for 6X beam and a CAX distance of 20 cm, the energy correction factor was estimated to be around 20 % [37], comparable with our result.

To note that in the off-axis range investigated, the calibration factor changes less than 3 % indicating that the quality of the beam does not vary significantly. It must be underline [6] that different LINAC can have the same nominal energy but different spectrum, in particular different soft components, therefore the calibration factor should be estimated in one's own working conditions.

Fetal dose estimated for 3DCRT are in general consistent with previously published data even if the comparison is difficult due to different set-up, geometry, and delivery machines. Antypas et al [23] reported dose in a range of 0.079 % to 0.085 % of the prescribed dose for a very early stage of pregnancy, the latter corresponding to 3.91 cGy for the entire treatment of 4600 cGy. At a similar fetal position, we found 0.063 % (2.67 cGy for a total of 4240 cGy). Mazonakis et al. [40] reported an average fetal dose of 0.089 % (4.44 cGy for dose prescription of 5000 cGy) by means a MNCP Monte Carlo simulation of a Elekta Linac: in a quite similar position we found 0.074 % (4.81 cGy for a dose prescription of 4240 cGy).

ViTAT technique provides some slight improvement in PTV homogeneity (2.5 %, 2.3 % SD for 3DCRT and 6X ViTAT) however, similarly to IMRT technique, the higher number of monitor unit (MU) required for modulation increase radiation leakage and peripheral dose [7,25]. Indeed, for the case under investigation, MU are 295 and 406 respectively for 3DCRT and ViTAT 6X (Table 1) and the ViTAT 6X out-of field dose increases by more than 30 % in the range of measurements (Fig. 3). Although the estimated fetal doses for both techniques were below the 10 cGy limit set by ICRP [41] (Table 2), 3DCRT should be preferred in a case of pregnancy. Otherwise, Fig. 3 shows that the dose from the 6XFFF ViTAT technique decreases faster with distance from the isocenter and becomes slightly lower than 3DCRT at large distances. This decrease in dose, when switching from the FF to the FFF beam, is mostly due to a decrease in scatter from the linac head and leakage, the latter being the major component at large distances from field edge. [11,42,43]. At 30 cm far from the isocenter and 10 cm depth, the percentage reduction of out-of-field dose from the 6XFFF ViTAT plan compared to the 6X ViTAT one was around 31 %: differences corroborated by Wijesooriya results in a case of a 10 × 10 cm^2 direct field [44]. Experiment results suggest that

Table 2
Measured absolute doses at different depth, CAX distance and for delivery techniques. Absolute doses are always lower than 10 cGy. Percentage values with respect to the prescribed dose of 4240 cGy are also reported.

Depth	CAX distance	6X 3DCRT		6X ViTAT		6FFF ViTAT	
		Dose Mean ± SD	Detector dose / prescribed dose	Dose Mean ± SD	Detector dose / prescribed dose	Dose Mean ± SD	Detector dose / prescribed dose
[cm]	[cm]	[cGy]	[%]	[cGy]	[%]	[cGy]	[%]
5	20	6.83 ± 0.25	0.161	9.59 ± 0.37	0.226	7.41 ± 0.35	0.175
	30	4.79 ± 0.17	0.113	6.78 ± 0.26	0.160	4.59 ± 0.22	0.108
	40	2.72 ± 0.10	0.064	3.68 ± 0.14	0.087	2.40 ± 0.11	0.057
10	20	5.10 ± 0.21	0.120	6.80 ± 0.28	0.160	5.55 ± 0.26	0.131
	25	3.92 ± 0.17	0.092	5.57 ± 0.23	0.131	4.36 ± 0.21	0.103
	30	3.14 ± 0.15	0.074	4.81 ± 0.19	0.113	3.31 ± 0.16	0.078
	35	2.67 ± 0.11	0.063	3.58 ± 0.14	0.084	2.49 ± 0.12	0.059
	40	1.97 ± 0.08	0.046	2.69 ± 0.11	0.063	1.90 ± 0.09	0.045
15	20	3.76 ± 0.14	0.089	5.23 ± 0.20	0.123	4.50 ± 0.21	0.106
	30	2.38 ± 0.09	0.056	2.86 ± 0.11	0.067	2.59 ± 0.12	0.061
	40	1.45 ± 0.05	0.034	1.86 ± 0.07	0.044	1.36 ± 0.06	0.032

6XFFF ViTAT can be used in place of 3DCRT while maintaining a similar fetal dose.

From the comparison between TPS-calculated dose and OSLD-measurements we found that at a distance of 20 cm from the isocenter and at depth of 10 cm the dose is underestimated by 41 %, 11 % and 34 % for 6X ViTAT, 6XFFF ViTAT and 3DCRT, respectively. This is in agreement with the severe underestimation of out-of-field dose in TPSs reported in literature [6,10,22,45]. Our results confirm the percent error of the measured to calculated peripheral dose for the 6XFFF photon beam reported by Covington et al. for Acuros dose calculation model [14], although their measurements were made for a 6 × 6 cm^2 field size.

Conclusions

The fetal dose is higher for the 6X ViTAT than for the 3DCRT technique, owing to its higher number of monitor units. However, we can benefit from the ViTAT technique for breast treatment by using FFF beams in order to reduce the fetal dose to a value comparable to that obtained with the standard 3DCRT technique.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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