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Dosimetric feasibility of an anthropomorphic three-dimensional PRESAGE® dosimeter for verification of single entry hybrid catheter accelerated partial breast brachytherapy

Khalid Iqbal[1,2,3], Geoffrey S. Ibbott[1], Ryan G. Lafratta[1], Kent A. Gifford[1], Muhammad Akram[2] and Saeed A. Buzdar[2]

[1]Department of Radiation Physics, The University of Texas MD Anderson Cancer Center, Houston, TX, USA, [2]Department of Physics, The Islamia University, Bahawalpur, Pakistan and [3]Department of Radiation Oncology, Shaukat Khanum Cancer Hospital & Research Center, Lahore, Pakistan

Original Article

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Author for correspondence:
Khalid Iqbal, Department Radiation Physics, The University of Texas MD Anderson Cancer Center, Houston, TX, USA. Tel: +924235905000. Fax: +924235945206.
E-mail: khalid_phy@yahoo.com

Abstract

Purpose: To determine the feasibility of an anthropomorphic breast polyurethane-based three-dimensional (3D) dosimeter with cavity to measure dose distributions and skin dose for a commercial strut-based applicator strut-adjusted volume implant (SAVI™) 6–1. *Materials and methods:* An anthropomorphic breast 3D dosimeter was created with a cavity to accommodate the SAVI™ strut-based device. 2 Gy was prescribed to the breast dosimeter having D_{95} to planning target volume evaluation (PTV_EVAL) while limiting 125% of the prescribed dose to the skin. Independent dose distribution verification was performed with GAFCHROMIC® EBT2 film. The dose distribution from the 3D dosimeter was compared to the distributions from commercial brachytherapy treatment planning system (TPS) and film. Point skin doses, line profiles and dose–volume histogram (DVHs) for the skin and PTV_EVAL were compared. *Results:* The maximum difference in skin dose for TPS and the 3D dosimeter was 4% whereas 41% between the TPS and EBT2 film. The maximum dose difference for line profiles between TPS, 3D dosimeter, and film was 4·1%. DVHs of skin and PTV_EVAL for TPS and 3D dosimeter differed by a maximum of 4% at 5 mm depth and skin differed by a maximum 1·5% between TPS and 3D dosimeter. The criterion for gamma analysis comparison was 92·5% at ± 5% ± 3 mm criterion. The TPS demonstrated at least ±5% comparability in predicting dose to the skin, PTV_EVAL and normal breast tissue. *Conclusions:* 3D anthropomorphic polyurethane dosimeter with cavity gives comparable results to the TPS dose predictions and GAFCHROMIC® EBT2 film results in the context of HDR brachytherapy.

Introduction

Accelerated partial breast irradiation (APBI) provided by high dose-rate (HDR) brachytherapy offers an excellent compact course of radiation due to a small number of fractions for early stage breast carcinoma.[1] APBI has been used by multiple methods which includes three-dimension conformal external radiotherapy, MammoSite® balloon internal radiation therapy and multiple catheter brachytherapy.[2–5] The MammoSite® brachytherapy system (Hologic, Marlborough, MA, USA) with a single dwell position has been widely accepted due to technically much easier to perform and axially symmetric dose distribution.[6] But one matter of concern in MammoSite® is inadequate balloon to skin distance even using multiple dwell positions which can change the shape of the dose distribution up to some extent. The recent development in APBI is strut-adjusted volume implant (SAVI™) device (Cianna Medical Inc., Aliso Viejo, CA, USA) which has 6, 8 or 10 peripheral source channels with one centre channel.[7] MammoSite® and multiple catheters of SAVI™ with struts adjusted volume combine the advantages of APBI treatment.[8,9]

APBI treatment with HDR brachytherapy delivered dose is accurate and reliable using Ir-92. Ir-192 is the most common source for remote after loader in HDR with advantages of high specific activity (450 Ci/g) that allow the construction of high activity source (10 Ci) of small diameter (0·6–1·1 mm).

Skin dose can be the limiting factor in radiation therapy treatments, and it is a fairly common cause of toxicity in radiation therapy treatment. The chosen planning optimisation strategy can also affect the skin dose.[10–18] Despite the clinical importance of skin dose, the literature contains scanty detail concerning the expected accuracy of radiation treatment planning and skin dose calculations. Using radiochromic film, Chung et al.[11] reported that two treatment planning systems (TPS's) (Pinnacle3, Royal Philips Electronics, Eindhoven, The Netherlands and CORVUS, North American Scientific, Chatsworth, CA, USA) overestimated

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surface dose by 7·4–18·5%. Zourari et al.[12] in 2015, made a dosimetric comparison using a contemporary (MBDCA) model-based dose calculation algorithm following TG 186 protocol and TG 43 techniques in HDR Ir-192 breast brachytherapy and found a maximum percentage difference of the order of 6% for $D_{10\,cc}$ for the skin. Shahid et al. presented that dosimetric differences between a commercially available treatments planning system utilising the TG43U1 dose calculation algorithm did not differ from measurements by more than 5–6% for points on the skin.[13]

In this work, we want to compare two parameters:

First, comparison of skin dose calculations for TPS and dosimeter. Physicians often ask planners this important clinical question. For optimisation to be reliable, calculated and measured skin dose must be correlated, even if the calculation contains a systematic error.[16,17]

Second, can the PRESAGE® (Heuris Pharma LLC, Skillman, NJ, USA) dosimeter be feasible for HDR brachytherapy dosimetry for breast having a cavity? Furthermore, we wished to determine the accuracy of the commercial brachytherapy TPS in predicting dose to the skin, planning target volume for plan evaluation (PTV_EVAL) and normal tissues. The literature has yet to address these important clinical questions for the Oncentra® (Nucletron, an Elekta Company, Elekta AB, Stockholm, Sweden) Brachy TPS. To answer our questions, we used PRESAGE® and GAFCHROMIC® EBT2 (International Specialty Products Inc., Wayne, NJ, USA) film to measure dose distributions delivered with the SAVI™ device. As EBT film is the first radiochromic film suitable for the use with doses as the typical doses occurring in radiotherapy.[14] The resulting knowledge will be useful when evaluating and comparing measured and calculated plans and also when developing optimisation strategies for the SAVI™ device.

Methods

SAVI™ devices

The SAVI™ is an interstitial type and APBI device with single entry brachytherapy. It includes the benefits of both MammoSite and multi-catheter and is available in 6, 8, 10 peripheral struts with a central strut. SAVI™ 6-1 was used in this work and inserted inside the lumpectomy cavity through a small incision and is inserted in a collapsed state and by the clockwise rotation of the knurled knob at the proximal end of the device; the peripheral struts are expanded as shown in Figure 1. The SAVI™ has 3·0 cm diameter and 6·1 cm long axis. The optimisation of dwell positions and weights is possible by multiple catheters to account for close vicinity of ribs, skin and pectoralis muscle. Dose conformity is obtained with additional peripheral catheters of the device which permit the user to more closely model in an interstitial implant.[13,14]

PRESAGE® dosimeter for optical-CT scanning

A PRESAGE® dosimeter (Heuris Pharma LLC, Skillman, NJ, USA) was moulded from a pre-mould mixture comprised of a solvent, leuco dye and free radical initiator. The formulation of PRESAGE® used in this study has Z_{eff} of 7·6 and a physical density of 1·07 g/cm^3. The physical dimensions of breast PRESAGE® dosimeter were 13·8 cm (length) by 12·4 cm (width) and 4·6 cm (height)[15–25] as shown in Figure 2a. The dosimeter was scanned with the Duke midsized optical scanner dedicated for the RPC (DMOS-RPC) (Duke University, Durham, NC, USA) using 1° per step to produce 360 projection images.[23,26] The parameters used during the optical scanning of PRESAGE dosimeter were refractive indices of the matching fluid and the dosimeter, attenuation coefficients of the fluid and the medium, wavelength of the light used, radius and position of the dosimeter. The refractive index of the matching fluid was set equal to the refractive index of the PRESAGE dosimeter which was 1·503.

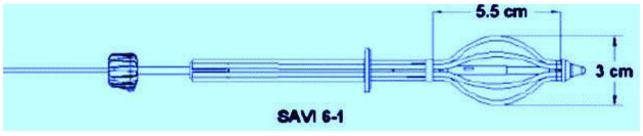

Figure 1. SAVI™ 6-1 size with peripheral struts expanded (Courtesy: Cianna Medical).

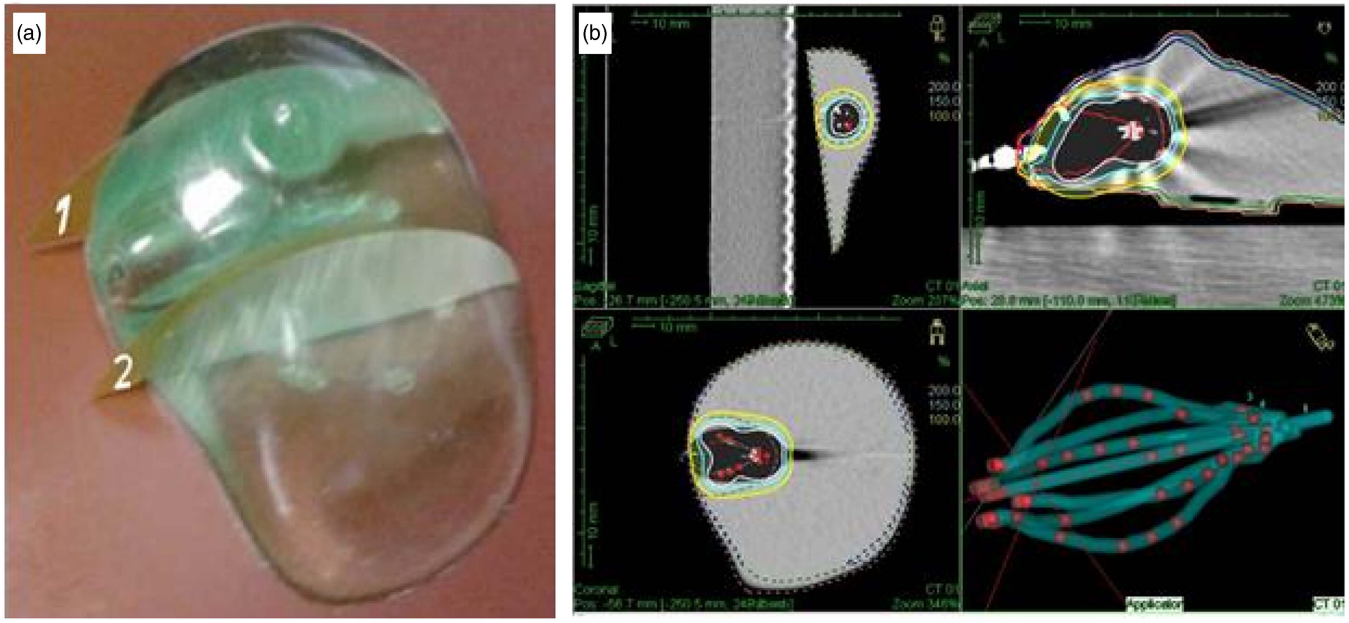

Figure 2. (a) PRESAGE®, dosimeter with EBT2 films inserted. (b) Brachytherapy treatment plan with dose distribution in three dimensions.

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The optical scanning and irradiation of the dosimeter and cuvettes were performed at room temperature (22°C). Transverse images were reconstructed by filtered back projection to a 1 mm voxel edge.[27] Radio-opaque markers are present on struts two, four and six of the device to allow struts identification in the treatment planning as shown in Figure 2b.

Treatment planning and delivery

A treatment planning X-ray CT scan with a slice thickness of 1·25 mm of the breast PRESAGE® dosimeter was acquired using a GE CT scanner (GE Healthcare Technologies, Waukesha, WI, USA). CT data were exported to the Oncentra® Masterplan version, 4.1 brachy planning workstation. The cavity was contoured as the periphery of the struts of the SAVI™ device. The skin was generated by contracting the external contour by 2 mm.[19] The PTV for plan optimisation (PTV_OPT) was generated by expanding the cavity 10 mm isotropically and limiting it by the skin. The PTV_EVAL was created by subtracting the cavity from the PTV_OPT. Figure 2 shows the external, PTV_EVAL and skin contours on an axial CT slice. Subvolumes were created by contracting the (external-PTV_OPT) by 1 mm, 3 mm and 5 mm isotropically. The inverse planning simulated annealing (IPSA) algorithm was used to optimally prescribe 2 Gy to the PTV_EVAL while limiting the maximum skin dose (D 0·1 cc) to or below 125% of the prescribed dose. An IPSA is simulated annealing optimisation algorithm and is based on the patient's anatomy contoured from the CT scan and with the help of volumetric or surface dose constraints. IPSA is capable of rapid generation of conformal plans by giving the dwell times distribution within the catheters.[20] 2 Gy was prescribed to the breast dosimeter having D_{95} to PTV_EVAL while limiting 125% of the prescribed dose to the skin using the Nucletron HDR microSelectron after loader. PTV_EVAL is considered as the difference between the expanded and the cavity volume.[21] PTV_EVAL was prescribed to receive 95% of the prescription dose which was equal to 2 Gy in each fraction. Cuvettes of PRESAGE® with a volume of 1 × 1 × 3 cm were irradiated in high impact polystyrene with 6 MV beam on a Varian 21EX linear accelerator. Dose levels were 0, 3, 6 and 9 Gy. The absorption of the material was determined by a Genesys 20 spectrophotometer (Thermo Fisher Scientific, Houston, TX, USA) before and post-irradiation and the optical density (OD) was compared with the dose delivered to calculate the PRESAGE® calibration.

EBT2 film dosimetry

Independent dose distribution verification was performed with GAFCHROMIC® EBT2 film. Temporal stability, directional independence and convenience of the self-developing radiochromic film were the basic reasons to use EBT2.[23] A PRESAGE® dosimeter was cut with a scalpel blade at its central, long axis and pieces of EBT2 film were placed between the PRESAGE® halves for line profile measurement and also on top of dosimeter for skin dose calculations. The PRESAGE dosimeter was irradiated with the films inserted. An OD to dose curve was measured in solid water with 6 MV photons from a Varian 21EX. The films were scanned in three colours (48-bit RGB) at a scanning resolution of 75 dpi in transmission mode on flatbed photo-scanner Epson-10000XL (Epson America, Inc., Long Beach, CA, USA). Each film was scanned in transmission mode but only the red channel was extracted for analysis because it has more sensitive response to dose as compared with blue and green channels.[28–32]

Data registration and dose analysis

The transverse images were reconstructed in terms of change in OD by the DMOS Matlab program (Duke University). Theses transverse images with dose distribution from DMOS and Oncentra® treatment plan were exported to the computational environment for radiotherapy research program (CERR) (Memorial Sloan Kettering Cancer Center, New York, NY, USA), Matlab-based software which is used to analyse and display the radiotherapy plans. CERR scaled the change in OD values to dose values with the help of the scale factor taken from the calibration curve. The dose distributions were generated by the datasets that were loaded and registered into CERR and then normalised to relative dose distributions. The calculated dose distribution from Oncentra® was compared with the measured distributions from PRESAGE® and EBT2. EBT2 scans were analysed using Image-J software (National Institutes of Health, USA).

Results and Discussion

Film and PRESAGE® calibration

Figure 3a shows the calibration curve (OD to dose) for the PRESAGE®. Figure 3b shows the calibration curve (OD to dose) for the EBT2 film. The uncertainty in net OD was estimated at 0·8% (1 SD) for PRESAGE® and 0·7% (1 SD) for EBT2 film. The net OD uncertainty was estimated by subtracting the pre-irradiation

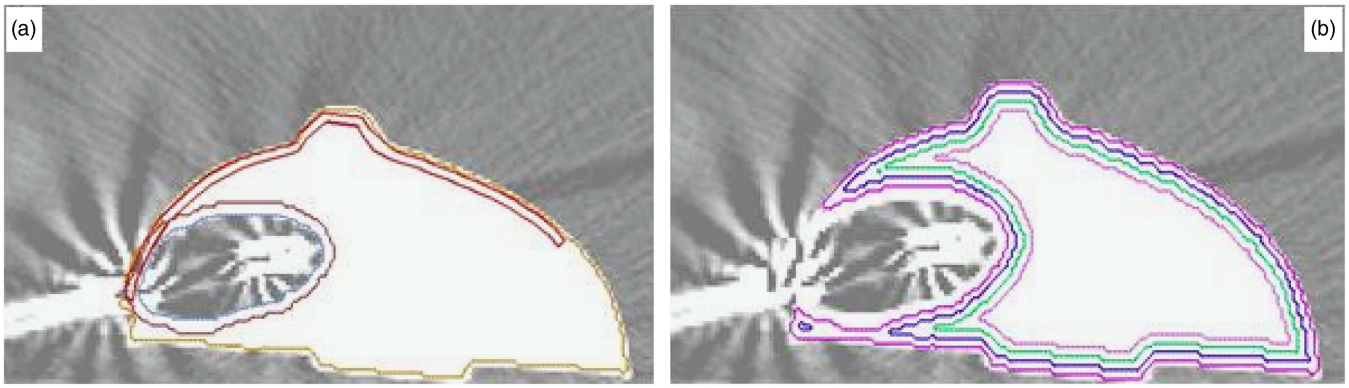

Figure 3. (a) Breast contours figures [external breast body, cavity, planning target volume evaluation (PTV_EVAL), skin]. (b) External body-PTV for plan optimisation: −1 mm, −3 mm, −5 mm.

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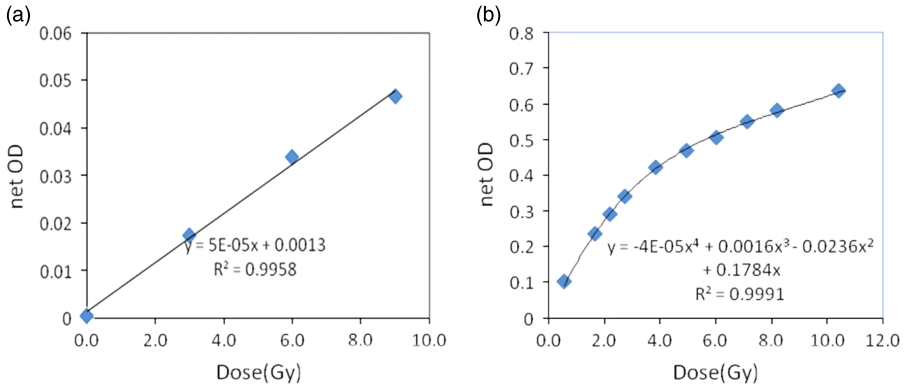

Figure 4. (a) Calibration curve [optical density (OD) to dose] for the PRESAGE®. (b) Calibration curve (OD to dose) for the EBT2 film.

scans from the post-irradiation scans. Sakhalkar et al. in 2009 and Guo et al. in 2006 have reported various uncertainties associated with the calibration process of EBT2 film and Presage intradosimeter consistency, temporal stability and temperature gradients in the literature.[24,33,34] In the case of PRESAGE® calibration, small volumes were irradiated for particular dose using from same batch of the PRESAGE®. The determination of using small volumes to calibrate large volumes was to introduce errors when comparing to dose distribution.[29,30,35] The volume effect uncertainty of the PRESAGE® required the use of normalisation as compare dose distribution to PRESAGE® dosimeter with EBT2 film and Oncentra® treatment planning. However, the dose-response linearity of the PRESAGE® has been extensively confirmed.[15] In this paper, the PTV_EVAL dose of the PRESAGE® was within the calibration uncertainty of planned dose as measured by the films. We therefore conclude that the PRESAGE® is relative dosimeter, by normalising D_{95} to PTV_EVAL and PRESAGE® linearity response did not introduce any limitation on data analysis.[36]

Table 1. Point skin dose differences between Oncentra®, PRESAGE® and EBT2

	Mean difference (%)	Median difference (%)	Max difference (%)	SD (%)
Oncentra® versus PRESAGE®				
Film 1	3·54	3·56	4·50	0·070
Film 2	2·85	2·84	3·80	0·097
Oncentra® versus EBT2				
Film 1	0·97	1·51	2·42	0·37
Film 2	0·53	0·57	1·15	0·66

Figure 4 illustrates the comparison between Oncentra®, PRESAGE® and EBT2 film for the two film planes. The maximum dose difference of both films was 4·5% between Oncentra® and PRESAGE® and 2·42% between Oncentra® and EBT2 film. The mean percentage differences of skin dose for film 1 and film 2 were 3·54 and 2·85%, respectively, between Oncentra® and PRESAGE®. Oncentra® and EBT2 mean differences of film 1 and film 2 were 0·97 and 0·53% at different selected number of points, respectively, as shown in Table 1.

Figure 5 illustrates the DVH comparison between and Oncentra® and PRESAGE® for the (a) skin and (b) A plot of dose versus relevant PTV_EVAL coverage parameters. The maximum per cent dose difference was 4% between Oncentra® and PRESAGE®. Preliminary investigations suggest the cause may be a reflection artefact of laser light from the underside of the top and bottom of the dosimeter.[32]

The PTV_EVAL V_{90} and V_{95} of Oncentra® and PRESAGE® were 99·6, 98·95% and 97, 96·59%, respectively (V_{95} is the volume receiving 95% of the prescribed dose). The PTV_EVAL V_{150} and V_{200} were well below the optimisation goals of $V_{150} < 50$ cc and $V_{200} < 20$ cc of the absolute volume (Protocol B-39/RTOG Protocol 0413)[37] as shown in Table 2.

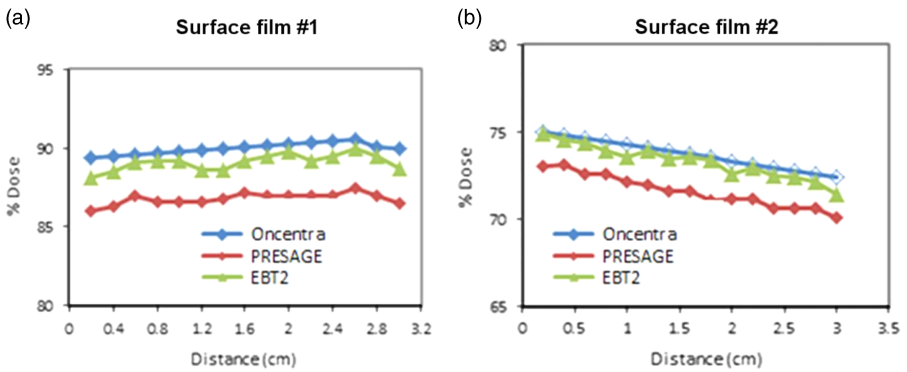

Figure 5. (a) Comparison of the calculated and measured point skin doses for PRESAGE®, Oncentra® Brachy Planning TPS and EBT2 film for film 1. (b) Comparison of the calculated and measured point skin doses for PRESAGE®, Oncentra® Brachy Planning TPS and EBT2 film for film 2.

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Table 2. Planning target volume evaluation (PTV_EVAL) parameters for Oncentra® and PRESAGE®

PTV_EVAL	Oncentra®	PRESAGE®
V_{90} (%)	99·60	97·00
V_{95} (%)	98·95	96·59
V_{100} (%)	96·23	94·25
V_{150} (cc)	18·65	16·73
V_{200} (cc)	11·70	10·93

Isodose line profiles

Figure 6 illustrates the dose line profile comparisons between Oncentra®, PRESAGE® and EBT2. The maximum line profile dose difference of both films was 2·84% between Oncentra® and PRESAGE® dosimeter and 4·06% between Oncentra® and EBT2 film. The mean percentage differences of line dose profiles of film 1 and film 2 were 2·25 and 1·80% between Oncentra® and PRESAGE®. Oncentra® and EBT2 mean percentage differences of film 1 and film 2 were 3·31 and 2·82% as shown in Table 3.

Normal breast tissue DVHs

Figure 7 illustrates the DVH comparisons between Oncentra® and PRESAGE® for normal breast tissue and normal breast tissue

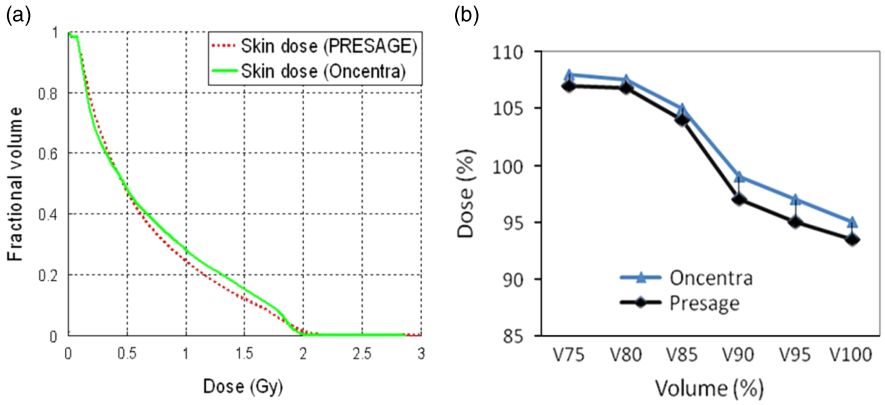

Figure 6. (a) Dose–volume histogram comparison between Oncentra® and PRESAGE® for skin. (b) Plot of dose versus relevant planning target volume evaluation coverage parameters for Oncentra® and PRESAGE®.

Table 3. Line profile comparisons between Oncentra®, PRESAGE® and EBT2 film

	Mean difference (%)	Median difference (%)	Max difference (%)	SD (%)
Oncentra® versus PRESAGE®				
Film 1	2·25	1·56	2·84	0·81
Film 2	1·80	1·71	2·12	0·93
Oncentra® versus EBT2				
Film 1	3·31	2·63	4·06	0·69
Film 2	2·82	2·59	3·42	0·68

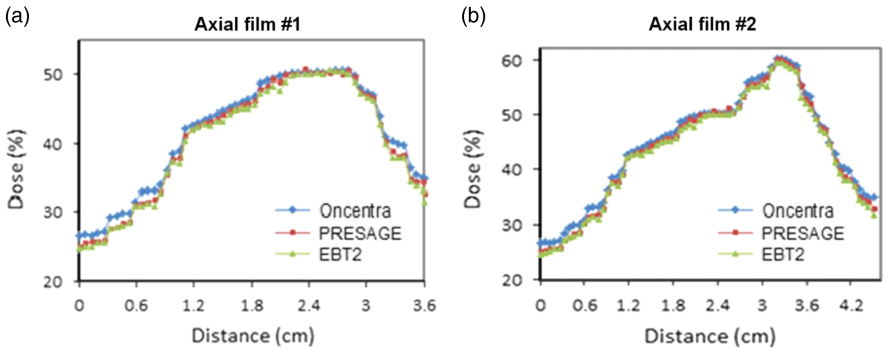

Figure 7. (a) Line profile comparison between Oncentra®, PRESAGE® and EBT2 film dose distributions of axial slice. (b) Line profile comparison between Oncentra®, PRESAGE® and EBT2 film dose distributions of axial slice.

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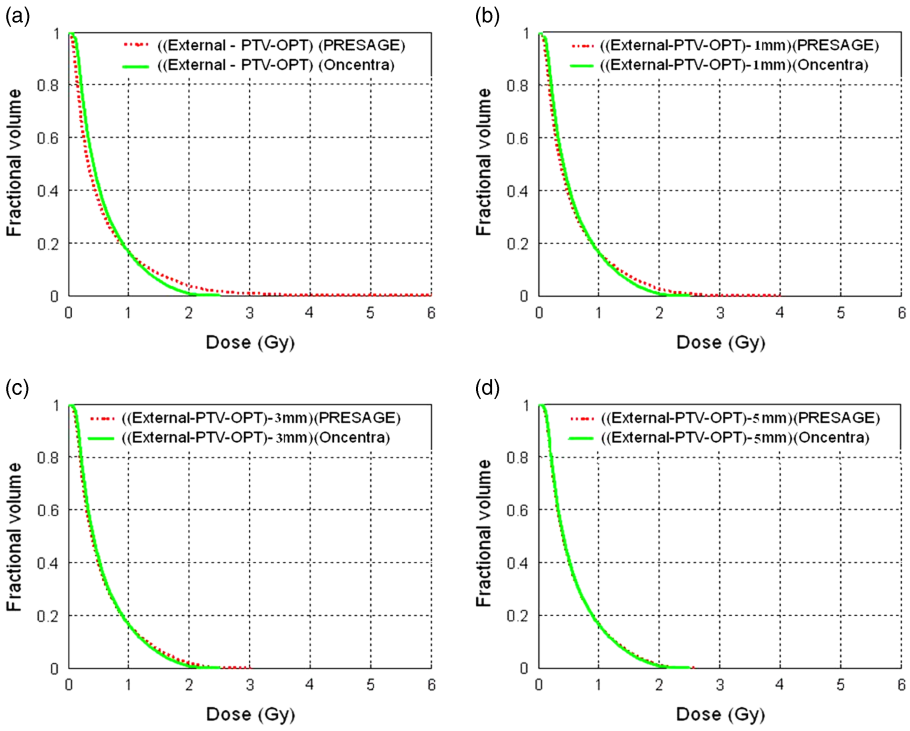

Figure 8. Dose–volume histogram comparisons between Oncentra® and PRESAGE® dose distributions. (a) External-planning target volume for plan optimisation (PTV_OPT). (b) External-PTV_OPT, −1 mm. (c) External-PTV_OPT, −3 mm. (d) External-PTV_OPT, −5 mm.

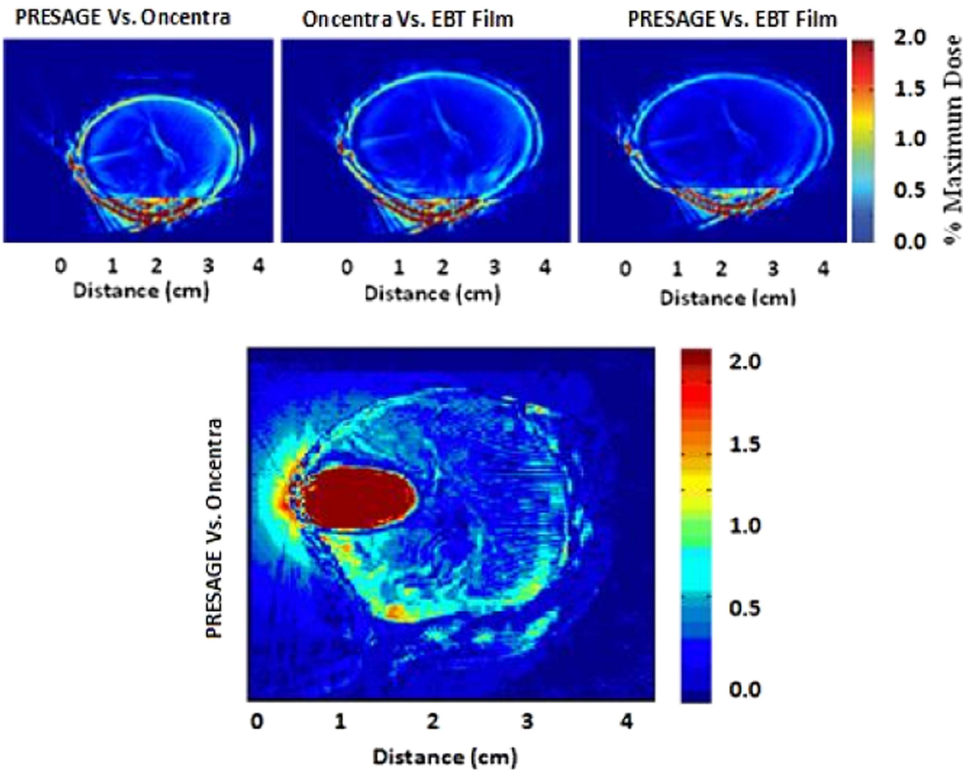

Figure 9. Gamma map comparisons of PRESAGE®/optical-CT , EBT2 film and Oncentra® treatment planning.

subvolumes. There are regions that show differences with Oncentra® near the edge of the dosimeter. This is likely due to edge artefacts in the PRESAGE® distribution. The edge artefacts were reduced by effective refractive index matching between the dosimeter and the matching fluid. The external-PTV_OPT DVH curve indicates that the PRESAGE® dose estimation was slightly less homogenous than that calculated by Oncentra®, with small regions of relative over and under dose occurring near the edges

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of the dosimeter. For the external-PTV_OPT, a 4% maximum dose difference was observed at upper and lower volume ends as shown in the Figure 7a. DVHs of the normal breast tissue subvolumes show that there are some edge artefacts resulting in maximum differences of 3·2 and 2·5% for the 1 and 3 mm subvolumes, respectively, as many studies reported earlier.[29,30] The normal breast tissue 5 mm subvolume DVH showed excellent agreement between Oncentra® and PRESAGE® with a maximum difference of 1·5% (Figure 8).

Gamma map comparison

Figure 9 is gamma comparisons of PRESAGE®/optical-CT, EBT2 film measurement and dose calculation of Oncentra® TPS at ±5% ± 3 mm criterion. The amount for the axial 2D gamma comparisons of EBT2 versus PRESAGE®, PRESAGE® versus Oncentra® and EBT2 versus Oncentra® were 92·4, 93·5 and 91·8%, respectively.

Conclusions

This work demonstrated that it is possible to fashion a breast PRESAGE® dosimeter with a cavity that will accommodate the SAVI™ device. This fact allows for patient-specific HDR treatment plan quality assurance. Further, these data show that it is also possible to obtain comparable dosimetry from an anthropomorphic PRESAGE® dosimeter. The Oncentra® TPS demonstrated comparable dose calculation up to ±5% for the skin, PTV_EVAL and normal breast tissue and 92·5% gamma map comparison at ±5% ± 3 mm criterion.

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