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Original paper

Measurement of dose exposure of image guidance in external beam accelerated partial breast irradiation: Evaluation of different techniques and linear accelerators

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ABSTRACT

Introduction: Verifying the patient position is always an essential part of the treatment process, especially in hypofractionated treatments such as accelerated partial breast irradiation (APBI). The purpose of the study was to compare five image guidance techniques with respect to imaging dose and image quality.
Methods and materials: We chose five types of imaging methods applicable for APBI and measured their dose exposure on four different accelerators (Synergy, TrueBeam, Artiste and CyberKnife). Absorbed dose was measured with ionization chamber in thorax phantom. Besides dose exposure image quality was also compared.
Results: The lowest dose exposure was measured with kV-kV planar imaging followed by kV-CBCT, MV-MV pair and MV-CBCT in ascending order. Average phantom dose with kV-kV image pair on CyberKnife was 0.01 cGy as the lowest and with MV-CBCT on Artiste was 7.11 cGy as the highest. Average dose exposures of MV-MV images with TrueBeam, Synergy and Artiste were 1.18 cGy, 2.13 cGy and 1.61 cGy, respectively, with similar image quality. For the same machines the doses of kV-CT imaging were comparable: 0.65 cGy, 0.65 cGy and 0.52 cGy, with some differences in image quality. MV-CBCT technique resulted in the highest dose and poorest image quality.
Conclusions: In APBI the position of the patient and tumour bed can be verified with many tools. When fiducials are available, often 2D imaging is enough to achieve appropriate positioning and the kV-kV method is recommended. Imaging with 2.5MV can also be a good solution instead of 6MV. Without fiducials 3D images should be acquired and the recommended method is the kV-CBCT.

1. Introduction:

Accelerated Partial Breast Irradiation (APBI) is a widespread treatment technique for selected low-risk breast cancer patients [1–4]. At the National Institute of Oncology a properly selected group of early staged low-risk breast cancer patients is treated with APBI after breast-conserving surgery. The rationale of this treatment is that only a part of the breast tissue is irradiated – the lumpectomy cavity with suitable margins – in order to reduce side effects, get better cosmetic outcome and reduce overall treatment time. In teletherapy, postoperative APBI can be delivered by traditional 3D-CRT, intensity-modulated “step & shoot” (SS), “sliding window” (SW) and “volumetric arc therapy” (VMAT) techniques [9–12]. At our institution intensity-modulated radiation therapy (IMRT) has been used since 2011 and more than 130 patients have been treated with it. Currently, at our institution APBI treatments are carried out with “sliding window” IMRT technique with a total dose of 36.9 Gy (9 × 4.1 Gy) using a twice-a-day fractionation [13,14]. The use of high fractional doses and reduced fraction number requires more accurate dose delivery than in conventional radiotherapy. To spare as much healthy breast tissue as possible decreased PTV margins are essential, what can be achieved by good patient positioning. Image Guided Radiation Therapy (IGRT) is an appropriate method to improve the accuracy of patient positioning and dose delivery by using frequent imaging during the treatment course [5–8]. The equipment used for IGRT can be divided into two groups: ionizing radiation based and non-ionizing radiation based systems. In this study

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Table 1
Imaging methods and their settings.

	TrueBeam		Synergy	Artiste	CyberKnife
kV planar imaging	120 kV, 5 mAs 15 cm × 15 cm		120 kV, 5 mAs 15 cm × 15 cm		120 kV, 5 mAs 15 cm × 15 cm
MV planar imaging	2.5 MV 1,5 MU 15 cm × 15 cm	6 MV 1,5 MU 15 cm × 15 cm	6 MV 2 MU 16 cm × 16 cm	6 MV 1,5 MU 15 cm × 15 cm	
In-room CT				120 kV, 31.2 mAs 3 mm slice thickness 1.45 pitch	
kV-CBCT	125 kV, 270 mAs 360° arc		120 kV, 264 mAs 360° arc		
MV-CBCT				6 MV 8 MU 200° arc	

we took into consideration all the ionizing radiation based tools that are available in external APBI.

The first group of image guidance is kV or MV 2D planar imaging. The imaging system can be mounted on the gantry (On-Board Imaging, OBI), or on the floor or ceiling of the treatment room (Stereoscopic kV imaging). In both cases at least 3 gold markers should be placed close to the lumpectomy cavity to provide secure target localisation. Computed tomography (CT) based methods are also widely used for APBI image guidance. At least the lumpectomy cavity should be visible on the volumetric imaging, but the additional use of surgical clips for localization is the optimal solution. The main advantage of these methods is, that anatomical changes and deformation of breast tissue can also be identified easily. This is very important, because the shapes of breast tissue and tumour bed are very sensitive for patient setup, especially for the position of the arms. We can acquire 3D volumetric information with CT-on-rail system or Cone-Beam CT (kV or MV) mounted on the gantry. The advantages of kV techniques for both 2D and 3D are good contrast, high spatial resolution and good soft tissue appearance with low imaging dose.

The purposes of our study were to compare the delivered dose with five image guidance techniques, to evaluate the differences between different linear accelerators from various vendors and to investigate the correlation between imaging dose and image quality. The same phantom and setup conditions were used to make the measurements repeatable and the different techniques and accelerators comparable. Most of the papers in the literature evaluated different techniques on a specific machine, but in this work different linear accelerators of four different vendors were compared.

2. Materials and methods

2.1. Linear accelerators

Imaging was performed on Synergy (Elekta AB Stockholm, Sweden), TrueBeam (Varian Medical Systems, Palo Alto, USA), Artiste (Siemens AG, Erlangen, Germany) and CyberKnife (Accuray Inc., Sunnyvale, USA) systems.

The TrueBeam machines are now equipped with the newest EPID with aSi-1200 detector (PortalVision^{TM}, Varian Medical Systems) which was used in this study. Physical dimensions of the active detector are 40 cm × 40 cm, the image size is 1280 × 1280 pixels and the pixel size is 0.34 mm × 0.34 mm. The kV source can be found on the arms, at 270° and the detector is situated opposite that. There is an option on the new versions to have a 2.5 MV photon energy, which can only be used for imaging purposes.

Siemens Artiste linear accelerator is equipped with PerkinElmer XRD 1640 xN19 ES a-Si EPIDs. The active area of the detector arrays is 41 cm × 41 cm with 1024 × 1024 image size with 0.4 mm × 0.4 mm pixel size. This machine offers only MV verification with 6 MV beam. The Artiste system has an alternative way to provide a kV imaging option with the Siemens Somatom Definition in-room CT mounted opposite the accelerator in the bunker. Before scanning the couch has to be rotated by 180° for image acquisition.

The Synergy accelerator is equipped with an iView GT a-Si EPID (Elekta, Crawley, UK) for image acquisition. The sensitive area of iView GT is 40 cm × 40 cm containing 1024 × 1024 pixels, and the pixel size is 0.39 mm × 0.39 mm. The kV source is mounted on the arms at 90° and the detector is situated opposite that.

The CyberKnife imaging system provides real-time imaging of the patient with two in-room ceiling mounted kV X-ray sources placed at 45° from the vertical along with flat panel detectors in the floor. The X-ray sources are positioned so that the generated beams intersect orthogonally creating an imaging centre located 92 cm from the floor. The number of pixels is 1024 × 1024 and the number of active pixels is 1012 × 1012, the pixel size is 0.40 mm and the total area is 41 cm × 41 cm.

2.2. 2D orthogonal paired imaging

Synergy and TrueBeam machines have both MV and kV sources so they are capable of using both techniques. In case of kV-kV imaging (Elekta, Varian, CyberKnife) 120 kV tube potential and 5 mAs tube current were used, offered by the default Thorax protocol of each machine (Table 1.). For Elekta and Varian the imaging field size at isocenter was 15 cm × 15 cm, and the images were taken from 0° and 90°, as left sided breast cancer was assumed. With CyberKnife the images are always acquired from angles of 45° and 315° and the field size at align center is 20.5 cm × 20.5 cm. In case of MV-MV paired imaging we used a field size of 15 cm × 15 cm at isocenter and 1.5 MU (Varian, Siemens) or 2 MU (Elekta). The 2.5 MV imaging mode was also investigated with TrueBeam under the same circumstances.

2.3. 3D volumetric imaging

In case of kV-CBCT default thorax protocols that were given by the vendors of the machines were used, 125 kV and 120 kV tube potential and 270 mAs and 264 mAs tube current for TrueBeam and Synergy, respectively. CT images were taken with a full 360° rotation with half bowtie filter for both accelerators. MV-CBCT imaging technique was only available on Artiste machine. The measurement was undertaken with the default protocol used in clinical practice. The only possible energy is 6 MV. 8 MUs were used during imaging and the gantry rotated 200° during one scan from 260° to 100°. For kV-Fan Beam in-room CT 120 kV tube voltage with 31.2 mAs and 3 mm slice thickness was used and the pitch was 1.45.

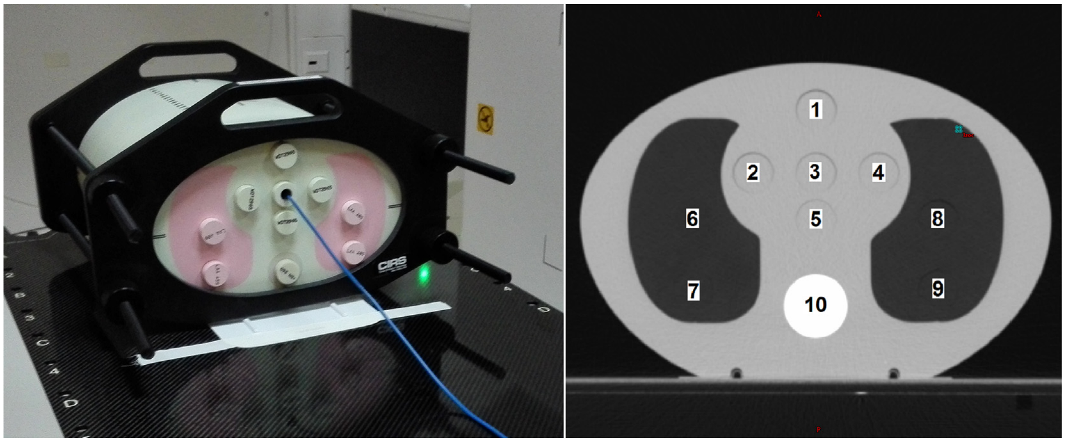

Fig. 1. The CIRS Model 74-007 IMRT Thorax Phantom and the measurement points.

2.4. The measurement

The point dose measurement was performed with a Farmer type ionization chamber (31003 PTW, Freiburg, Germany), connected to a PTW Unidos electrometer. The chamber was calibrated by the national primary standard dosimetry laboratory for Co60 and multiple kV energies. Dose calculations were performed according to the TRS-398 formalism. Half-value layer was measured for all kV sources and the specific calibration factor for the specific kV energy was interpolated. The evaluated MV energies of all accelerators were calibrated with reference conditions: in case of delivering 100 MU, 1 Gy should be measured at d_{max} for the 10 × 10 field at 100 cm SSD. For the measurements the CIRS Model 74-007 IMRT Thorax Phantom (CIRS, Norfolk, VA, USA) was used which is made of tissue equivalent materials and consists of three different inhomogeneities (normal tissue, bone and lung) (Fig. 1.). The ionization chamber can be placed in different inserts in ten different points of the phantom. Point 1 represents the sternum, points 2–4 represent the heart, point 5 illustrates the oesophagus, point 6 displays the anterior and point 7 the posterior part of the ipsilateral lung, point 8 displays the anterior and point 9 the posterior part of the contralateral lung. The dose of the skin was not measured.

The measurements were undertaken with a phantom positioned for left sided partial breast radiotherapy. The isocenter was positioned within the treated breast, the same position that would be used for treatment. First the phantom was aligned to the default zero positions marked with crosses on the body of the phantom. Then the treatment couch was shifted 9 cm laterally, and 6 cm down to get a clinical breast treatment setup. In the case of fan beam CT imaging could not be performed in the shifted position so the couch was centred.

The measurements were performed shortly after maintenance of the machines, and special care was taken of precise imaging and dose delivery system calibration. The calibration values were within tolerance of baseline parameters recorded during the acceptance tests. The pre-set factory protocols for thorax region were used for imaging, because the aim was to evaluate the general difference. To ensure stability the doses were measured three times in every point and the measurement in the first point was repeated again at the end.

2.5. Image quality

In the case of 2D planar imaging LEEDS TOR 18FG (Leeds Test Objects Ltd, North Yorkshire, UK) phantom was used to investigate the quality of the images (Fig. 2.). This phantom is basically designed for the quality control of mammography machines. The phantom has 18 discs of 8 mm diameter and 21 bar patterns. The spatial resolution and contrast can be specified by determining the lowest contrast disc and the smallest discernible group of bars visible in the image. Above 80 kVp and 100 mAs the acquired images cannot be evaluated, therefore a 20 cm thick slab phantom, simulating the patient's body, was placed on the tabletop to get information about the image quality. Beside kV-kV and MV-MV paired imaging, 2.5 MV imaging was also investigated.

A Catphan 604 Phantom (The Phantom Laboratory, NY, USA) was used for the evaluation of the image quality of 3D CBCT images including geometric distortion, spatial resolution, low contrast, HU constancy, uniformity, and the noise of CBCT (Fig. 3.). The phantom can be divided into four parts, the first of which is made for uniformity check. A special material with constant CT number (between 5 and 18HU) can be found here. To check the uniformity of the imaging the CT numbers were measured in the edge and also in the middle of the phantom in 5 squares. The second part is dedicated to check the geometrical distortion of the imaging and the CT number linearity. The scan section has 10 different inserts, the Hounsfield units of which are between −1000 and +1000. This section also contains 4 balls made of Teflon which are 50 mm away from each other, shaping a square to check the geometrical distortion and the circular symmetry of the system. The third part is dedicated to check the spatial resolution. This section has a 1 through 21 line pair per centimetre high resolution test gauge. The gauge is cut from 2 mm thick aluminium sheets and cast into epoxy. The resolution was determined by the number of bars that could be visible separately to the naked-eye. The low-level contrast of the image set can be evaluated in the fourth section. It has three groups of inserts with various diameters and contrasts. The actual contrast levels are measured by making region of interest measurements over the larger target, and in the local background area. The three groups have nominal target contrast levels of 1%, 0,5% and 0,3%.

3. Results

The point dose measurements were performed in ten points in the phantom (see Fig. 1). The results are summarized in Table 2 for all of the imaging techniques. The average standard deviation of dose in all measurements was 0,6%. In case of CyberKnife and TrueBeam the measurements were repeated after six months to get information about the repeatability and the dose differences in each points were 3,3% and 4,5% on average for Cyberknife and TrueBeam respectively.

The comparison of the results regarding the linear accelerator of each vendor can be found in Fig. 4.

3.1. kV-kV image comparison

In the case of kV-kV imaging, the maximum dose was under 0.1 cGy in every point. The lowest dose was found in point 7 and its value was under 0.01 cGy. The trends of the dose distribution were the same for

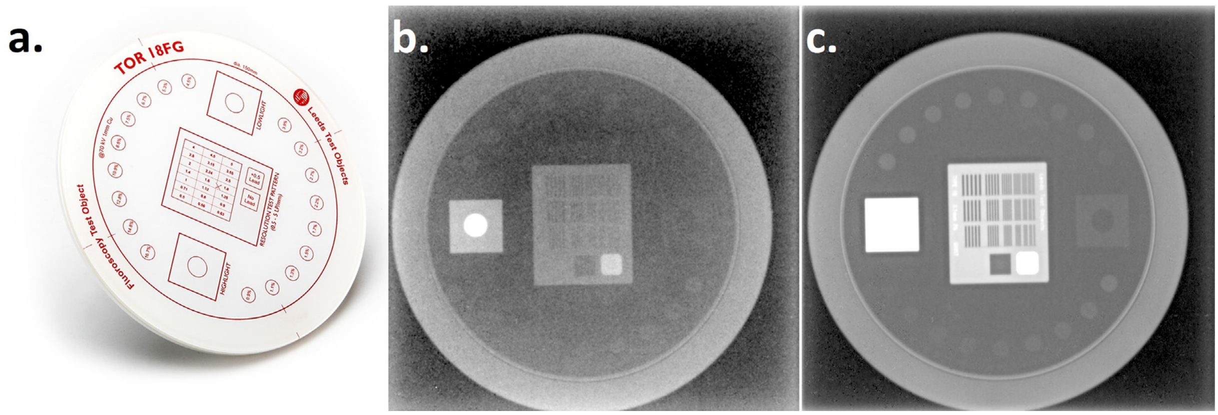

Fig. 2. a) Leeds TOR 18FG phantom and its image b) with 6MV and c) with 2.5MVon TrueBeam.

TrueBeam and Synergy machines. The biggest difference between the two machines was 0.03 cGy and the mean dose of all points was identical. Imaging on CyberKnife system resulted in 0.01 cGy mean dose. The highest value of 0.02 cGy occurred in point 1. The lowest doses were 0.002 cGy and 0.003 cGy in the contralateral lung. Also, in point 4 and 8 the doses were 4–6 times lower than on Synergy or TrueBeam.

3.2. Fan beam CT

Fan Beam CT caused homogenous distribution in the whole phantom, as the phantom and the couch were centered. The highest dose was 0.57 cGy in point 4 and the deviation from this dose was under 0.23 cGy in all cases. The lowest value was 0.34 cGy which was found in point 10.

3.3. Mv-CBCT

MV-CBCT caused the highest patient dose of all the investigated methods. The maximum dose was 8.35 cGy, located in the sternum. The lowest dose was 6,1 cGy measured in the spine. The mean dose was 7.11 cGy. The distribution of the dose was the same as of the other techniques, increased dose was detected in point 4 and 8: 7.39 cGy and 7.34 cGy respectively. Compared to kV-CBCT imaging, these values were 11.6 times higher on average.

3.4. kV-CBCT comparison

We investigated the kV-CBCT imaging of two vendors and the highest dose was measured in the sternum (0.96 cGy–TrueBeam and 0.84 cGy – Synergy) and in the ipsilateral lung (0.82 cGy – TrueBeam and 0.89 cGy – Synergy). The lowest dose appeared in the spine with both machines (0.3 cGy). The highest difference between the two

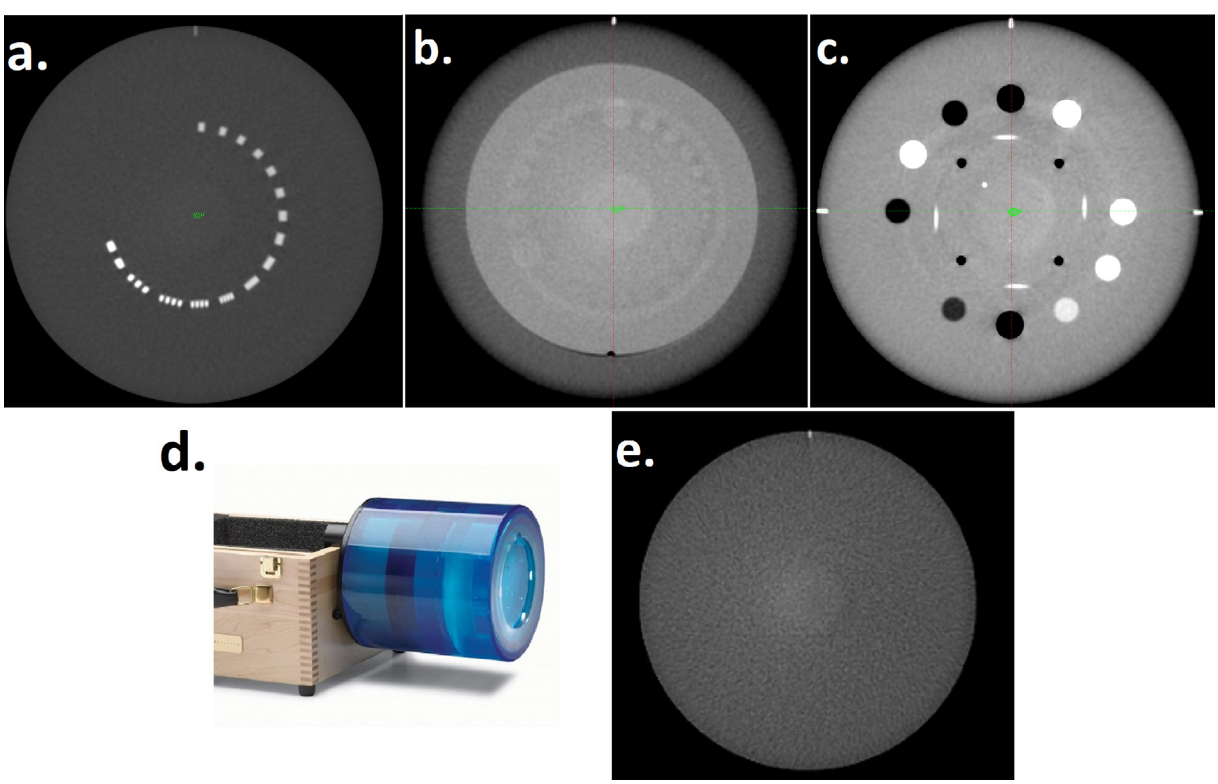

Fig. 3. Catphan phantom a.) Spatial resolution section b.) Low contrast resolution section c.) Geometry distortion section d.) Commercial photo of the phantom e.) Uniformity section.

Table 2
Point doses of different imaging techniques measured in thorax phantom.

Patient dose in thorax phantom [cGy]											
Point of measurement	2D Planar imaging							3D imaging			
	kV-kV			MV-MV				kV-CBCT		Fan-Beam kV-CT	MV-CBCT
	TrueBeam	Synergy	CyberKnife	TrueBeam		Synergy	Artiste	TrueBeam	Snyergy	Artiste	Artiste
				2.5 MV	6MV	6MV	6MV				
1.	0.05	0.02	0.02	0.61	1.07	1.95	1.43	0.96	0.84	0.56	8.35
2.	0.02	0.02	0.01	0.65	0.89	1.57	1.20	0.62	0.67	0.56	7.41
3.	0.03	0.03	0.01	0.96	1.15	2.18	1.60	0.74	0.69	0.55	7.23
4.	0.05	0.06	0.01	2.16	2.58	4.45	3.52	0.89	0.86	0.57	7.39
5.	0.02	0.04	0.01	0.91	1.15	2.29	1.62	0.60	0.58	0.52	6.65
6.	0.01	0.01	0.003	0.45	0.70	1.25	0.96	0.48	0.56	0.53	7.20
7.	0.01	0.01	0.002	0.10	0.12	0.25	0.17	0.46	0.49	0.49	6.72
8.	0.06	0.07	0.01	2.32	2.68	4.58	3.62	0.82	0.89	0.52	7.35
9.	0.06	0.09	0.01	1.09	1.25	1.94	1.66	0.66	0.64	0.51	6.70
10.	0.01	0.04	0.003	0.17	0.17	0.87	0.28	0.30	0.31	0.34	6.11
Average	0.04	0.04	0.01	0.94	1.18	2.13	1.61	0.65	0.65	0.52	7.11

machines was 0.12 cGy and the mean dose of all points was identical.

3.5. MV-MV image comparison

Considering the MV-MV imaging method, the maximum dose was measured in points 4 and 8. The lowest dose was noticed in the lower part of the contralateral lung (under 0.25 cGy) and the spine (under 0.2 cGy). In every point imaging with Synergy machine caused the highest doses in all points followed by Artiste and TrueBeam in order. The highest doses were noticed in point 4 (4.45 – 3.52 – 2.58 cGy respectively) and point 8 (4.58 – 3.62 – 2.68 cGy respectively). Images with Artiste and TrueBeam were taken under the same circumstances.

3.6. MV – 6 MV imaging comparisons

Studies have shown that with the newly available 2.5 MV imaging on Varian TrueBeam machines the patient dose can be reduced significantly and also better image quality can be achieved [15,16]. The mean measured dose in all 10 points for 2.5 MV and 6 MV imaging was 0.94 cGy and 1.18 cGy, respectively. The largest dose difference was observed in point 1 where a 43% difference was detected. In the rest of the points the difference was 27%, 17%, 16%, 21%, 35%, 14%, 13%, 12%, 0%, respectively. The highest doses were measured in point 4 and point 8 with both imaging techniques. In these points the values were significantly higher than in any other point; for 2.5 MV imaging they were 2.16 cGy and 2.33 cGy and with 6 MV imaging 2.58 cGy and 2.68 cGy. The detailed dosimetric results of this study can be found in Table 2.

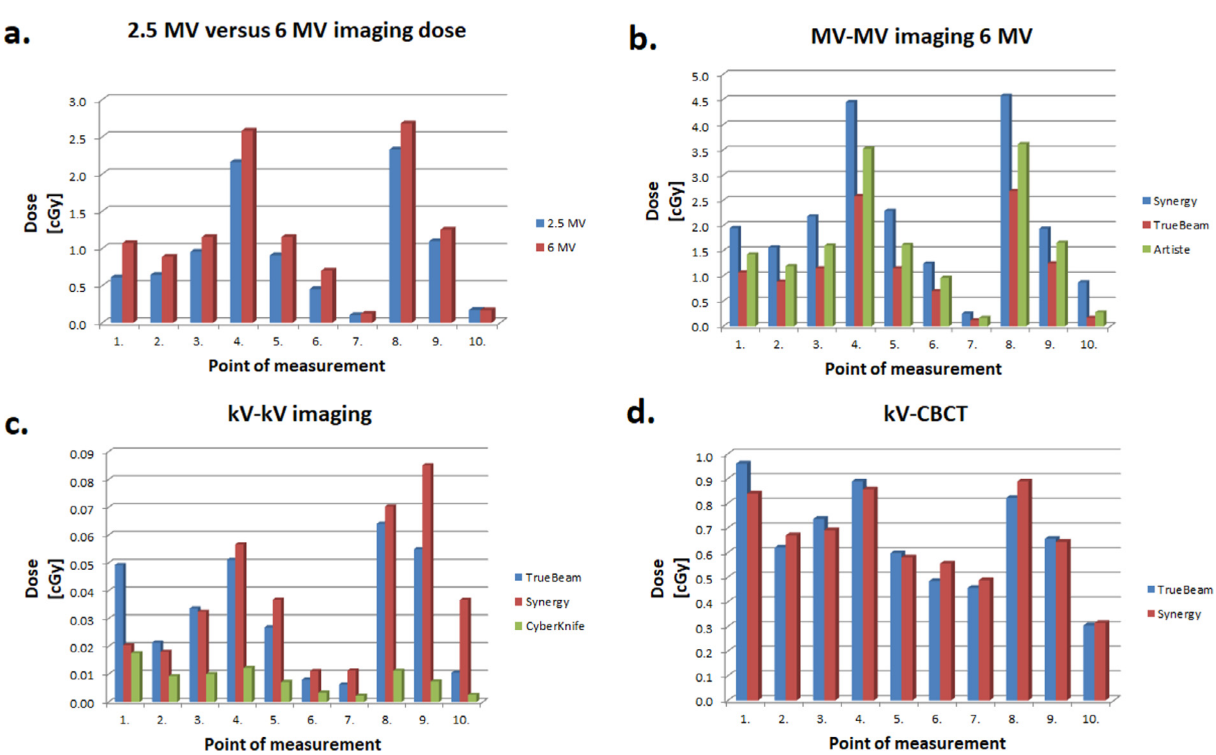

Fig. 4. Point dose comparison of different imaging techniques: a.) 2.5 MV and 6 MV, b.) MV-MV pair, c.) kV-kV pair and d.) kV-CBCT.

Table 3
Contrast resolutions and spatial resolutions of MV images with Leeds phantom.

Contrast (MV AP image)	TrueBeam				Synergy	Artiste
	2.5 MV		6 MV		6 MV	6 MV
	Low dose	High quality	Low dose	High quality		
Number of visible discs	17	17	8	10	11	13
Contrast [%]	0.011	0.011	0.053	0.039	0.032	0.022
Spatial resolution	9	9	2	3	4	5
[LP/mm]	1.25	1.25	0.56	0.63	0.71	0.8

3.7. Image quality for kV-kV and MV-MV imaging

For kV-kV images in spatial resolution section 5 blocks were distinguishable with Synergy and 9 with TrueBeam and CyberKnife. Low contrast resolution could not be defined with this phantom in the kV energy range without absorbing material. Using 20 cm thick Slab phantom all the 18 discs were visible on kV images with TrueBeam and Synergy machines which refers to 0.9% contrast level. 10 blocks from the 21 bar pattern could be distinguished which means 1.4 LP/mm spatial resolution.

Regarding contrast and spatial resolution there was no significant difference between 6 MV images of Artiste and Synergy machines. Lower doses were measured with TrueBeam, however, the contrast resolution and spatial resolution showed worse quality. Altogether 13 discs were visible with Artiste (which means 2.2% contrast level), 11 with Synergy (3.2% contrast level) and 10 with TrueBeam (5.3% contrast level). The spatial resolution was 0.8 LP/mm with Artiste, 0.71 LP/mm with Synergy and 0.56 LP/mm with TrueBeam. As far as the 2.5 MV imaging is concerned with TrueBeam machine, both parameters were significantly better. We could achieve 1.1% contrast level and 1.25 LP/mm spatial resolution (Table 3.).

3.8. CT image quality

Image sets acquired with kV-CBCT (Synergy and TrueBeam) and Fan Beam CT (Siemens) were investigated. As far as circular symmetry is concerned the differences were under 1.8% (0.9 mm) in all cases. The highest differences regarding directions were 0.5 mm, 0.8 mm and 0.7 mm for Synergy, TrueBeam and Siemens Helical CT respectively (Table 4.).

The spatial resolution was poorer with Synergy which means that only 1.25 mm resolution was achievable with this machine. 0.83 mm spatial resolution was detected with the two other imaging systems.

As for the contrast resolution a 1.0% contrast level was detected with all three imaging systems. The first three discs with 15 mm, 9 mm and 8 mm diameter were visible with Artiste and Synergy. With TrueBeam we could see one more disc with 7 mm diameter.

The quality assurance cannot be performed with Catphan phantom in the case of MV-CBCT. Due to the high energy the acquired image sets are too noisy to be able to process them.

4. Discussion

Nowadays an external beam therapy treatment always includes a verification process that can vary due to the location of the target volume, available tools and other circumstances. Hwang et al. [17] observed 2.9 mm ± 1.4 mm average setup error vector when taking MV images of patients with breast cancer with free breathing. The intrafraction error vector was found to be in range of 2.9 mm ± 1.3 mm and 3.4 mm ± 1.8 mm depending on the observer. These measurements verify that image guidance is mandatory when using high fraction doses and small PTV margins.

Table 4
Circular symmetry and contrast resolutions and spatial resolutions of CT images with Catphan phantom.

Circular symmetry of imaging system	Default	TrueBeam	Synergy	Artiste
		kV-CBCT		Helical CT
Horizontal up [mm]	50	50.5	49.3	50.3
Vertical left [mm]	50	50.8	49.5	50.2
Vertical right [mm]	50	50.4	49.5	50.2
Horizontal down [mm]	50	50.3	49.1	50.7

Spatial Resolution	TrueBeam	Synergy	Artiste
	kV-CBCT		Helical CT
Line pair/cm resolved	6	4	6
mm resolved	0.83	1.25	0.83

Low contrast resolution	TrueBeam	Synergy	Artiste
	kV-CBCT		Helical CT
Contrast level	1.0%	1.0%	1.0%
Number of visible discs	4	3	3
Disc diameter resolved [mm]	7	8	8

The quality of life and life expectancy of patients treated with breast irradiation is growing steadily. Therefore, there are more cases where secondary tumours can develop. Because of the increasing number of imaging, an appropriate imaging technique must be chosen with respect to the additional dose delivered to the patient [18]. The dose of imaging methods has been investigated in several studies so far and different values can be found in the literature. Table 5 shows articles and their results with respect to the imaging technique.

Based on our IMRT APBI protocol, the dose limit of the heart is: V15% < 10% ($V_{5.5Gy}$ < 10%) in the case of right sided tumours, while in the case of left sided tumours, the value of $V_{1.8\ Gy}$ to the heart had to be smaller than for conventional whole breast irradiation. In left sided ABPI cases the additional imaging dose must be taken into account in order to protect the heart as much as possible.

The lowest dose was detected with kV-kV imaging technique in our study. To obtain 2D information about the patient kV imaging is recommended to be used instead of MV imaging in the case of APBI. On the other hand, obtaining information about the intra-fraction motion of the patient MV imaging with the treatment beam could be used without causing additional dose to the patient [17]. Doses caused by kV-kV imaging with traditional linacs were in the range of 0.01–0.1 cGy. Comparing the two linacs Synergy caused higher dose in seven measuring points with the same quality indices. The lowest doses were detected with the CyberKnife's imaging system.

In most of the points the highest dose with MV-MV imaging was measured on Synergy followed by Artiste and TrueBeam. The higher values with Snyergy can be explained with the 0,5 higher MU that was used by the standard protocol. The quality of the images was the best with Artiste followed by Synergy and then TrueBeam. The maximum doses of MV-MV imaging were significantly higher than kV-CBCT's in points that were exposed by both fields. These dose values were within

Table 5
Patient dose values found in the literature for various measuring methods.

Author and article	Method	Points of measurement	Tools-phantom	Accelerator	Parameters	Measured dose
Winey et al. [24]	kV-CBCT	Left breast Left lung Right breast Right lung	Cirs thorax phantom + house made breast attachment	Varian Clinac	125 kVp, 80 mA 25 ms/ projection Half fan mode, half bow tie filter	9.06 cGy 4.85 cGy 2.75 cGy 2.42 cGy
Quinn et al. [25]	kV-CBCT	Left breast Right breast Heart	TLD	Elekta Synergy	120 kVp, 140 mAs, 270° arc	0.51 cGy 0.39 cGy 0.4 cGy
Bahig et al. [22]	kV-CBCT	Left breast Right breast Heart	Ion chamber	Elekta Synergy	120 kVp 400 mAs	1.00 cGy 0.36 cGy 0.36 cGy
	MV-EPID	Left breast Right breast Heart	Ion chamber		6 MV 2 MU 10 cm x 18 cm field	4.44 cGy 0.04 cGy 0.03 cGy
Walter et al. [21]	MV EPID	Skin	In-vivo	Elekta Synergy	6 MV 5 MU	Avg 12.7 cGy
	kV-EPID	Skin	In-vivo		120 kV, 40 ms/frame AP: 25 mA Lat: 32 mA 27.7 cm × 27.7 cm	Avg 0.18 cGy
Alvarado et al. [20]	kV-EPID	Left breast Right breast Heart	Film	Varian 21iX		0.25 cGy 0.05 cGy 0.15 cGy
	kV-CBCT	Left breast Right breast Heart				0.8 cGy 0.8 cGy 1.05 cGy
Gayou et al. [26]	MV-CBCT	Isocenter 0° 90° 180° 270°	Ion chamber	Siemens Primus	10MU 200° arc	9.2 cGy 12.1 cGy 9.7 cGy 4.1 cGy 8.2 cGy
Li et al. [23]	MV-CBCT	Heart Left Lung Right lung Left breast	Ion chamber CIRS thorax phantom	Varian Halcyon	10 MU 200°arc	8.45 cGy 7.16 cGy 7.19 cGy 9.71 cGy
	MV-EPID	Heart Left Lung Right lung Left breast			4 MU Various field sizes In-Target and Extra-target scenario	3.36 cGy 3.72 cGy 0.80 cGy 4.32 cGy
Canbolat et al. [27]	kV stereoscopy	Abdomen	TLD and film	CyberKnife	120 kV and 10 mAs 100 kv and 90 mAs 20 cm × 20 cm field size	0.04 cGy 0.24 cGy
Qi et al [29]	Fan Beam CT		Rando phantom TLD	Siemens Somatom	120 kV 25 mAs 1.0 pitch	0.19 cGy

a range of 0.1–4.6 cGy and 0.3–0.96 cGy with kV-CBCT. MV imaging with 2.5 MV could be an appropriate way to acquire better image quality along with less noise and less dose.

CT caused higher average dose in the whole body, but it is worth using this technique because of the advantages of 3D information. Due to the delivered dose and the better image quality kV-CBCT should be used instead of MV-CBCT. On-rail fan-beam CT caused the lowest doses with similar image quality results, but the disadvantage of this technique is that the couch has to be rotated by 180° together with the patient between imaging and treatment and this can result in additional patient positioning errors.

kV-planar imaging is expected to cause the lowest dose to patients. Santos et al. [19] estimated an average dose for an image between 0.1 and 0.3 cGy in their review. Alvarado et al. [20] measured doses from standard kilovoltage radiographic imaging with a RANDO thorax phantom with films. They found that the results are in an interval of 0.05–0.4 cGy. These are lower values than ours in this study. They used lower tube voltage and tube current and this may explain the differences. Walter et al. [21] measured 0.18 cGy on average with ion chambers placed on patients' skin.

With MV planar imaging 4.44 cGy was reported to the ipsilateral breast, 0.04 cGy to the contralateral breast and 0.03 cGy to the heart by Bahig et al. [22]. They used Farmer ionization chamber in a custom-designed female phantom and the settings in the measurement were similar to the ones in our study. The trend of their results fits to our values; they got an outstanding value in the ipsilateral breast and lung but the decrease of dose gradient was larger. The value in the heart was significantly lower than in our study due to the fact that the anatomy of the phantom was quite different. Li et al. [23] investigated normal tissue doses from MV-MV imaging with Halcyon machines. They measured the dose in a CIRS thorax phantom with breast attachment. They found 3.36, 3.72 cGy in the heart and left lung when the tissues are in field and 0.80 cGy for the right lung outside the field using high-quality mode with 4 MU. As for left breast the dose ranged from 0.80 cGy to 4.3 cGy depending on the location of the isocenter. Moreover, Walter et al. [21] published 12.7 cGy on average measured on patients' skin, but they applied 5 MU instead of 1.5 MU.

The impact of kV-CBCT imaging has been the topic of numerous other articles. This is the most commonly used verification form for APBI patients. Winey et al. [24] measured the dose in a CIRS thorax solid water phantom with a Farmer ionization chamber. They attached an in-house made breast attachment to the phantom in order to simulate the breast more accurately. They found 4.85 cGy in the left lung and 2.42 cGy in the right lung. Quinn et al. [25] measured the dose with TL dosimeters in a CIRS anthropomorphic breast phantom. They simulated a left sided breast cancer patient and they reported 0.51 cGy in the ipsilateral breast, 0.39 cGy in the contralateral breast and 0.4 cGy in the heart, which values are lower than our results. Bahig et al. [22]

reported higher values – 1 cGy in the ipsilateral breast - under comparable circumstances than in our experiment. Alvarado et al. [20] also found the doses in the interval of 0.8–1.05 cGy with the default imaging protocol. They achieved better results when they changed the settings but did not report any details about the quality of the images.

In their work Gayou et al. [26] showed the absolute doses of MV-CBCT. They used a cylindrical phantom with 30 cm diameter and 15 cm length to simulate a pelvis case. The five measurement locations were at the isocenter and at four positions located 1 cm below the phantom surface at 0°, 90°, 180°, and 270° clockwise. In the isocenter they measured 9.2 cGy and in the peripheral points between 4.1 and 12.1 cGy. They used 10 MU and 200° arc for the imaging. Li et al. [23] found 8.45, 7.16, 7.19 cGy to heart, left lung and right lung respectively and 9.71 cGy to left breast using the same settings with Halcyon machine simulating a left-sided treatment. According to our default thorax protocol we used 8 MU and 200° for the image acquisition and measured doses between 6.1 and 8.3 cGy.

Fewer results can be found in the literature related to CyberKnife. The work of Canbolat et al. [27] focused on skin dose measurements with films or thermoluminescent dosimeters. They used 20 cm × 20 cm field size and the most commonly used energies of 90, 100, 110 and 120 kVp, with 3 mAs levels. For each measurement 80 consecutive images were acquired to ensure sufficient dose deposition in the dosimeters. The acquired data were averaged to obtain the dose per image. Thus, they found doses in the range from 0.04 to 0.24 cGy. The manufacturer released a review [28] about patient doses in which they reported 0.024 cGy for the setting that we used.

Qi et al. [29] measured dose with four CT scanner models and three study protocols. They used a Rando phantom with breast modules. Twenty thermoluminescent dosimeters were placed inside the breast modules to measure breast tissue dose. The dose was reported to be within 0.15–0.22 cGy with default lung scanning protocols that mostly matched our protocol. Santos et al. [19] predicted higher values than our results. They published 1–3 cGy average dose for CT-on-rail imaging. In our investigation we got doses between 0.3 and 0.6 cGy.

The limitation of our work, that the dose to skin was not measured and evaluated. Our results showing dose differences between kV and MV imaging may not be valid near the surface.

5. Conclusion

All image guidance techniques applicable for APBI were evaluated with respect to delivered dose and image quality. One possible approach to reduce the absorbed dose to patients is to use lower energies for imaging when it is available on the system. According to our study, orthogonal-angled kV-kV paired 2-D planar imaging results in the lowest dose during verification. To reduce patient dose planar imaging with 2.5 MV can be a good method instead of 6 MV imaging. This means that we can acquire images with better quality at higher contrast level and less noise.

Without fiducial markers 3D CT imaging is required to get volumetric information of the target position. On the other hand, CT imaging takes more time – in some cases this may be considered, according to the patient's condition and the possible setup uncertainties, especially in the case of CT on rail imaging. The CBCT techniques reduce these effects, but the dose to organs and image quality are much better with kV energy than with MV energy. There were no significant differences regarding image quality between each vendor using similar imaging settings. As far as the measured doses are concerned significant difference was shown between the three vendors with MV-MV imaging where TrueBeam caused the lowest dose followed by Artiste and then Synergy. With kV planar imaging the doses were lower with TrueBeam in 7 of the 10 points than with Synergy, but CyberKnife caused the lowest doses. With kV-CBCT significant difference cannot be detected between the two manufacturers.

Based on our results in the case of accelerated partial breast irradiation we suggest using kV-kV orthogonal imaging with fiducial markers, which causes the lowest dose and offers good image quality. kV-CBCT is the optimal solution to overcome the lack of fiducials by providing 3D information and correct patient position.

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