

IGRT

Phantom and in-vivo measurements of dose exposure by image-guided radiotherapy (IGRT): MV portal images vs. kV portal images vs. cone-beam CT

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Abstract

Purpose: Positioning verification is usually performed with treatment beam (MV) portal images (PI) using an electronic portal imaging device (EPID). A new alternative is the use of a low energy photon source (kV) and an additional EPID mounted to the accelerator gantry. This system may be used for PI or – with rotating gantry – as cone-beam CT (CBCT). The dose delivered to the patient by different imaging processes was measured.

Methods and materials: A total of 15 in-vivo dose measurements were done in five patients receiving prostate IMRT. For anterior–posterior (AP) and lateral PI with MV and kV photons measurement points were inside the rectum and at the patient's skin. Dose for CBCT was measured in the rectum. Additional measurements for CBCT were done in a cylindrical CT-dose-index (CTDI) phantom to determine peripheral, central and weighted CTDI.

Results: The dose for AP MV PI was 57.8 mGy at the surface and 33.9 mGy in the rectum, for lateral MV PI 69.4 mGy and 31.7 mGy, respectively (5 MU/exposure). The dose for AP kV PI was 0.8 mGy at the surface and 0.2 mGy in the rectum, for lateral PI 1.1 mGy and 0.1 mGy, respectively. For a CBCT the rectal dose was 17.2 mGy. The peripheral CTDI was 23.6 mGy and the center dose was 10.2 mGy, resulting in a weighted CTDI of 19.1 mGy in the phantom and an estimated surface dose of ≤ 28 mGy.

Conclusions: Even taking into account an RBE (Relative Biological Effectiveness) of 2 for kV vs. MV radiation, for kV PI the delivered dose is lower and image quality is better than for MV PI. CBCT provides a 3D-image dataset and dose exposure for one scan is lower than for two MV PI, thus rendering frequent volume imaging during a fractionated course of radiotherapy possible.

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Optimal tumor control with acceptable side effects requires sufficient dose in the target volume, while dose to surrounding organs at risk is kept to a minimum. The treatment of extracranial targets is especially susceptible to positioning errors and internal organ motion due to respiration or changing organ volumes for example bladder and rectum filling.

To compensate for systematic errors and target movement, a planning target volume (PTV) is created by adding a margin to the clinical target volume (CTV) [31]. As a consequence, parts of organs at risk may be inside the PTV, which limits the dose to the target [22,23]. If the correct positions of target and organs at risk are known right before a treatment and if the patient's position is then corrected according to the displacement of the target, it is possible to reduce the margin around the CTV and thus lower the dose in organs at risk [17].

The term "image guidance" or "image-guided radiotherapy" (IGRT) has been ascribed to the process of locating the target position or a suitable surrogate by using imaging modalities in direct conjunction with the treatment (typically "in-treatment-room"). While stereotactic ultrasound has recently been introduced to enable positioning of ultrasound-accessible soft tissue targets [20,26], the standard procedure to determine the position of the patient has been to acquire two perpendicular portal images (PI) of the patient with the treatment beam (MV) using a square field and a low number of monitor units (MU) [11]. These images, detected with a film or an electronic portal imaging device (EPID), provide information about the positioning of the patient's bony structure as a surrogate for the actual target position. After matching the PI to reference images, the positioning correction can be calculated (2D/2D matching).

A more detailed view of the bony structure and soft tissue can be achieved by using photons of lower energy, for example with an X-ray source inside the treatment room emitting photons with a maximum energy of 80–140 keV. While these devices provide images of the bony anatomy with better quality than MV PI can offer, soft tissue information is still limited to high contrast situations such as identification of lesions within the lung.

If, however, the X-ray source and a flat panel detector are mounted to the gantry of the linear accelerator, it is not only possible to acquire planar images, but also to acquire multiple projections of the patients during a 360° rotation resulting in a “cone-beam CT scan” (CBCT), that can be used for a volume reconstruction in transversal, coronal and sagittal slices providing 3D bone and soft tissue image information [13,15,18]. With these reconstructions it is possible to locate the target volume directly before a treatment session and to reposition the patient based on matching of CBCT and treatment planning CT.

To maximally exploit the benefit of image guidance (reduced margins), either the target position has to be visualized and corrected before each treatment fraction (on-line) [16,30] or the treatment margin has to be adapted to a known target movement after 5–10 treatment days (off-line) [31], or the treatment margin is generated by using more than one planning CT [2].

While image guidance with ultrasound is not critical with regard to radiation exposure, image guidance with photons results in additional dose to the patient. Therefore, dose measurements for different imaging strategies are of utmost interest, especially when daily imaging is intended. To provide a basis for discussions regarding handling of additional dose because of image guidance, we measured dose at the surface and deep in the body of patients as a consequence of planar MV PI, planar kV-imaging as well as volume imaging (CBCT). To estimate the computed tomography dose index (CTDI) for comparison with dose reference values (DRV, released by the national radiation protection office [3]) measurements were performed in several areas of an acrylic cylindrical phantom.

Materials and methods

Patient measurements were approved by the Institutional Ethics Committee. After the nature of the procedure was explained and informed consent was obtained, in-vivo measurements were performed three times for every imaging modality in five patients treated for prostate cancer with intensity modulated radiotherapy (IMRT). Probes approved for in-vivo measurements were placed both at the surface of the patients (kV and MV PI only) and inside the rectum (PI and CBCT). All ionisation chambers used in this work are from PTW Freiburg, Freiburg, Germany. Phantom measurements for determination of the volume computed tomography dose index (CTDI) for a cone-beam CT scan were done. All images were acquired on a 6 MV linear accelerator (Synergy™, Elekta, Crawley, UK) equipped with a CBCT (XVI™, Elekta, Crawley, UK).

Dose measurement for AP and lateral portal images

For the surface measurements of two perpendicular portal images, one in anterior–posterior (AP) and one in lateral direction, a semi-flexible ionisation chamber (PTW 31003) with a nominal application range for energies between 30 kV and 50 MV and a sensitive volume of 0.3 cm³ was used. The chamber was fixed to the patients’ skin in the middle of the irradiated field used for position verification.

The rectal measurements were done with a micro-chamber (PTW 23323, nominal application range between 60 kV and 50 MV, sensitive volume 0.1 cm³). The chamber was placed inside the rectum, in crano-caudal direction at the level of the symphysis, the position of the chamber was checked with the first measurement in AP direction.

The dose in both chambers was measured simultaneously for every portal image. Images with the treatment beam (6 MV) were done with a field size of (20 cm)² at the isocenter using 5 MU per exposure. The X-ray images with a size of (27.67 cm)² at the isocenter were done with 120 kV, 25 mA and 40 ms/frame acquiring five frames for one AP image (equals 5 mA s) and with 120 kV, 32 mA and 40 ms/frame also using five frames for lateral images (equals 6.4 mA s).

For portal images with the treatment beam, the skin chamber was covered with a build-up cap of 3 mm PMMA, for images with the kV-source it was uncovered, as the chamber cover was expected to be sufficient for dose build-up. To correct for the energy dependence of the chambers the measured dose values were corrected with calibration factors (given by PTW) according to the energy of the treatment beam and the X-ray source.

Dose measurement for cone-beam CT

The in-vivo dosimetry for cone-beam CT imaging was done inside the rectum with the micro-chamber mentioned above. The chamber remained in the same position as it was for the dose measurement for portal images. An image sequence of approximately 650 projections was acquired during a 360° gantry rotation and was used for three-dimensional reconstruction of the irradiated volume. The X-ray source characteristics for a single projection were 120 kV, 25 mA and 40 ms, which results in approximately 650 mA s for a full scan, the field size was (27.67 cm)² at the isocenter using a lateral field offset of 11.5 cm to get a reconstructed volume with 42,6 cm diameter.

The dose for a cone-beam CT image sequence was measured in all patients three times during the course of their fractionated treatment.

Phantom measurements for cone-beam CT

For the computed tomography dose index (CTDI) measurements an acrylic cylindrical phantom with a diameter of 32 cm and 15 cm height (PTW) was used. The phantom has five holes to place an ionisation chamber, one in the center and the others at 0°, 90°, 180° and 270° each with a distance of 1 cm to the surface of the phantom. Three dose measurements were done in all five positions for a full volume scan with the kV-source. The central dose (CTD_c) was measured in the middle of the phantom, the peripheral dose (CTDI_p) is the average of measurements in the holes at 0°, 90°, 180° and 270°. The weighted CTDI_w is calculated

from the central and peripheral dose measurements as follows:

$$\text{CTDI}_w = \frac{1}{3}\text{CTDI}_c + \frac{2}{3}\text{CTDI}_p$$

The dose measurements were done with two different chambers: a CT-chamber (PTW 30009) with 3.14 cm³ measuring volume and a sensitive length of 10 cm and a 0.3 cm³ ionisation chamber (PTW 31013). As the irradiated volume is longer than 10 cm, both chambers were irradiated over the full length. For comparison reasons the dose measured with the CT-chamber was divided by 10 to calculate the CTDI for 1 cm.

Results

Dose measurements for AP and lateral portal images

The average dose standard deviation over all patients and treatments for AP portal images with the treatment beam was 57.8 ± 1.2 mGy (11.56 mGy/MU) at the surface and 33.9 ± 1.2 mGy (6.78 mGy/MU) in the rectum (see Table 1). For lateral images the dose was 69.4 ± 1.4 mGy (13.88 mGy/MU) at the surface and 31.7 ± 1.8 mGy (6.34 mGy/MU) inside the rectum. The higher value for the skin dose in lateral images can be explained by the smaller source-surface distance for lateral images compared to AP images. The lower dose inside the rectum for lateral images can be explained first by a longer distance from skin to chamber and second by more bony structures being between source and chamber.

The dose measurements for the X-ray images resulted in approximately 1–2% of the dose for the images with the treatment beam: for AP images the dose was 0.8 ± 0.1 mGy at the surface and 0.2 ± 0.1 mGy in the rectum. For lateral images the dose at the skin (1.1 ± 0.2 mGy) was also higher than for AP images acquired with the kV-source, but still much less than the dose for images acquired with the treatment beam. Inside the rectum the average dose was 0.1 ± 0.04 mGy.

Dose measurement for cone-beam CT

The expected maximum D_{\max} and minimum dose D_{\min} inside the rectum for a cone-beam CT scan can be calculated from the results of the dose measurement for AP and lateral

images as follows: $D_{\max} = n/5 D_{\text{AP}}$ and $D_{\min} = n/5 D_{\text{lat}}$ with D_{AP} being the dose for an AP image (using five frames), D_{lat} the dose for a lateral image (also using five frames) and n the number of frames for a CT scan.

The average dose inside the rectum for a 360° volume scan with approximately $n = 650$ projections was 17.2 ± 2.8 mGy, what is inside the expected range from $D_{\min} = 16.9$ mGy to $D_{\max} = 24.7$ mGy.

Phantom measurements for cone-beam CT

The average CTDI_c in the center of the phantom according to 1 cm length measured with the CT-chamber was 10.2 ± 0.1 mGy, the peripheral CTDI_p (averaged over the four measuring points close to the surface) was 23.6 ± 2.1 mGy. These values result in a weighted dose of CTDI_w = 19.1 ± 1.4 mGy for a 360° volume scan. For the 0.3 cm³ chamber the center dose was 11.4 ± 0.1 mGy, the peripheral dose 25.4 ± 1.8 mGy resulting in a weighted dose of 20.7 ± 1.2 mGy. The higher doses measured with the 0.3 cm³ chamber are the result of a sensitive measuring length of slightly more than 1 cm.

Discussion

While MV portal imaging with films was the standard procedure for patient positioning during the last decades, image quality was relatively poor despite significant additional dose when images had to be acquired from angles different to the treatment beam orientations. This dose, that is added to the planned dose by the imaging process, depends on the mode of image acquisition. Electronic portal imaging based on amorphous silicon detectors has significantly improved image quality for MV-imaging, but suffers from the same basic problems as film-based planar MV-imaging, these being lack of soft tissue contrast and confinement to 2D/2D or 2D/3D image matching.

For two perpendicular MV-images made with the treatment beam using a low number of MU (5 MU each, the standard dose for film-based PI), the additional dose to the organ at risk (rectum) was approximately 6.6 cGy in our measurements. For a patient treated with 60 Gy to the prostate (2 Gy fractions) and positioning control twice per week, the additional dose to the rectum would be 0.79 Gy. These values are higher than in [27], as we used more MU for one MV-image in this study. These values can be easily scaled for modern EPID-systems, using our estimate of approximately 1.3 mGy/MU. At our department, EPID imaging in the pelvis is routinely done with 5 MU, resulting in a total dose of approximately 12 mGy per AP and lateral image set.

The additional physical dose added by MV portal images to the rectum could be taken into account during the planning process concerning dose limits to the organ at risk. This is done by some radiation oncology departments [7,27] although its biological impact, given the low single dose, is difficult to estimate [9,28]. Concern mainly relates to stochastic risk rather than deterministic risk, although there may be exceptions (superficial organs at risk that are exposed to higher doses than in the body center due to the dose characteristics of kV CBCT and that are also in the treatment beam (breast, lenses),

Table 1
Results of in-vivo dose measurements (mGy)

Dose (mGy)	MV		kV		CBCT
	AP	Lateral	AP	Lateral	
<i>Surface</i>					
av	57.78	69.42	0.75	1.12	
SD	1.17	1.41	0.13	0.24	
<i>Rectum</i>					
av	33.90	31.69	0.19	0.13	17.23
SD	1.81	1.75	0.08	0.04	2.76

Bold values are used to emphasize the average value of dose measurements.

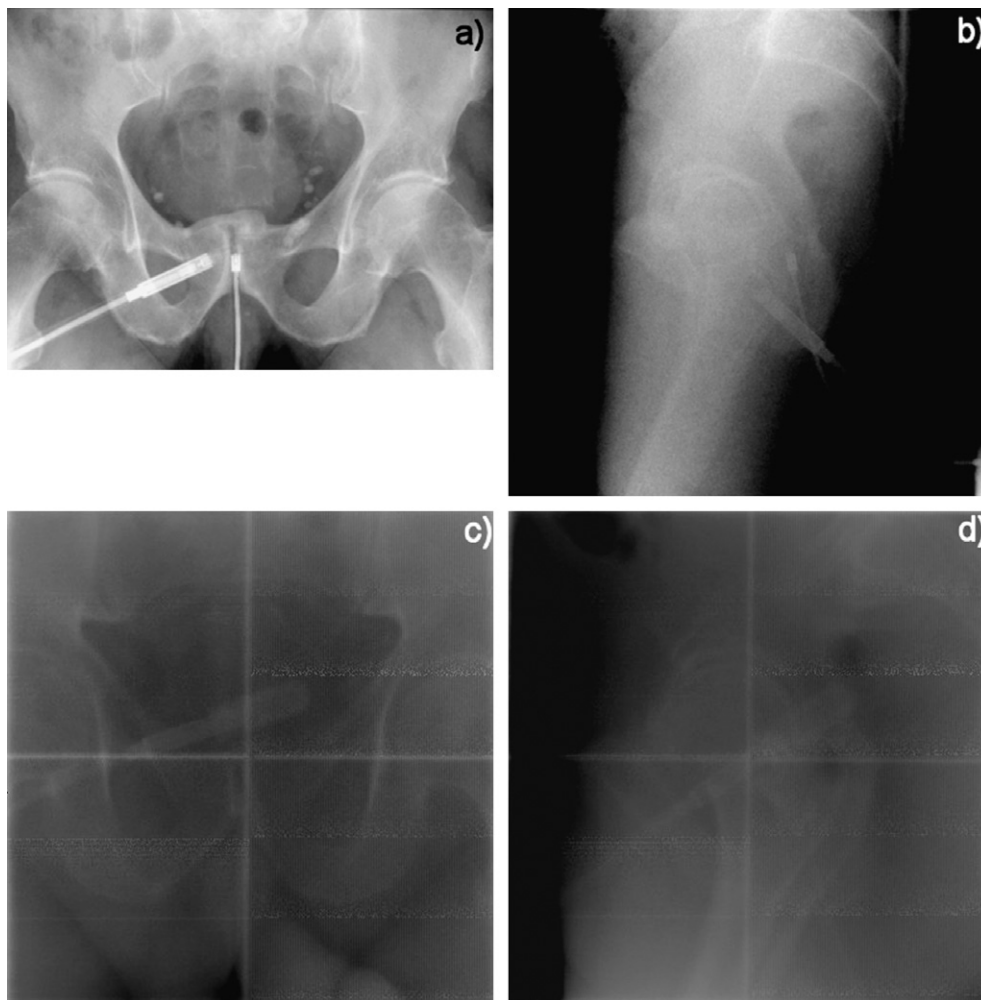


Fig. 1. Portal images (a) kV-source 0°, (b) kV-source 90°, (c) MV-source 0° and (d) MV-source 90°.

daily use with high doses, etc.) as pointed out by Amer et al. [1].

The dose to the rectum for two portal images made with the kV-source is approximately 99% lower than for portal images made with the treatment beam at 5 MU/exposure. The dose at the skin is still 98% lower for kV-images. Even with daily imaging, this dose does certainly not have to be taken into account for the dose prescription. A second advantage of the kV portal images is improved quality when compared with conventional MV portal images, even if amorphous silicon detectors are used for both imaging modalities (see Fig. 1).

The additional dose to the rectum measured in vivo for a 360° volume scan, that can be reconstructed in transversal, coronal and sagittal slices to give a three-dimensional view of the patient (see Fig. 2), is at 17.2 mGy still approximately 73% lower than for two MV portal images at 5 MU/exposure and is in the range of what is reported with anthropomorphic phantom measurements [1,29]. The CTDI-phantom measurements show that the dose 1 cm below the surface is higher than the dose measured in the middle of the phantom (due to the energy of the photons and the corresponding depth dose distribution). The peripheral dose at 1 cm

depth in the phantom corresponds to approximately 90% of the skin dose for 120 kV photon depth-dose-curve [5]. According to this, a conservative estimation of the skin dose would be 28 mGy. However, this is still lower than the skin dose for two MV portal images (up to 69 mGy) for 5 MU/exposure. The doses measured for the 360° volume scan are in the same range as reported skin doses for pelvis patients in [1,18], and CTDI measurements reported in [29], the exact values depending on the respective acquisition protocol (full vs. partial rotation, FOV, etc.). When compared to diagnostic reference values (DRV) [3] of conventional computed tomography, the measured $CTDI_w$ (19.1 ± 1.4 mGy) is lower than the corresponding (German) DRV for pelvis CT of 28 mGy.

Even lower doses seem possible when image reconstruction is based on fewer projections and reduced acquisition angle [12,25,32] and if quantum efficiency and signal-to-noise ratio of detectors are further improved [24]. Doses for lung imaging with kV CBCT may already be lowered to 6 mGy [1] and doses of 50–150 mGy have been reported to yield images of sufficient quality with experimental and clinical devices for MV-based volume imaging [8,19,21,24] with 80 mGy being a reasonable synoptical estimate for

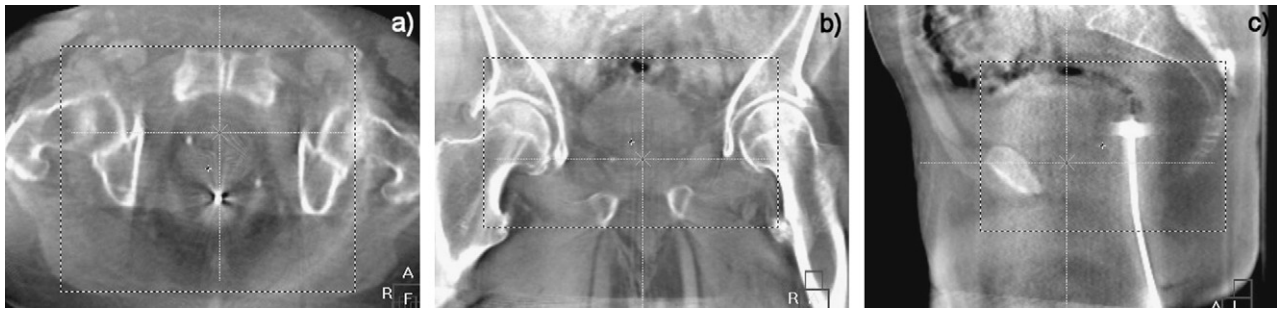


Fig. 2. (a) Transversal, (b) coronal and (c) sagittal reconstruction of a 360° volume scan.

the minimum dose to yield acceptable image quality in the pelvis with these systems. Despite all obvious advantages (better image quality, lower physical dose than MV CBCT), two disadvantages have to be considered when kV radiation is used, though: It is not possible to directly account for the additional dose during the planning process as it may be done with MV CBCT [8,19]. A second disadvantage is the higher Relative Biological Effectiveness (RBE) for kV radiation. While Hill [10] suggested a range of 2–4 for the RBE of kV vs. MV radiation with chromosomal damage as the endpoint, the most likely estimate seems to be a value of 2 according to recent data, both for small receptors and large ones such as the human body [3,4,14]. Taking this into account, however, biological dose for kV CBCT is still lower (50%) than published MV data with currently better image quality and – applying this factor to physical dose – kV dose could also be taken into account for treatment planning with sufficient accuracy when a respective beam model is created in the treatment planning system.

Another approach to volume imaging is offered by the concept of helical tomotherapy. Since the design of this treatment device is modelled like a CT, adding the feature of volume image acquisition is logical. Preliminary data on the applied doses during pre-treatment MV-imaging are higher (30 mGy) than our measurements for CBCT [6] and the system suffers, on the other hand, from a high integral/scatter dose during the actual treatment.

As not only bones, but also soft tissue is visible in the reconstruction of a volume scan, the image information obtained from this volume scan allows for soft tissue positioning of the patient, facilitates potential correction of rotational errors with 6-degree-of-freedom couchtops, offers reliable automatic 3D/3D image matching based on bony anatomy and therefore provides easy and fast superior positioning in critical clinical situations such as treatment of paraspinal tumor. Volume imaging with low additional dose will therefore without any doubt gain importance in precision radiotherapy in the near future.

Conclusion

Planar imaging with a gantry-mounted kV-source is a reliable tool for fast verification of patient positioning, as the dose is lower and image quality is better compared to portal imaging with the treatment beam. Three-dimensional infor-

mation about patient alignment can be gathered with the help of a cone-beam CT scan. If both imaging modalities are available and due to the fact that the dose used for one volume scan is lower than the dose typically used for portal images acquired with the treatment beam, the tested kV cone-beam CT is well suited for daily position verification, especially if patient positioning is critical to apply high doses close to organs at risk safely.

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