First clinical tests using a liquid-filled electronic portal imaging device and a convolution model for the verification of the midplane dose

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Abstract

Background and purpose: Recently, algorithms have been developed to derive the patient dose from portal dose measurements using a liquid-filled electronic portal imaging device. These algorithms have already been validated for several phantom geometries irradiated under clinical conditions. It is the aim of the present study to investigate the applicability of a liquid-filled electronic portal imaging device in combination with these algorithms for two-dimensional midplane dose verification in clinical practice.

Measurements and methods: Portal dose images were obtained during several patient treatments under routine clinical conditions. Measurements were performed to verify the midplane dose during radiotherapy of larynx cancer with 4 MV beams, breast and lung cancer with 8 MV beams and prostate cancer with both 8 and 18 MV beams. Midplane doses, determined from portal dose measurements and analyzed with our algorithms, were compared with midplane doses calculated with our three-dimensional (3D) treatment planning system (TPS).

Results: For the larynx treatment the measured 2D midplane dose agreed within 2.0% with TPS calculations in most parts of the field. Larger differences were found in a small region below the skin due to the absence of electron equilibrium, which is not taken into account in our portal dose analysis. For breast irradiations the measured midplane dose showed a homogeneous distribution in the AP direction in the axial plane, while high dose regions were observed in the cranial and caudal part of the breast. Portal dose measurements and TPS calculations agreed within 2.5% for most of the prostate and lung irradiations. For a few of the prostate and lung treatments larger local differences were found due to differences between the actual patient anatomy and the planning CT data, e.g. as a result of variable gas filling in the rectum and anatomical changes in the lung.

Conclusions: Portal dose measurements with a liquid-filled electronic portal imaging device can be used to determine the 2D midplane dose for various treatment sites in clinical practice. Portal in vivo dosimetry has proven to be important in detecting changes in the patient’s anatomy and its influence on the dose delivery. It is concluded that portal dosimetry is an excellent tool for accurate and independent verification of the dose in the entire (2D) midplane during patient treatment. However, a limited number of patients were involved in this study and the results are therefore preliminary. More research is needed to fully assess the clinical value of portal dose measurements. © 1998 Elsevier Science Ireland Ltd. All rights reserved

Keywords: Portal imaging; Midplane dosimetry; In vivo dosimetry; Electronic portal imaging device

1. Introduction

In vivo dosimetry using diodes or TLDs is performed in many institutions for the verification of dose delivery during patient treatment [7,14,15]. A limitation of this kind of technique is that the dose can only be verified at a few points. Therefore, several authors have investigated the possibility of using portal images obtained with film, a diode array or an electronic portal imaging device (EPID) for a more extensive verification of dose delivery [1–4,8–13,16, 17,20,23,25–28].

In some institutions models have been developed to calculate the dose distribution behind the patient at the position of the portal imaging device, i.e. to predict portal dose images [20,27]. The dose delivery can then be verified by comparing this calculated portal dose image with the portal dose image measured with a portal imaging device.
Another possibility is to use portal dose information to determine patient dose values and to compare these values with those calculated by a treatment planning system. Several studies were performed to investigate the direct use of transmission dose data to predict exit dose distributions [9,11,12,23]. In these studies it has been demonstrated that transmission dose images correspond very well with relative exit dose distributions when small air gaps between phantom and detector are applied.

Normally, transmission dose data are obtained at distances of 30 cm or more between the patient and the portal imaging device. At these large air gaps the agreement between transmission and exit dose distribution decreases to 8% or worse [9,11,12], which is not sufficient for clinical dose verification [5,22]. Therefore, we have developed several algorithms to use portal images obtained with a liquid-filled electronic portal imaging device at clinically applied patient–detector distances to determine accurate 2D exit and midplane dose distributions under several clinical conditions [1–4]. In addition, absolute exit and midplane dose values are obtained with our models. In this way not only the relative dose distribution, but also the absolute dose delivery can be verified. The use of these models has been extensively validated for homogeneous and inhomogeneous phantoms under various clinical conditions [1], but they have not yet been applied in clinical practice.

It is the objective of this study to investigate the practical application of a liquid-filled electronic portal imaging device in combination with our models to verify the 2D midplane dose delivery during patient treatment. Midplane dose distributions will be determined for several types of patient treatment and compared with the midplane dose distribution calculated with our 3D treatment planning system.

2. Materials and methods

2.1. Definitions

The transmission dose is defined as the dose to water measured in a mini-phantom (‘in air’) at a given position behind a phantom or patient. The exit dose is defined as the dose to water measured in a phantom or patient at a distance of the depth of the maximum dose upstream from the exit surface. The midline point is defined as the point in the middle of the patient between the entrance and exit positions on the central beam axis. The midplane dose is the dose distribution in a plane through the midline point perpendicular to the central beam axis, i.e. parallel to the surface of the EPID.

2.2. The liquid-filled electronic portal imaging device (EPID)

Portal dose measurements were performed with a liquid-filled electronic portal imaging device (EPID). The EPID has been developed in our institution [21,24,25] and is based on a matrix of 256 × 256 liquid-filled ionization chambers in a sensitive area of 32 × 32 cm². This detector is commercially available as the PortalVision system (Varian International). For transmission dose measurements, an additional build-up layer is positioned on top of the EPID in order to produce the maximum dose at the position of the ionization chambers [3]. Therefore, the thickness of this additional layer depends upon the beam energy. The dosimetric characteristics of this device have been described extensively [3,8,9,26,28]. In these studies it has been shown that transmission dose distributions can be measured with this EPID within 1% compared with ionization chamber measurements [3,8,9].

2.3. Determination of exit and midplane doses from portal dose measurements

The transmission dose images are converted to exit dose distribution by applying a convolution model. The development and application of this model have been described elsewhere [2,4]. In order to correct for inhomogeneities, the convolution model uses the radiological path length, which is determined from the ratio of transmission doses measured with and without a patient. An advantage of this procedure is that inhomogeneities are taken into account without using CT data. However, this method requires an additional portal dose measurement for each beam without the patient. For exit dose determination the 3D body contour is needed, which is derived from CT data. In the future we might derive the 3D body contour with an independent 3D body contour device placed in the treatment room.

Subsequently, these exit dose distributions are used to obtain the midplane dose by rescaling the contribution of primary and scattered doses between the exit position and midplane. This conversion is given by

\[ D_{\text{midplane}} = D_{\text{exit}} \cdot \text{ISQL} \cdot \left[ \sqrt{T} \right]^{-1} \cdot \exp(-\mu d_m) \cdot \left[ 1 + \text{SPR}_{\text{midplane}} \right] / \left[ 1 + \text{SPR}_{\text{exit}} \right] \]

where \( D_{\text{midplane}} \) and \( D_{\text{exit}} \) are the two-dimensional midplane and exit dose distributions, respectively. ISQL is the inverse square law correction. \([T]^{-1}\exp(-\mu d_m)\) is the attenuation between the midplane and exit position, where the transmission \( T \) is determined from the ratio of the transmission dose measured with and without a patient. \( \mu \) is the total linear mass attenuation coefficient and \( d_m \) is the distance of the depth of the maximum dose. \( \text{SPR}_{\text{midplane}} \) and \( \text{SPR}_{\text{exit}} \) are the scatter-to-primary ratios at the midplane and exit position, respectively. \( [1 + \text{SPR}_{\text{midplane}}] / [1 + \text{SPR}_{\text{exit}}] \) therefore takes the difference in the contribution of the scattered dose between the midplane and exit position into account. To apply this conversion algorithm, it is assumed that patients are homogeneous or that inhomogeneities are distributed symmetrically around the mid-
plane [1]. In a previous study it has been shown, however, that accurate midplane dose distributions are not only obtained for homogeneous and symmetrical inhomogeneous phantoms, but also for asymmetrical inhomogeneous phantoms when applying two opposing fields [1]. Because these conditions frequently occur in clinical practice, our models can be used to determine the midplane dose for many clinical situations. It was found that for these situations midplane doses can be determined accurately, i.e. within 2.5% relative to ionization chamber measurements [1]. However, our model (Eq. (1)) overestimates the dose when electron equilibrium is not present, e.g. close (0.5 cm) to the field edge or just below the skin for tangential fields [1]. The midplane dose method can also be applied when 3D body contour data are not available. For the latter situation the method is applied by first computing the exit dose in a flat plane through the exit position on the central beam axis and parallel to the EPID surface. This exit dose is then further converted to the midplane dose using Eq. (1). In a previous phantom study [1] it was found that with the latter procedure the midplane dose can be determined within 2.5% relative to ionization chamber midplane dose measurements.

2.4. Patient dose calculations

Midplane dose values determined from portal dose measurements will be compared with midplane dose values calculated with our 3D treatment planning system (TPS) (UMPlan, V339). After entering the CT data into the TPS, relative dose calculations are performed using a 1D correction for inhomogeneities based on the equivalent path length along a ray-line from the focus to the point of interest. A drawback of such a simple 1D correction algorithm is that lateral photon and electron transport are only globally taken into account. Consequently, dose calculations near the boundary of inhomogeneities are less accurate. Dose calculations were performed with a calculation grid of 5 mm, except for the larynx plans where a grid size of 2 mm was used. The dose contribution of each beam at the specification point provided by the TPS is used in a separate program to calculate the number of monitor units. The latter program has been described elsewhere [7].

2.5. Patient measurements

A number of different patient studies were performed to evaluate the applicability of our EPID for the verification of the dose delivery under several clinical situations. Midplane doses were obtained during radiotherapy of five patients with larynx cancer, two patients with breast cancer, five patients with lung cancer and 10 patients with prostate or bladder cancer using two different techniques.

EPID portal dose measurements were performed at three beam qualities, i.e. 4 MV (Dynaryx, BBC) and 8 and 18 MV (SL 20, Philips). The EPID was positioned at the maximum distance from the source to simplify the elimination of patient scatter [2,4], which resulted in source–detector distances of 185 cm at the 4 MV beam and 166 cm at the 8 and 18 MV beams. Motorized wedges of 45° at 4 MV and 55° at 8 and 18 MV were applied. For each patient one additional portal dose measurement was performed for each open and wedged field without the patient. The latter measurements were necessary to determine the radiological path length through the patient. In the next sections, the irradiation techniques and portal dose measurements for each treatment will be described.

2.5.1. Radiotherapy of larynx cancer

Patients are treated in the supine position and an individual cast made of 2 mm thick polyethylene is used for immobilization. Markers for patient set-up, field centre and field edges are indicated on the cast. The irradiation consists of an isocentric technique of two lateral opposing tangential 4 MV beams. Wedges are applied to compensate for the curvature of the neck and wedge angles vary between 30 and 45°. The applied field sizes are, on average, 6 × 6 cm² at the isocentre. Portal dose measurements were performed during both the wedged and the open fractions of each beam. Measurements were performed on two days (fractions of 2 Gy) during the second week of treatment. After the patient treatment the total midplane dose resulting from both lateral open and wedged beams was calculated. For this treatment technique the midplane dose corresponds with the dose distribution in the sagittal plane.

2.5.2. Radiotherapy of breast cancer

The patient is treated in the supine position with the ipsilateral arm abducted by 90° or more to avoid irradiation of the upper arm. The external irradiation of the breast consists of an isocentric technique of two nearly opposing tangential 8 MV beams. The beams are rotated relative to each other to align the dorsal field edges. Collimator rotations are applied to minimize the irradiated lung volume. Wedges are applied to take the curvature of the breast into account. For this treatment site the treatment planning is normally performed in an axial plane using a simple 2D planning system and CT data are not acquired routinely. This means that a comparison between portal dose measurements and treatment planning cannot be made. Therefore, the midplane dose was determined with the EPID for only a few patients to demonstrate that portal dose measurements provide valuable additional information about the dose delivery and distribution in the (sagittal) plane perpendicular to the axial plane, as will be shown later.

2.5.3. Radiotherapy of lung cancer

For five patients with lung cancer the midplane (coronal plane) dose resulting from a simple isocentric anterior-posterior (AP-PA) irradiation technique was verified. Patients were treated in the supine position with open and wedged 8 MV beams. Irregular field shapes were created with a
To perform a 2D comparison of the measured midplane dose with the dose distribution calculated with the TPS, the latter dose distribution was sampled with a smaller grid size than the grid size used for the calculations, i.e. the sample grid was taken as being equal to the pixel size of our portal imager. No systematic differences were found as a result of this procedure. In order to compare the calculated and measured midplane doses, it was assumed that there were no patient set-up deviations during the portal dose measurements, i.e. the field edges were aligned. The patient’s set-up was verified and corrected routinely using portal images which were obtained before the portal dose measurements were performed. Up to now dosimetric and geometric verification has been performed on separate days for practical reasons. In the future we plan to perform geometric and dosimetric verification of the patient’s treatment with the EPID simultaneously. In a previous study [3] it has been shown that the use of additional build-up material on the EPID during portal dose measurements deteriorates the quality of the images only at high beam energies (>8 MV). However, the influence of using additional build-up material on the accuracy of the patient set-up verification still remains to be investigated. In the next sections, the results of portal dosimetry will be presented in more detail for each patient group.

3.1. Midplane dose measured during radiotherapy of larynx cancer

For all patients in this group, the measured dose at the isocentre differed by a maximum of 1.8% from the dose calculated with the monitor unit calculation program. On average, the ratio between the measured and prescribed doses was 1.004 with a standard deviation of 0.9% (Table 1). For individual patients the reproducibility of the measurements was 0.7% (1 SD), while a maximum difference of 1.5% between portal dose measurements for the same patient was found. In Fig. 1, the dose distributions in the sagittal plane are given in colourwash display, i.e. each dose group of 2% is represented by another colour. A high dose region in the cranial-dorsal part of the field occurs at the position where the air cavity (trachea) becomes larger, which is typical for all patients in this group. In Fig. 1a the dose distribution calculated by our TPS is given and in Fig. 1b the measured dose distribution in the sagittal plane is given. In Fig. 1c, the percentage difference between the measured and calculated doses is shown. Finally, in Fig. 1d histograms are presented showing the relative surface as a function of the percentage difference between the measured and calculated doses. Histograms were calculated both for the entire area within the field outlines and for the field area minus a 0.5 cm penumbra region. Fig. 1c and the histograms presented in Fig. 1d show that for most parts of the field, the agreement between the measured and calculated doses is within 2%. Large (local) differences of 5% or more, however, occur just below the skin of the

<table>
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<th>Treatment site</th>
<th>Ratio between measured and calculated dose (SD)</th>
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<tr>
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<tr>
<td>Breast</td>
<td>0.996 (0.011)</td>
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<tr>
<td>Prostate</td>
<td>1.014 (0.011)</td>
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patient and near the field edges, i.e. in regions without electron equilibrium.

3.2. Midplane dose measured during radiotherapy of breast cancer

The midplane dose was measured for two patients with breast cancer. No comparison between measured and calculated dose distributions in the midplane was made because these patients were not routinely planned with our 3D TPS. For breast patients treatment planning was performed in a few planes using a 2D TPS. It was found (Table 1) that the ratio between the measured and prescribed doses at the dose specification point (isocentre) for these patients was 0.996 (SD 1.1%). Midplane dose distributions for these two patients are given in Fig. 2a,b. It can be seen that near the isocentre the dose was within 2% relative to the prescribed dose of 2 Gy. In the caudal and cranial part of the breast just

Fig. 1. Midplane (sagittal) dose distributions obtained during radiotherapy of larynx cancer with 4 MV wedged beams. The red contours indicate the field outline. (a) Midplane dose distribution calculated by a 3D treatment planning system (TPS). (b) Midplane dose distribution determined from portal dose measurements (EPID). (c) Percentage difference between calculated and measured midplane doses. (d) Relative surface-% dose difference histograms calculated from (c) for the entire radiation field (solid bars) and for the area minus a 0.5 cm penumbra region (hatched bars). The latter area is indicated in (c) with the yellow contour.

Fig. 2. Midplane dose distributions obtained during radiotherapy of the breast using two tangential 8 MV wedged fields for two patients. The red contours indicate the field outlines.
below the skin the dose was significantly increased to about 11% (relative to the dose at the isocentre), while no strong variation of dose was found in the AP direction, i.e. along the intersecting line of the axial plane and midplane.

3.3. Midplane dose measured during radiotherapy of lung cancer

For patients treated for lung cancer the dose distribution in the coronal plane was determined from portal dose measurements. In Fig. 3 the dose resulting from an AP-PA irradiation is presented for one of the patients. Because of the simple irradiation technique and the presence of large inhomogeneities in the patient, large dose variations of 10% within the field typically occurred for all patients included in this study. In Fig. 3a,b the dose calculated by our TPS and the dose determined from the portal dose measurements are shown for one of the patients. Similar results were obtained for most other patients. The measured midplane dose agreed, on average, within 2.5% with the dose calculated by our TPS for most parts of the field, as shown in Fig. 3c. Differences larger than 2.5% between the measured and calculated midplane doses occurred occasionally only for small regions within the radiation field. However, for one of the patients a very large difference between the measured and calculated midplane doses of 10% and more was found. In Fig. 3d,e,f the results obtained in the coronal plane for this patient are given. It was found that the midplane dose measured on the sixth day of treatment differed significantly from the calculated dose in the caudal and lateral parts of the field. Simulator films taken before and during treatment showed that for this patient a significant change in the lung anatomy occurred during the first week of treatment, which explains the large difference between the measured and calculated doses (Fig. 3f) which will be elucidated in Section 4.

3.4. Midplane dose measured during radiotherapy of prostate cancer

For the AP field the dose distribution in the coronal plane and for the lateral fields the dose in the sagittal plane were determined from portal dose measurements. The total dose delivered at the isocentre (or another dose specification point) was obtained by adding the dose at the isocentre determined for the AP field and the lateral fields. The average dose at the isocentre measured with the EPID for all 10 patients was 1.4% higher than the prescribed dose with a standard deviation of 1.1% (Table 1). By excluding those measurements which were disturbed by the presence of gas in the rectum, the average agreement improved to within 1.0% with a standard deviation of 0.8%. In Fig. 4a,b the difference between the measured and calculated midplane doses for the AP field on two different days is illustrated. These figures demonstrate that large local and temporary differences between the measured and calculated dose delivery can be found, due to the presence of gas in the rectum, while in other parts of the field the measured and calculated dose values agree very well. Fig. 4a,b also shows that small differences of up to 4% between the measured and calculated doses were found at the position of the pelvic bone in the portal image (dark green areas in Fig. 4a,b).

In Fig. 4c,d a comparison between the measured and calculated doses in the sagittal plane resulting from the irradiation with lateral 18 MV fields is given. Results obtained with lateral 8 MV beams were similar to those obtained with the 18 MV beams. Fig. 4c,d shows that the measured midplane dose for the lateral fields agrees within 2% with the calculated midplane dose for most parts of the field, except for a region with gas in the rectum on one of the days.

4. Discussion

4.1. Discussion of results

Generally, midplane doses determined from portal dose measurements agreed in the entire field within 2.5% with dose values obtained with our TPS. Accurate midplane doses were obtained for all beam qualities in open and wedged beams and the influence of inhomogeneities on the dose delivery was accurately taken into account. However, this accuracy was obtained after exclusion of regions without electron equilibrium, i.e. the regions (0.5 cm) near the patient contour and field edges, which are elucidated in the histograms given in Fig. 1d. Histograms were also derived for the other treatment sites, yielding similar results. The observed accuracies correspond with those found in a previous phantom study [1]. Furthermore, larger deviations were also observed when large anatomical changes during the treatment period occurred, as will be discussed in more detail.

The results obtained during irradiation of the larynx demonstrated that portal dose measurements overestimated the dose calculated by our TPS in a small region below the skin. In a previous study it has already been shown that our model overestimates the dose in regions where electron equilibrium is not present [1]. Because the influence of the electron non-equilibrium is only present in a small part of the field, the results obtained for this treatment site can still be used to verify wedge orientation, wedge angle and dose delivery, i.e. to verify the monitor unit calculations. In previous studies [1,4] it has been shown that our convolution model performs sufficiently accurately, i.e. within 1.5% relative to ionization chamber measurements, for this treatment site to allow an independent verification of the dose delivery. In addition, it can be concluded that dose variations caused by the patient’s anatomy (trachea) are measured very well, i.e. within 2%.

The irradiation technique of the breast is similar to the larynx irradiation technique, i.e. for these tangential fields
Fig. 3. Midplane (coronal) dose distributions obtained during irradiation of the lung with two opposing (AP-PA) 8 MV wedged beams. (a,b) Typical dose distributions calculated by our 3D treatment planning system and determined from portal dose measurements. (c) The percentage difference between calculated (a) and measured (b) midplane doses. (d,e) Midplane dose distributions for one patient, showing large differences between calculated (d) and measured (e) midplane doses. (f) The difference between calculated and measured midplane doses. (g,h) Simulator films obtained before treatment (g) and after the start of treatment (h) for this patient. (d–h) Clear demonstration of the influence of changes in the patient’s anatomy on the midplane dose distribution.

Fig. 4. Comparison of the measured midplane dose with the calculated (TPS) midplane dose for the AP 8 MV field (a,b) and two lateral opposing wedged 18 MV fields (c,d) of the prostate irradiation. (a,b) The results measured on two different days for the AP field, showing the influence of gas in the rectum on the measured dose values. (c,d) The results obtained for the lateral fields.
and the midplane dose is also overestimated in a small region below the contour of the breast. Because CT data are not available for this treatment site, it is not possible to perform a 3D calculation by our TPS and no quantitative evaluation of the measured midplane dose can be made. However, the observed dose variations can be explained qualitatively. For this treatment site wedges are applied to compensate for the breast curvature in the AP direction. Wedge orientation and wedge angle are optimized with a 2D treatment plan in an axial plane. Therefore, dose variations in the AP direction, i.e. along the intersecting line of the midplane and axial plane, should be small (<2%). The results presented in Fig. 2a,b clearly show that the applied wedges accurately compensate for the breast curvature in this direction, as planned. In the cranial-caudal direction the curvature of the breast is, however, not compensated. The observed high dose variations (up to 11% relative to the dose at the isocentre) can be expected in the cranial and caudal part of the breast, i.e. at those positions in the field where the thickness of the breast varies considerably. These large dose variations were also observed by Damen et al. [6]. The measured dose at the isocentre agrees very well with the prescribed dose of 2 Gy. The latter result is in close agreement with data shown by Damen et al. [6] and by Heukelom et al. [14]. In the latter study [14] the dose at the isocentre determined with conventional in vivo dosimetry using diodes was within 2% of our 2D TPS calculations for breast irradiations with 8 MV wedged beams. Therefore, it can be concluded that portal dosimetry is suitable to verify the monitor unit calculation for this treatment site.

The large variations in the midplane dose, as measured for lung irradiations, were generally within 2.5% relative to the dose values predicted with the TPS for most patients (Fig. 3c). However, both our model and the TPS do not take the electron transport into account, which means that the dose near the edge between the lung and the mediastinum will be overestimated by both calculations [1,18]. The influence of the absence of electron equilibrium on the accuracy of the midplane dose measurements was investigated in a previous study [1]. In that study it was shown that differences between the calculated and measured midplane doses in a lung phantom can be substantial (10%) for small field sizes, while differences were smaller than 3% for field sizes larger than 10 × 10 cm². Typical clinical results are shown in Fig. 3a,b,c. For one of the patients a large discrepancy of 10% or more between the measured and calculated doses was observed in the caudal and lateral parts of the field. To explain these significant differences, X-ray films were obtained during a second simulation of the patient treatment after 1 week of the start of radiotherapy. The films showed that the anatomy of the lung (volume) was drastically changed with respect to the anatomy at the first simulation obtained shortly before the start of treatment, as shown in Fig. 3a,b,c. The anatomical geometry at the sixth day of treatment differed from the CT data used for treatment planning resulting in large differences between calculated and measured midplane dose values. Although electron transport is not taken into account, this case demonstrates that portal dose measurements are useful and sufficiently accurate to confirm that the patient's anatomy is still accurately represented by the CT data and, if large changes occur, to evaluate the influence of these anatomical variations on the dose delivery.

Results obtained during prostate irradiations showed that portal dose measurements can be used for an accurate and efficient verification of the midplane dose. At the moment the dose delivery for prostate irradiations is verified routinely in our institution with in vivo dose measurements using diodes [7]. With these measurements it was found [7] that the dose at the isocentre is calculated with our 3D TPS with an accuracy of within 1.3% (1 SD). The ratio between the dose at the isocentre derived from our portal dose measurements and diode measurements was 0.988 ± 0.011 (1 SD), indicating that the determination of the midplane dose from portal dose measurements is sufficiently accurate to allow dose delivery verification during conformal radiotherapy of the prostate. During the diode measurements portal images are acquired to verify patient set-up but provide, in addition, information on the position of the diodes. Frequently, large gas volumes are present in the rectum, which hamper these in vivo exit dose measurements. Measurements are then repeated until reliable dose values are obtained. Using portal dose measurements the midplane dose can be verified in an entire plane. Therefore, the dose delivery can still be verified because gas volumes in the rectum are only influencing a small part of the field, as can be seen in Fig. 4a,b. For the AP fields we found regions where the measured dose was about 3% lower than the calculated dose, due to the presence of the pelvic bone. These differences occur because our models assume that inhomogeneities are symmetrically distributed around the midplane, while for the AP field this assumption is not valid. Furthermore, it was found that portal dose measurements for the lateral fields are sufficiently accurate to allow the verification of wedge orientation and angle. Therefore, it is concluded that portal dosimetry is an efficient and accurate way of verifying the dose delivery during radiotherapy of prostate cancer.

It should be noted that in this study we investigated the feasibility of portal dose measurements for two-dimensional in vivo dosimetry in the clinic. Therefore, the methods for portal dosimetry were tested for several different treatment sites but with a limited number of patients. In the future we plan to study the use of portal dose measurements for in vivo dosimetry purposes for specific treatment sites using larger numbers of patients. The main purpose of those studies will be to investigate variations and deviations in 2D dose delivery and to determine action criteria based on the observed variations and/or changes in the dose distribution. In addition, several other clinical studies will be performed. For instance, we plan to use portal dose measurements for the evaluation of the dose distribution during radiotherapy of tumours situated in the head and neck region. If CT data are
not available for treatment planning, portal dose measurements provide valuable additional information about the influence of the patient’s anatomy (inhomogeneity) on the dose distribution. Portal dosimetry will also allow a more extensive evaluation of the accuracy of 2D and 3D treatment plans. Furthermore, because wedges do not sufficiently compensate patient contour and tissue inhomogeneity for several treatment sites, we will study whether inhomogeneities in the dose distribution, measured with our EPID, e.g., for the larynx, lung and breast irradiations, can be used to design intensity modulated beams in order to obtain a more homogeneous dose distribution. Another possibility is to use portal dose measurements to study the frequency and extent of variation of patient anatomy between simulation (or CT data acquisition) and the start of treatment and/or during treatment of the patient. Finally, the results obtained during radiotherapy of the prostate showed that a gas volume is frequently present in the radiation field, indicating that the clinical target volume can move within or out of the radiation field or that its shape can change as a result of variable rectum filling. The use of portal dosimetry to evaluate the influence of organ motion or organ deformations on the dose delivery for this treatment site will also be studied.

4.2. Origins of errors of portal dosimetry during clinical use

The uncertainty of transmission dose measurements with the EPID and the limitations of the convolution model to convert transmission dose data to exit and/or midplane dose distributions were already extensively described in previous studies [1–4]. In this section we will briefly discuss the origin of some of the errors which can deteriorate the accuracy of midplane dose measurements with the EPID during clinical use.

The EPID is sufficiently stable to allow verification of the calibration with a frequency of once every 3 months [10]. However, the sensitivity of the EPID may change after collision of the EPID with the treatment couch, when a high environmental temperature or humidity has occurred or when electronic parts have been replaced. When these situations occur, the EPID calibration must be repeated.

Differences between actual and intended source–detector distances have a large effect on the calculated midplane dose (inverse square law). The use of a fixed source–detector distance for dosimetric applications of the EPID is therefore preferred. Computerized retractable EPID arms may not always have such a high positional accuracy. For the latter situation the correct source–detector distance must be measured either by using the distance meter of the accelerator or with an independent tool.

When the calibration is valid and the correct source–detector distance has been applied, constant differences over the entire radiation field between calculated and measured midplane doses may be the result of errors in patient set-up, monitor unit calculation or variations in patient anatomy. To trace the origin of these kinds of deviations it is necessary to determine the position of the patient by geometrical analysis of the portal images and/or to perform additional entrance dose measurements using diodes or TLDs.

Local differences between calculated and measured midplane doses are often the result of a change in anatomy relative to the planning CT data, as was shown in this study. However, local deviations can also result from the uncertainty in midplane dose determinations under asymmetrical conditions. Accurate midplane doses are only obtained when inhomogeneities are distributed symmetrically around the midplane or when the results from two opposing fields are combined, as was described in a previous study [1]. When these conditions are not valid, the EPID can still be used for 2D exit dosimetry, for which these restrictions do not exist [2,4]. However, EPID exit dose measurements require the 3D body contour.

5. Conclusions

Portal dose measurements performed with a liquid-filled electronic portal imaging device and analyzed with our algorithms can be used to determine the midplane dose within 2.5% relative to treatment planning calculations in most parts of the radiation field for various treatment sites in clinical practice. However, using our models accurate midplane dose values are only obtained in the presence of electron equilibrium. We have demonstrated that with portal dose measurements it is possible to verify not only the absolute dose delivery, i.e., the monitor unit calculation, but also to evaluate deviations between the actual and calculated dose distribution caused by differences between patient anatomy and planning CT data. It is concluded that portal dosimetry is a powerful tool for accurate dosimetric verification of patient treatments. In this study a limited number of patients were involved and results are therefore preliminary. In the future more research is needed to fully evaluate the clinical use of portal dosimetry.

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