

● *Technical Innovation and Notes*

A QUALITY CONTROL STUDY OF THE ACCURACY OF PATIENT POSITIONING IN IRRADIATION OF PELVIC FIELDS

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Purpose: Determining and improving the accuracy of patient positioning in pelvic fields.

Methods and Materials: Small pelvic fields were studied in 16 patients treated for urological cancers using a three-field isocentric technique. Large pelvic fields were studied in 17 gynecological cancer patients treated with anterior and posterior (AP-PA) parallel opposed fields. Quantitative analysis of 645 megavolt images and comparison to 82 simulation images were carried out.

Results: Small pelvic fields: for the position of the patient in the field, standard deviations of the difference between simulation (SIM) and treatment (MV) images were 3.4 mm in the lateral direction, 5.3 mm in the cranio-caudal direction, and 4.8 mm in the ventro-dorsal direction. Alterations in the positioning technique were made and tested. Large pelvic fields: differences between simulation and treatment images for the position of the patient in the field were 4 mm [1 standard deviation (SD)] in the lateral direction and 6.5 mm in the cranio-caudal direction. A systematic shift of the treatment field in the cranial direction had occurred in the majority of patients. A positioning technique using laser lines and marking of the caudal field border was shown to be more accurate.

Conclusion: Studies of positioning accuracy in routine irradiation techniques are needed to obtain data for definition of the margins for each treatment site at each institution. Random variations should be kept at a minimum by monitoring and improving positioning techniques. Treatment verification by megavolt imaging or film should be used to detect and correct systematic variations early in the treatment series.

Quality assurance in radiotherapy, Portal imaging, Treatment verification, Patient positioning, Pelvic fields.

INTRODUCTION

The introduction of highly sophisticated radiotherapy treatment equipment with multileaf collimators and of three-dimensional (3D) planning systems with Beam's Eye View facilities allows for high precision therapy to be delivered to the target volume with optimal sparing of normal tissues. As described in the International Commission on Radiation Units and Measurements (ICRU) 50 report (17), the planning target volume (PTV) is defined as the clinical target volume (CTV) [i.e., gross tumor volume (GTV) and the region of subclinical disease] with an added margin to compensate for the effects of organ and patient movement and inaccuracies in beam and pa-

tient setup. The definition of this margin is essential, as it should be small enough to spare normal tissues and large enough to ensure irradiation of the CTV to the prescribed dose. The reproducibility of day-to-day patient setup might well be the crucial factor for determination of the size of the margins for each treatment technique at each individual institution.

In the Dr. Daniel den Hoed Cancer Center (DDHCC), a series of prospective quality control studies is being carried out to determine the accuracy of current positioning techniques. If the technique studied is shown to be reliable and reproducible within acceptable limits, small and safe margins can be defined around the CTV involved. If the study yields higher error rates than ex-

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pected, the technique should be altered to improve its accuracy, after which the reproducibility should again be checked to ascertain the size of margins to be used.

In earlier studies the accuracy of patient positioning was evaluated in mantle field irradiation (10), in head and neck cancer (16) and in irradiation of breast cancer (9). The studies of head and neck cancer and of mantle fields showed modest error rates as compared to literature data. However, the study of patient positioning in breast cancer yielded larger error rates than was expected, stressing the importance of continuous attention to the accuracy of "routine" irradiation techniques. The present study was carried out to evaluate the accuracy of patient positioning in irradiation of pelvic fields. The study consisted of two parts, investigating treatment setup accuracy in small and large pelvic fields, respectively.

METHODS AND MATERIALS

Two separate studies were carried out. In the first study, the accuracy of patient positioning in irradiation of small pelvic fields for urological cancers was investigated. The study group consisted of 16 patients treated for bladder or prostate cancer between October 1989 and June 1990. In the second study, carried out between July 1990 and March 1991, large pelvic fields were investigated in 17 patients treated for cancer of the cervix or endometrium. In addition to both studies, follow-up studies were done to check if alterations, made as a result of the studies, had, indeed, improved positioning accuracy. The design and the results of the studies will be described separately.

Treatment technique in urological cancer

All patients were treated using computerized tomography (CT) planning. The patient was positioned for CT scanning in the supine treatment position on a flat couch. Using alignment lasers, a cranio-caudal midline reference line and two lateral lines were drawn on the patient's skin. Oral contrast was used for small bowel visualization, and a radio-opaque catheter was placed on the cranio-caudal reference line. The CT slice thickness and spacing were 10 mm. The CT information was sent to a planning system. The outlines of the target volume and of the organs at risk were drawn in every slice by the radiation oncologist responsible for the patient's treatment. The GTV was defined as the prostate gland (including, except for T1 tumors, the seminal vesicles) or the bladder, respectively. Usually, for the PTV a margin of 1.5 cm was added (0.5 cm for subclinical spread and an additional 1 cm to allow for patient movement and geometrical inaccuracies). A three-field isocentric technique with an anterior (AP) field and two wedged posterior oblique (PO) fields was used in all patients. The dose was specified at the isocenter. Simulation of the treatment plan was carried out. At simulation, a field center tattoo was placed, and two lateral skin markings were drawn at equal heights to minimize rotation of the pelvis. Treatment was carried

out using 6 MV photons from a linear accelerator at a source-isocenter distance of 100 cm. All fields were treated daily, five times a week, to a total dose of 66 Gy using 2 Gy fractions. Prostate cancer patients were both CT scanned and treated with a full bladder to push the small bowel out of the field; patients with bladder cancer were asked to empty their bladder before scanning and treatment to keep the treatment volume as small as possible. The patients were positioned on the treatment couch in the same position as at CT scanning and simulation. Alignment was carried out using wall pointers. The source-skin distance (SSD) was calculated from the treatment plan and was used for patient setup. At the time of the study, no treatment verification/registration system was operational at the accelerator.

Follow-up studies

In 1991, alterations in the positioning technique were made that consisted of the use of a styrofoam table top to prevent sagging of the polycarbonate (mylar) film window, and the use of the isocenter-couch distance for patient setup. Furthermore, regular megavolt imaging was used at the first treatment fraction. A pilot study was carried out in August 1991 to check if positioning accuracy had been improved.

In 1992, a Netherlands collaborating group for Megavolt Imaging was started and a verification and correction procedure for small urological fields was designed and tested. As a pilot study, a series of nine patients, treated December 1992 to January 1993, was studied to determine the feasibility of this procedure, and its effect on the incidence and magnitude of systematic errors.

Treatment technique in gynecological cancer

All patients were treated to the whole pelvis using anterior (AP) and posterior (PA) parallel-opposed fields encompassing the (site of the) uterus and adnexa, the parametria, the proximal two-thirds of the vagina, and the hypogastric and common iliac lymph node drainage areas. Patient positioning was carried out using a standardized technique developed in the DDHCC and in use since the early 1970s. This technique was designed at the time to avoid the use of skin markings on these often obese patients and use the pelvic bones for setup instead. The patient is positioned in the supine position on a special device consisting of a thin aluminium plate and two vertical hip supports with centimeter scales (Fig. 1a). Rotation of the pelvis is prevented by placing small metal plates over the hip supports and comparing the scales to ensure equal height on both sides. A so-called pair of compasses is used to ensure correct midline positioning of the patient (Fig. 1b). A vertical stand is fixed to the aluminium plate and a vertical pin is attached to the horizontal bar of the stand (Fig. 1c). The pin is then pushed against the pubic bone and the position of the pin on the horizontal bar is measured and noted for definition and daily reproduction of the cranio-caudal level of the field center. Using this

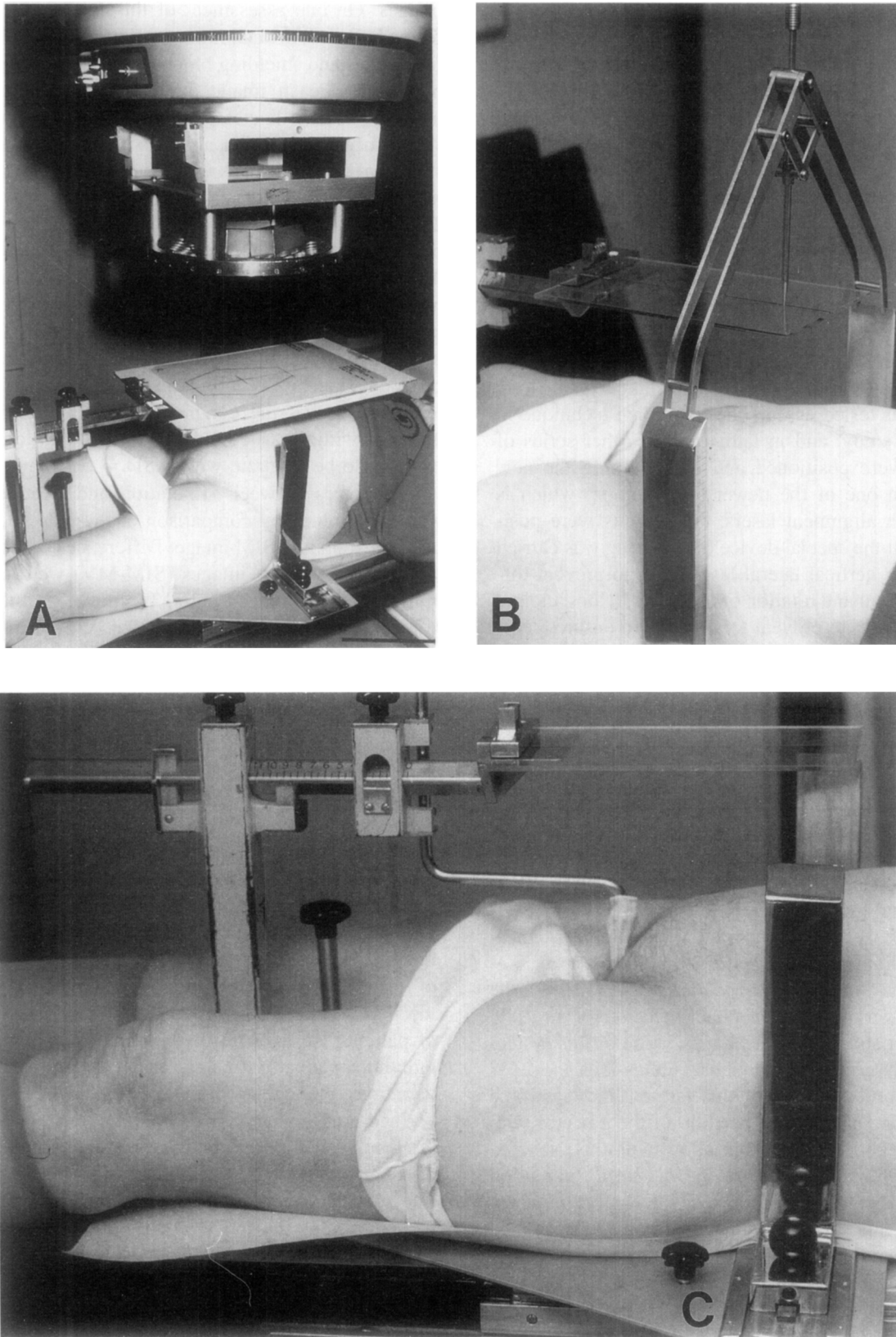


Fig. 1. The positioning device for gynecological cancer patients. (a) Base plate, hip supports, and transparent sheet for block placement. (b) Midline positioning of the patient. (c) The vertical pin for cranio-caudal field orientation.

technique, the positioning of the patient takes approximately 7 min.

At simulation, the cranial, caudal, and lateral edges of the treatment field are defined, and simulation films are taken. The radiation oncologist indicates the treatment field on the simulation films, after which a transparent sheet is produced to be used for daily placement of the shielding blocks. Divergent shielding blocks are aligned to the markings on the transparent sheet and are fixed to a tray on the head of the linear accelerator. Both AP and PA fields are treated daily to a total dose of 46 Gy in 2 Gy fractions, using 6 MV photons at an SSD of 100 cm.

Follow-up study

In 1992, an alternative positioning technique using long laser lines was tested against the traditional technique in a small pilot study, and in late 1993 a further series of 15 patients were positioned and treated using the new technique. On one of the newer accelerators,² which is equipped with alignment lasers, the patients were positioned without the special device. Positioning was carried out using long vertical lateral laser lines, to prevent torsion of the patient and rotation of the pelvis; a longitudinal midline laser line, to prevent torsion and to ensure a correct midline position of the patient; and a long transversal line with tattoos, for marking the caudal field border. In this positioning technique, the caudal field border and the transversal laser line are the main parameters for setup.

Megavolt imaging and analysis of the data

For both study groups, megavolt imaging was carried out twice a week throughout treatment. Images were obtained of all treatment fields using a fast electronic fluoroscopic portal imaging system.³ This system was developed in the DDHCC in collaboration with Philips Medical Systems Radiotherapy and the Laboratory of Space Research Leiden. After a prototype phase (1985–1989), the product type was installed on a linear accelerator⁴ in 1989. The characteristics and clinical application of this system have been described in previous publications (1, 2, 9, 29). An important feature of this fast on-line electronic imaging device is the fixed position of the detector with regard to the beam axis. This allows for the use of a common coordinate system in the digitized simulation (SIM) and megavolt (MV) images with the origin at the beam center and the orientation of the axes determined by the collimation system.

A total number of 645 MV images (406 and 239 images of the small and large pelvic fields, respectively) was obtained in addition to 82 (48 and 34) digitized SIM

images. On-line assessment of the images was not performed. Relevant anatomical points and points on the field edges and shielding blocks were defined (Fig. 2) and indicated in each image on the video monitor with a mouse. The coordinates of these points were loaded in a spreadsheet, and further analysis was performed using a statistical software package.⁵ The reproducibility of the indication of the points on the video monitor was checked. The standard deviation of repeated indications of the points in the same image was 0.5 mm for both small and large pelvic fields. Field edge detection was carried out by applying the Sobel gradient operator twice to each unprocessed image in four orthogonal directions, resulting in a small black envelope between two white bars, the black envelope representing the true field edge (9). Earlier tests had shown the congruity of the field edges thus obtained with the true field edges (by definition the 50% isodose) to be accurate with 1 SD = 0.7 mm.

Differences between simulation and treatment setup were determined by comparison of the MV images with the corresponding SIM image. Differences between simulation and treatment images (SIM-MV) were calculated in millimeters at the isocenter. The position of the patient in the treatment field, the field size, and the position of shielding blocks were determined independently. This method of analysis was described in more detail in a previous publication (9).

The overall accuracy of a patient positioning technique is reflected by the standard deviations of the mean SIM-MV differences, averaged over all patients. If mean values of SIM-MV differences are close to zero, there are no overall systematic variations. However, for individual patients, systematic variations do occur. To separate random and systematic variations and to identify individual systematic variations, further analysis was carried out. To identify the random variation of a parameter, the spread of the SIM-MV differences around the corresponding mean was calculated in each patient. For the total group of patients the average of these standard deviations for individual patients was taken as a measure for the random variations [defined as σ by Bijhold *et al.* (7)]. It was verified that the average standard deviation was close to the result calculated by taking the “within-patients” sum of squares divided by the number of degrees of freedom. The systematic variation of a parameter was calculated by determining the spread (1 SD) in the individual mean SIM-MV differences. The mean value of these individual mean SIM-MV differences represents the overall systematic variation, and the standard deviation of this distribution represents the magnitude of individual systematic

² Siemens KD2, Siemens Medical Laboratories, Concord, CA.

³ Philips SRI-100 Radiotherapy Imaging System, Philips Medical Systems Radiotherapy, Crawley, West Sussex RH10 2RR, UK.

⁴ Philips SL-75/10, Philips Medical Systems Radiotherapy, Crawley, West Sussex RH10 2RR, UK.

⁵ STATA, release 3.1; Stata Corporation, College Station, TX.

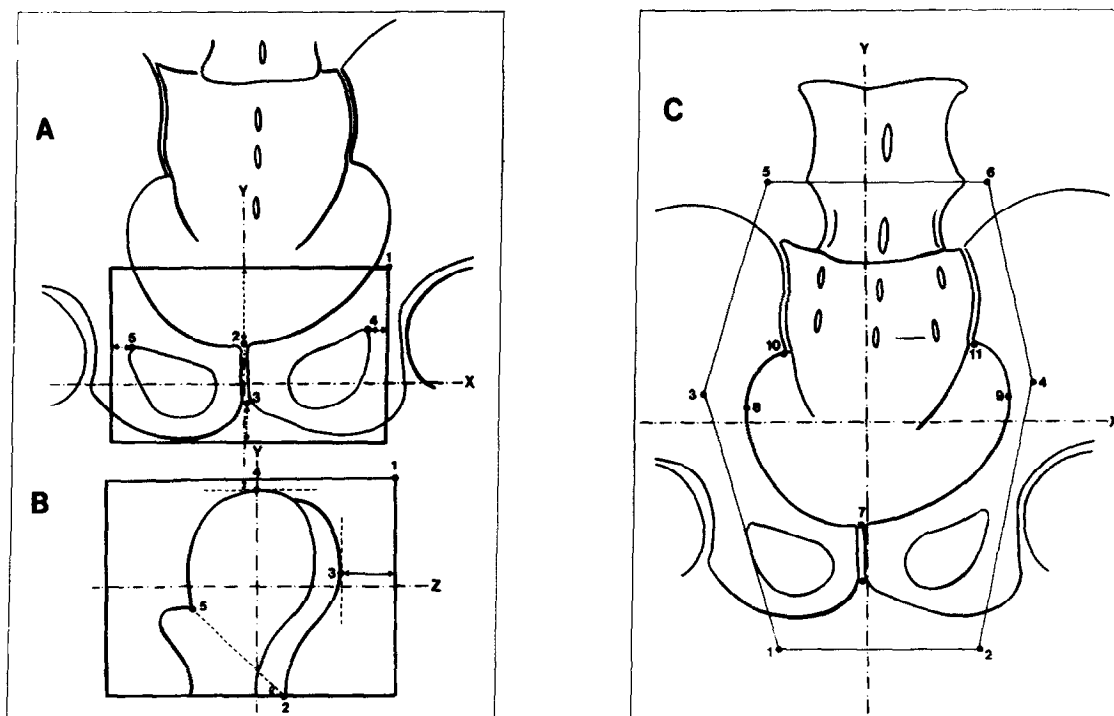


Fig. 2. (A) Diagram of a small pelvic field for urological cancer: AP field. 1: upper left field corner. 2: upper margin of pubic symphysis. 3: lower margin of pubic symphysis. 4: upper corner of left obturator foramen. 5: upper corner of right obturator foramen. (B) Diagram of a small pelvic field for urological cancer: PO field. 1: upper ventral field corner. 2: intersection of the femoral shaft with the caudal field border. 3: ventral border of the femoral head. 4: cranial border of the femoral head. (C) Diagram of a large pelvic field for gynecological cancer. 1-6: intersection of the shielding blocks with the field edges. 7: upper margin of pubic symphysis. 8: lateral edge of true pelvis, right. 9: lateral edge of true pelvis, left. 10: inferior aspect of sacroiliac joint, right. 11: inferior aspect of sacroiliac joint, left.

variations [corresponding with Σ as defined by Bijhold *et al.* (7)]. Thus, the *overall* accuracy is represented by the overall SD; the *random* variation by σ , the average SD of the SIM-MV differences per patient; and the *systematic* variation by Σ , the SD of the mean SIM-MV differences.

RESULTS

Small pelvic fields for urological cancer

In AP fields, field size variations were surprisingly high (SD = 4.8 mm for both field width and length; extreme values of SIM-MV differences were 38 and 40 mm). This was found to be caused by the erroneous interchange of field width and length on three occasions (three patients, for each patient at one fraction). A record-and-verify system was not yet operational at the time. Excluding these three patients, SDs for field width and length were 2.0 and 2.7 mm, with extreme values of 3 and 10 mm. For PO fields, field size SDs were 3.0 (width) and 5.1 mm (length). The interchange of field width and length had been detected and corrected before irradiating the PO fields in two patients. Exclusion of the third patient yielded field size SDs for the PO fields of 2.8 mm (width) and 3.6 mm (length).

For AP fields, the position of the patient in the field was analyzed using four bony landmarks (Fig. 2a). The

position of the patient in the field was more accurate in the medio-lateral (ML) direction (SD 3.3–3.8 mm) than in the cranio-caudal (CC) direction (SD 5.3–5.7 mm).

For PO fields, the femoral heads were used to analyze the position of the patient in the field (Fig. 2b, points 2 and 3 for the ventro-dorsal direction, and point 4 for the cranio-caudal direction). Rotation in the hip joint was measured by calculation of the angle between a line connecting points 2 and 5 and the caudal field border. The SD of this angle was 5.0°. As rotation in the hip joint does influence the position of point 2 in the ventro-dorsal direction, it was decided that point 3 be used for analysis of the position of the patient in the field for the ventro-dorsal direction.

In Tables 1 and 2, the overall accuracy (SD) of patient positioning is presented, along with the systematic (Σ) and random (σ) components, for AP and PO fields, respectively.

Follow-up studies

In Figure 3, the results of the study of nine patients using the verification and correction rule are compared to those of the first study. Random errors were reduced to 2.7 mm (x), 2.5 mm (y), and 2.3 mm (z), and systematic errors to 1.3 mm (x), 2.0 mm (y), and 2.1 mm (z), respectively. This improvement appeared to be statistically sig-

Table 1. Differences between simulation and treatment (SIM-MV*): small pelvic fields (AP)

Patient points and field size [†] (Fig. 2a)	SD* mm	Systematic*	Random*
		Σ mm	σ mm
Field width	x	2.0	1.4
Field length	y	2.7	1.8
Pubic symph (2)	x	3.4	2.5
Range points 2-5	x	3.3-3.8	2.2-2.8
Pubic symph (2)	y	5.3	3.8
Range points 2-5	y	5.3-5.7	3.9-4.6

* The standard deviation (SD) of the mean values of the difference between the position of the respective points, or of the field size, in the simulation and treatment images (SIM-MV), the systematic variations, and the random variations. For definition and calculation, see text.

[†] Field size after exclusion of three field width-length interchanges (see text).

nificant for the systematic errors in the lateral direction [$p = 0.04$ with the F -test, $p = 0.06$ with a nonparametric test (Wilcoxon rank sum test)]. The improvement in the cranio-caudal direction did not yet reach statistical significance ($p = 0.09$).

Large pelvic fields for gynecological cancer

In these fields, the field length is determined by the actual cranial and caudal field (collimator) edges, while the field width is determined by a combination of the field edges and the shielding blocks. In 13 patients, the field was too long with respect to the detector, so in these patients the field length could not be measured. The results for field length are those of the remaining four patients (71 measurements). The other parameters could be measured in all patients. As the results for AP and PA fields differed only minimally, they were analyzed together.

The results are presented in Table 3. For representation of the position of the patient in the field, both the pubic symphysis (point 7) and a combination of points 7, 8, and

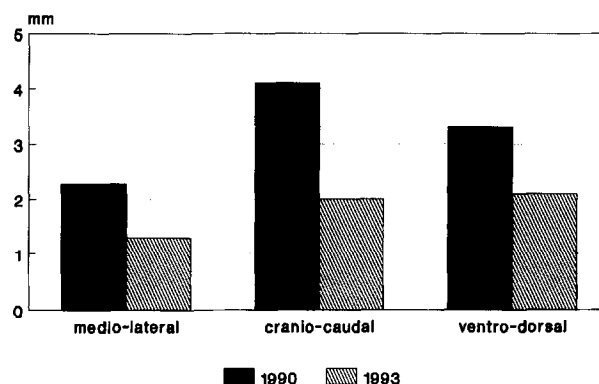
Table 2. Differences between simulation and treatment (SIM-MV*): small pelvic fields (right and left oblique fields combined)

Patient points and field size [†] (Fig. 2b)	SD* mm	Systematic*	Random*
		Σ mm	σ mm
Field width (z)	2.8	2.2	1.9
Field length (y)	3.6	3.0	2.0
Femoral head (3) (z)	4.8	3.3	3.7
Femoral head (4) (y)	5.7	4.2	3.6

* The standard deviation (SD) of the mean values of the difference between the position of the respective points, or of the field size, in the simulation and treatment images (SIM-MV), the systematic variations, and the random variations. For definition and calculation, see text.

[†] Field size after exclusion of the patient with a field width-length interchange (see text).

A Systematic variation 1990-1993 small pelvic fields



B Random variation 1990-1993 small pelvic fields

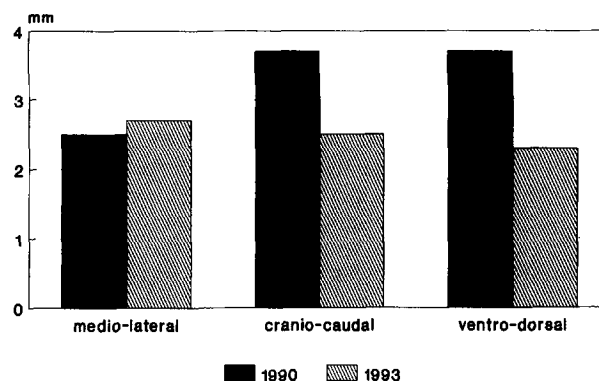


Fig. 3. Histograms of (A) systematic and (B) random variations (1 SD) in the position of the patient in small pelvic fields in, respectively, the medio-lateral, cranio-caudal, and ventro-dorsal directions. Comparison of the results of the 1990 study and the 1993 feasibility study using the verification and correction procedure. Note the reduction in systematic errors in the 1993 study.

9 (x-direction) and 7, 10, and 11 (y-direction) were used (Fig. 2c and Table 3). Small differences between these values could be caused by a rotational component. For the position of the patient in the cranio-caudal direction, mean SIM-MV differences were 2.3 mm (mean movement of the MV field in the cranial direction), with SD values of 6.3-7.3 mm and both random and systematic components of 4.5-5 mm. As illustrated in Fig. 4, systematic deviations occurred for most patients, with a field shift in the cranial direction in the majority of patients.

In-plane rotation of the patient was measured by calculating the slope of the lines connecting point 7 and points 8, 9, 10, and 11, respectively; the results were essentially the same, with 1 SD = 3° and extreme values up to 11°.

Follow-up study

Table 4 summarizes the positioning accuracy of the 15 patients positioned using the technique with long laser

Table 3. Differences between simulation and treatment (SIM-MV): large pelvic fields (AP and PA combined)

Patients points and field size (Fig. 2c)	Mean SIM-MV* mm	SD* mm	Systematic* Σ mm	Random* σ mm
Field width (x)	0.2	4.1	3.5	1.9
Field length (y)	1.8	2.8	2.5	1.3
Pubic symphysis (7) x	0.7	4.4	3.1	3.4
Pubic symphysis (7) y	2.3	6.3	4.4	4.5
Patient position (x): range points 7-9	0.7-0.7	3.6-4.4	2.5-3.1	2.7-3.4
Patient position (y): range points 7, 10, 11	1.8-3.3	6.3-7.3	4.4-5.1	4.5-5.3
Rotation along z-axis (7-8; 7-9)	1.0°	3.1°	2.2°	2.2°

* The mean values of the differences between the position of the respective points, or of the field size, in the simulation and treatment images (SIM-MV), the standard deviation (SD) of the mean, the systematic variations, and the random variations. A negative value of a mean SIM-MV difference represents a mean shift of that point in the MV images in the right lateral (x) or cranial (y) direction.

lines and marking of the caudal field border. As this study had been carried out with megavolt films, the possibilities for contrast enhancement were more limited than in the previous study. As a result, the presence of the shielding block tray in the images often impaired the assessment of the exact location of the pubic symphysis in the x-direction and of the sacro-iliac joints in both the x- and y-directions. Thus, the pubic symphysis was used to represent the position of the patient in the y-direction and the points on the lateral pelvic edges (points 8 and 9 in Fig. 2c) to represent the position in the x-direction. The results for the medio-lateral direction turned out to be essentially the same as those from the traditional technique (Tables 3 and 4). For the cranio-caudal direction, however, positioning accuracy was improved (Σ 3.1 mm vs. 4.4 mm; σ 3.0 mm vs. 4.5 mm); this difference was statistically significant for σ ($p < 0.01$) using the Student *t*-test (mean comparison test). For Σ , the difference was not statistically significant [$p = 0.45$ according to the *F*-test and according to a nonparametric test (Wilcoxon rank sum test)].

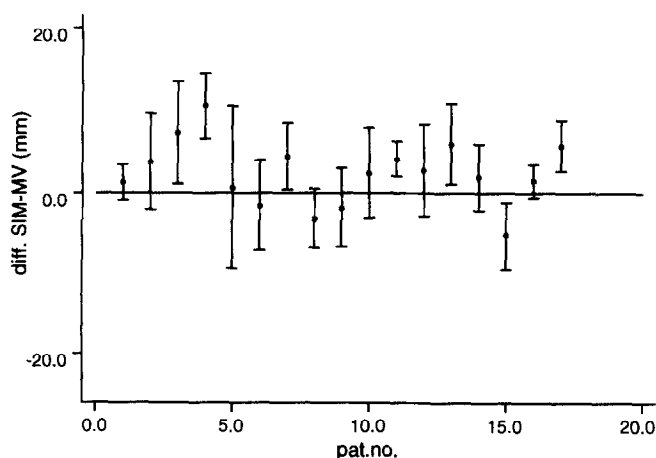


Fig. 4. Large pelvic fields for gynecological cancer. Diagram of the SIM-MV differences for the position of the pubic symphysis (point 7 in Fig. 2c) in the cranio-caudal direction: mean differences and standard deviations of the mean per patient. Note the systematic shift of various patients in the caudal direction (field moving in the cranial direction).

To determine if the position of the pubic symphysis was, indeed, representative of the cranio-caudal position of the patient in the treatment field (rotational influences could cause differences between the position of this point and the points on the sacro-iliac joints), we determined the position of the patient using an anatomical match in a subset of five patients. The pelvic rim was indicated in the treatment images, and by matching this contour with that in the simulation image, SIM-MV differences for the medio-lateral and cranio-caudal directions could be calculated, as well as the in-plane rotation. The SDs for both directions turned out to be similar to those determined by analyzing the position of the pubic symphysis for the y-direction and the points on the pelvic rim for the x-direction. Rotations were shown to be modest: mean -0.5° , SD 1.6° , extremes -5° to $+3^\circ$.

DISCUSSION

Recent literature has shown an increase in studies of the accuracy of patient positioning for various tumor sites and positioning techniques. Particularly reports on an increase in recurrence rates (18) and/or reduction in survival rates (30) caused by underdosage in the field margins, have alerted radiation oncologists to the possible clinical impact of positioning inaccuracies. Studies have demonstrated that attention to adequate margins around the target volume and regular use of treatment verification results in a reduction of error rates (14, 19, 27). These findings have led to an increased use of portal imaging and to the development of fast electronic portal imaging devices, allowing both quick on-line estimates of the setup accuracy and extensive off-line analyses. The present interest in conformal therapy has made exact knowledge of the accuracy of the positioning technique involved, and its verification, essential.

Pelvic fields have been the subject of several studies of positioning accuracy (7, 11-13, 23), since in general surveys of positioning accuracy (8, 22) the pelvis was shown to be a site of relatively large errors, and because the pelvis is a site of high-dose curative treatment with the presence of

Table 4. Differences between simulation and treatment (SIM-MV): large pelvic fields (positioning technique with long laser lines and marking of the caudal field border; AP and PA combined)

Patient points and field size (Fig. 2c)	Mean SIM-MV* mm	SD* mm	Systematic* Σ mm	Random* σ mm
Field width (x)	-0.1	3.6	3.1	1.7
Field length (y)	-2.0	3.7	2.5	2.5
Patient position (8, 9); x	0.8-1.3	4.0-4.5	2.3-3.1	3.2-3.3
Patient position (7); y	-1.5	4.2	3.1	3.0
Rotation along z-axis (7-8; 7-9)	-0.5	1.6	1.1	1.1

* The mean values of the differences between the position of the respective points, or of the field size, in the simulation and treatment images (SIM-MV), the standard deviation (SD), the systematic variations, and the random variations. A negative value of a mean SIM-MV difference represents a mean shift of that point in the MV images in the right lateral (x) or cranial (y) direction.

critical, dose-limiting normal tissues. Rabinowitz *et al.* (22) found for pelvic fields an average SIM-MV discrepancy of 5.6 mm and an average worst case discrepancy of 8.4 mm. Griffiths *et al.* (13) studied various setup methods in 20 patients treated to parallel opposed pelvic fields for gynecological cancers. Standard deviations for lateral shift were 1.4-2.7 mm; for cranio-caudal shift they were 2.9-4.5 mm. The use of alignment lasers reduced both the incidence and the maximum value of lateral shift errors. Errors were larger when a mattress was used and with increasing patient diameter. In a study of on-line portal imaging by De Neve *et al.* (11), 566 parallel opposed pelvic fields were evaluated in 13 patients. Portal images were immediately evaluated and, whenever a visible error was detected, corrective table adjustments were applied using a telecontrolled patient couch. In 54.5% of the fields, adjustments were performed. A setup method matching a longitudinal laser line and the caudal field border was shown to be more accurate in the cranio-caudal direction. Portal imaging and adjustments caused a 45% mean increase in treatment time. Balter *et al.* (3) performed simulations of on-line repositioning. He showed that repositioning of the field for those treatments in which an error of ≥ 1 cm is found, results in improvement in the cumulative dose distribution.

Bijhold *et al.* (7) developed a decision protocol for correction of systematic errors in patients receiving three-field pelvic irradiation for prostate cancer. A 3D displacement vector was calculated from the 2D vectors measured in the AP and lateral fields. Using a 99 or 95% confidence level based on the average value of the vectors measured, a decision rule was applied: a correction was performed if the deviation was outside the confidence region. On consecutive days additional images were taken, and the resulting displacement vectors were averaged with the previous vectors. Thus, by averaging, the influence of random variations on the displacement vector decreased, and the action level could be taken lower (i.e., at the 67% confidence level). The average systematic and random shifts for all patients were 1.2 mm and 1.7 mm in the lateral direction and 2 mm and 2.4 mm in the cranio-caudal direction, resulting in an overall SD of 3 mm.

In the present study, as in most of the other studies, the variations in patient position were larger in the cranio-caudal

direction than in the lateral direction. Systematic and random components of the overall variations were similar, a finding that is in agreement with those of Bijhold *et al.* (7) and Huizenga *et al.* (16). As the study consisted of two separate patient groups, irradiated to different target volumes and using different positioning and treatment techniques, these will be discussed separately.

Small pelvic fields for urological cancer

The overall accuracy of patient position in the lateral direction was within acceptable limits (1 SD 3.4 mm), but for both the cranio-caudal and ventro-dorsal directions, the SDs were ≥ 5 mm. The variations in the cranio-caudal direction might be due to movement of the skin markings relative to the patient's anatomy. Respiration, weight loss, and possibly relaxation of the patient might be factors causing movement of the center tattoo, and rotation in the hip joints might result in movement of the lateral skin markings.

The variations in the ventro-dorsal direction were considered to be mainly due to two factors. First, the practice to calculate the SSD from the treatment plan and use this for patient setup could be a source of errors, as the SSD is influenced by abdominal movement (respiration) and patient diameter (weight loss). Secondly, it was found that the polycarbonate (mylar) film window of the treatment couch was not rigid enough and tended to sag under the patients' weight, thus causing errors in the ventro-dorsal direction. It was subsequently decided that the isocenter-couch distance was to be used for patient setup instead of the SSD, and that a rigid styrofoam table top would be used to prevent sagging of the polycarbonate (mylar) film window. Furthermore, a verification protocol was started for all patients, in which on-line verification of the treatment field was carried out at the first or second treatment session. If, by on-line comparison of the treatment field with the simulation image a relevant inaccuracy was found, the patient was repositioned. If this did not improve the accuracy, the simulation procedure was repeated before the next treatment fraction.

In 1993, a pilot study was carried out in a study group of four patients to check if the alterations had led to an improvement of accuracy. Standard deviations for patient

position were 4.2 mm in the lateral direction, 2.9 mm in the cranio-caudal direction, and 4.5 mm in the ventro-dorsal direction. Standard deviations for field width and length were 2 mm, reflecting the present use of a verification system on the accelerator. As these results were from only a small group of patients, no tests for significance were performed. It was concluded that there was a trend of improved accuracy in the cranio-caudal and ventro-dorsal directions, and this technique was subsequently used in the 1992–1993 study. This study, using a verification and correction protocol, did yield a statistically significant improvement in the systematic variations (Fig. 3a).

Both in the present study and in the other studies of positioning accuracy in pelvic fields, the position of the pelvic bony structures in the field was used to ascertain the setup accuracy. However, the true accuracy of the treatment can only be judged in this way if the assumption that the position of the prostate and/or the bladder within the pelvis is more or less fixed is correct. The question of to what extent the bony structures of the pelvis represent the true position of the prostate or the bladder in the field, has been addressed by several authors (4, 5, 15, 20, 28), using ^{125}I seed implants or CT scans to compare the position of the prostate to that of the bony pelvis. Results of these studies have been summarized in Table 5. It can be concluded from these studies that prostate motion within the bony pelvis is not insignificant, and that studies measuring the motion of the borders of the prostate gland on a series of CT scans yield larger shifts than studies measuring the motion of implanted ^{125}I seeds. Thus, prostate motion has to be taken into account when choosing the margin around the CTV for patient and/or organ movement and geometrical inaccuracies. If values of 1 mm (1 SD) for the lateral direction, 2 mm for cranio-caudal direction, and 5 mm for the ventro-dorsal direction are taken to represent the average prostate motion for the supine position as observed in these studies, then these data can be incorporated into the margin needed to account for positioning variations. In Table 6, an example of the calculation of margins is given: the SDs for prostate motion and those for positioning variations in the respective directions, as observed in the present study, have been added quadratically, and the 95% confidence interval

(2 SD) was chosen to represent a safe margin. Table 6 shows margins to account for positioning inaccuracies as found in the present study, and the reduction of the size of margin that could be obtained in the “ideal” situation in which regular verification eliminates the systematic variations. Roach *et al.* (24) calculated margins to account for setup variations and organ motion as well. In a theoretical patient, treated with a six-field conformal technique, margins for all six field directions were calculated using data on positioning variations, organ motion, and extracapsular extension in the respective directions. Using this sophisticated approach, margins ranging from 0.75–2.25 cm were required to ensure adequate coverage of the target volume while minimizing the volume of normal tissues irradiated. From studies as these it is clear that in situations where the tightest possible margins are chosen (as in conformal therapy), the size of the margin should be based on positioning studies, performed in the same institution, to prevent marginal misses.

Large pelvic fields for gynecological cancer

The large SDs (6.3 and 6.9 mm) for patient position in the cranio-caudal direction were considered unacceptable. This finding, and the fact that systematic shifts of the treatment field had occurred mostly in the cranial direction, while the caudal field border is the most critical anatomical edge, prompted a search for the cause of these deviations. It was concluded that in this positioning technique the vertical pin (which is pushed against the pubic bone) was the only factor determining the cranio-caudal orientation of the patient. As this pushing of the pin is uncomfortable for the patients, especially in the second half of the treatment series, technologists may feel somewhat awkward using it. As a result, the pressure applied is susceptible to variations in use by different technologists and to variations over the treatment weeks. A pilot study was carried out to determine if the technique could be improved by drawing transverse skin markings over the iliac spine on both sides and placing a tattoo over the sternum, and using these markings for cranio-caudal field orientation instead of the pin. However, this pilot study yielded essentially the same results as the previous study (results not shown). Combining these findings and the

Table 5. Displacement of the prostate gland within the bony pelvis: literature data on prostate motion

Author	Method	x*	SD* y*	z*
Hoekstra <i>et al.</i> (13)	I-seeds	1 mm	2 mm	1.5 mm
Balter <i>et al.</i> (3)	markers	0.8 mm	1.8 mm	2.2 mm
Ten Haken <i>et al.</i> (23)	I-seeds/CT	—	—	average 3 mm
Beard <i>et al.</i> (4)	CT scans	0–3 mm	—	0–16 mm
	supine	median 1	—	median 4.5
Melian <i>et al.</i> (18)	CT scans	0–15 mm	—	0–30 mm
	prone			

* The standard deviations (SD) of displacement, or the range of absolute displacements, in the medio-lateral (x), cranio-caudal (y), and ventro-dorsal (z) directions.

Table 6. Margins* calculated to account for geometrical inaccuracies in the treatment of pelvic fields for urological cancer

Direction	Margin based on overall accuracy of patient position	Margin based on overall accuracy and prostate motion	Margin based on random errors and prostate motion
Cranio-caudal	10 mm	11 mm	9 mm
Medio-lateral	7 mm	7 mm	6 mm
Ventro-dorsal	10 mm	14 mm	12 mm

* The margin is defined as the 95% confidence interval (2 SD). Standard deviations (SD) for positioning accuracy and prostate motion have been added quadratically and rounded off to integral mm.

results of De Neve *et al.* (11), who found a significantly higher accuracy for a positioning technique in which a longitudinal laser line and the lower field border were matched, a second pilot study was set up. Four patients were positioned without the special device using long laser lines and marking of the caudal field border. This study group was compared with a group of four patients treated on the same accelerator using the traditional positioning technique. Preliminary data of this study showed the new positioning technique to be much more reliable (results not shown). For this reason a larger follow-up study was carried out testing the accuracy of this new positioning technique. The position of the patients in the cranio-caudal direction was shown to be more accurate.

Immobilization

The question of to what extent immobilization of patients contributes to the setup accuracy has been addressed by several authors. Soffen *et al.* (26) compared setup accuracy in seven prostate cancer patients, immobilized with alpha cradle body casts, to that in a matched control group who were not casted. The median daily error for the casted group was 1 mm, while it was 3 mm for the noncasted group. The 10% largest daily variations were eliminated using the cast. Rosenthal *et al.* (25) compared two groups of 11 prostate cancer patients: one group was treated with alpha cradle immobilization, the other was not immobilized. The mean \pm 1 SD of the simulation to treatment variability was 4 mm \pm 2.6 mm using immobilization, compared to 6 mm \pm 4.5 mm without immobilization. Mitine *et al.* (21), however, comparing 6 patients treated without immobilization in the supine position to 12 patients in alpha cradle casts, 6 supine and 6 prone, observed a similar accuracy for the lateral direction and an improved accuracy for the cranio-caudal direction in the supine group when alpha cradle casts were used, but worse results in the group treated in the prone position in the alpha cradle cast as compared to the supine group without immobilization. It is extremely difficult to compare these results to each other and to our results. Different treatment techniques (six-field, four-field, and three-field) have been used; often a single measurement has been performed in each direction, and results have been presented in very different ways. Taking the percentage of SIM-MV differences \leq 1 cm as a measure of setup accuracy, then alpha cradle casts seem to be increasing

precision (98% vs. 85% in Rosenthal *et al.*'s study (25) and 100% vs. some 96% in the analysis of Soffen *et al.* (26)). In our study, 10% of urological cancer patients showed errors \geq 1 cm, which was reduced to a minimum of 1% using the verification and correction procedure on a routine basis. For the gynecological fields, accuracy obviously was worse, which is a common finding. Positioning accuracy diminishes with increasing patient weight (11, 13, 23). The field center is located in an area susceptible to movement (respiration, loose abdominal wall), and alignment often proves to be difficult. The immobilization system as traditionally used in our institute, using bony structures for set up, did not result in an acceptable setup accuracy. The use of the caudal field border as the most important parameter for alignment did result in an improvement in accuracy. This field border is located in the pubic area, which is much less susceptible to variations and is thus much easier to reproduce. Using alpha cradle casts in these patients might lead to further improvements in accuracy; this will be the subject of a future study.

The increased use of megavolt imaging and the results of positioning studies have focused attention on positioning accuracy and its relevance for the choice of margins. However, the studies have also raised the issue of how to implement their findings in clinical practice. Should we perform on-line verification of all fields on all patients and set limits of tolerance that technologists can use when deciding to irradiate or to adjust? Is it worthwhile to try and correct all random errors and accidental mistakes? At present, at most institutions, a verification system is operational on the accelerators which, if used with narrow tolerance settings, will prevent a large number of the accidental errors. For example, the interchanges of field length and width found in our study would have been prevented if the verification system had been operational at that time. Correction of all random errors would require continuous on-line verification. Setup corrections are time-consuming and disturbing both for technologists and patients. In daily clinical practice, the number of corrections should be kept as small as possible. It seems, therefore, to be far more efficient to obtain knowledge of the magnitude of random errors for the various treatment techniques at each institution by means of positioning studies like the present one, and to improve positioning techniques if large random errors are found. The margin to be added around the clinical target volume to compensate for

inaccuracies in patient setup can, thus, be chosen on the basis of the magnitude of random variations observed. Then, efforts can be concentrated on detecting and correcting systematic errors early in the treatment series.

Through analysis of a number of megavolt images obtained during the first week(s) of treatment, it can be determined early in the treatment series whether a systematic error is present. Correction is then only applied if the displacement (averaged over the measurements made so far) exceeds an action level, which is decreased at each subsequent measurement. In this way, correction of random deviations, which would result in further errors, is prevented. A verification and correction procedure developed by Bijhold *et al.* (7) and Bel *et al.* (6) is presently being used by a Netherlands collaborating group for megavolt imaging, and tested in daily practice in three radiotherapy centers. Data from previous positioning studies in pelvic irradiation for urological cancer, carried out in each of the centers, have been used to choose the

number of megavolt images to be taken and to set action levels for each center. The results of the first series of patients treated in our institution using this verification and correction procedure shows promising results (Fig. 3). To determine if such a protocol does consistently reduce error rates and if the workload is acceptable in daily practice in busy radiotherapy departments, the combined results from a large number of patients will be presented in a joint publication.

In conclusion, the present study on positioning accuracy in irradiation of small and large pelvic fields showed larger errors than was expected. Positioning techniques were improved and checked again for their accuracy. Margins to be taken around the clinical target volume to account for geometrical inaccuracies should be based on the results of positioning studies carried out in the same institution. Verification and correction protocols will be increasingly important, especially in conformal therapy.

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