On the use of a non-isocentric C-arm as a brachytherapy localiser and the multiparametric fit method in reconstruction of the Fletcher-Suit-Delclos applicator

Ph.D. Thesis

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1. Introduction

For the intracavitary brachytherapy treatment planning the knowledge of the applicator's geometrical arrangement is needed. The traditional way of the applicator reconstruction is based on pairs of biplane X-ray projections. Recently sectional CT or MR images are increasingly used. The pairs of biplane reconstruction images can be obtained by a conventional X-ray machine located in the brachytherapy treatment room, or by the therapy simulator. The most advanced equipment in biplane reconstruction is the Integrated Brachytherapy Unit (IBU). Unless an IBU or an X-ray unit located in the brachytherapy treatment room, the patient needs to be transported to the simulator or radiography room to obtain the reconstruction images and needs to be transported to the brachytherapy treatment room to administer the irradiation. There is a risk involved in such transportation of applicator displacement with not tightly fixed Fletcher-Suit-Delclos (FSD) applicators.

At our Department for the brachytherapy treatment planning a therapy simulator and mobile C-arm fluoroscopy unit (C-arm) are available. The use of the mobile C-arm X-ray machine as a brachytherapy localiser is not typical.

2. Objective

Our development aimed to use of the C-arm located in the brachytherapy treatment room in reconstruction of brachytherapy catheters, similarly to the IBU, using digital images obtained by the image intensifier of the C-arm, instead of using film (**A**). The brachytherapy treatment planning systems require setup parameters, including the magnification factors of the the images. For the use of images obtained by the C-arm, these parameters have to be determined previously. We aimed to develop an alternative method in reconstruction of the Fletcher-Suit-Delclos applicator incorporating the determination of the magnification factors (**B**). We demonstrate the treatment planning with the PLATO Brachytherapy Planning System (PLATO BPS) based on the reconstruction images obtained by the C-arm (**C**) .

3. Materials and methods

A. Introducing the mobile C-arm in applicator reconstruction

A1. Preliminary investigations

We digitised the video signal from the image intensifier and tested the feasibility of the usual reconstruction methods with pairs of secondary capture images obtained by a mobile C-arm fluoroscopy unit.

1. The semi-orthogonal method has been found to be the least applicable because of the small gap between the X-ray tube and the reconstruction jig, resulting in too large magnification factors, unacceptable by the PLATO Brachytherapy Planning System v13.7 (BPS).
2. The orthogonal reconstruction method has been found applicable, although the overlapping of the ovoids on the lateral images has been the main drawback, as well as the poor visibility of the radio-opaque markers.

3. The variable angle reconstruction method has been found most applicable using pairs of posterior-anterior (PA) and posterior oblique (PO) images.

A2. Taking isocentric images with a non-isocentric C-arm

The PLATO BPS v.13.7 uses the semi-orthogonal, the isocentric orthogonal, the variable angle and the IBU reconstruction methods. One of the problems with the images obtained by the C-arm is, that the equipment is not isocentric by construction, resulting in movement of the main beam's axis with the C-arm's orbital angle. We resolved this problem by taking the images after shifting the C-arm laterally and axially, until the main beam axis intercepts the selected point of the applicator on the reconstruction images.

A3. Determination of the magnification factors of the images

The magnification factors of the reconstruction images obtained by a therapy simulator or an IBU are known exactly, or with the semi-orthogonal method the magnification factors are determined by a reconstruction jig. The second problem with the images obtained by the C-arm is, that the magnification factor of the image is not known exactly and varies with the C-arm's orbital angle. One of our methods in determination of the magnification factor pertained to the isocenter is based on the measurement of the magnified distance of two radio-opaque markers being at the isocenter. This method can be used, if the applicator's inclination from the images axis is small. We developed an other method based on multi-parametric fit in determination of the magnification factors of the inclined applicators, or for catheters located not exactly at the isocenter.

A4. The distortion of the image intensifier

The third problem with the digital images is, that on the image edges and corners show pincushion distortion. We determined the low distortion area suitable for the accurate catheter reconstruction. We also tested feasibility of a commercial software package (Nero PhotoSnap) for the distortion correction.

B. Development of the multi-parametric fit (MPF) reconstruction method

B1. Introduction

Using the PLATO BPS with the pairs of reconstruction images the magnification factor have to be determined previously. The MPF method suitable for reconstruction of the FSD applicator, incorporating the determination of the magnification factors of the reconstruction images. The MPF method relies on known positions of the dummy sources inserted into the ovoid and the tandem. The geometrical arrangement of the tandem and the ovoids' of the actual FSD insertion is specified with 12 parameters. The limited freedom of the movements of the applicator's parts due to the fixation mechanism is taken into account.

B2. The principle of the MPF method

For reconstruction of the actual FSD applicator with the MPF method pairs of PA and PO images are needed. We digitise the dummy source positions inserted into the applicator. The MPF algorithm computes the values of the parameters of the actual FSD insertion with the following process:

1. We compute the dummy source co-ordinates of the FSD applicator pertained to the initial values of parameters.
2. The PA and PO projections of the dummy sources are generated.
3. We compare the co-ordinates of the digitised and of the computed dummy sources by the sum of squares of 2D differences.
4. The parameters, including the magnification factors are varied step by step using the simplex algorithm.
5. We generate the PA and PO projections the new FSD applicator geometry with the modified parameters.
6. The process is repeated until the best fit of the digitised and the computed dummy source co-ordinates is achieved.

The parameters of the best fit specify the reconstructed FSD applicator geometry.

B3. The accuracy assessment of the MPF method

We assessed the accuracy of the MPF method with the following methods:

1. We prepared a tandem phantom. We placed it in different angles and we reconstructed it with PA and PO images.
2. We reconstructed FSD insertions with different geometrical

arrangements of the tandem and the ovoids.

3. We developed two program versions of the MPF method. With the two-steps version first the tandem is reconstructed and the magnification factors of the images are determined, while in second step the ovoids are reconstructed. With the second program version the FSD applicator's parts are reconstructed in a single process.

B4. Determining the magnification factors of the reconstruction images using multi-parametric fit

We also apply the multi-parametric fit in determination of the magnification factors of the reconstruction images. We adapt a linear section of 2 cm length with 3D translations and 2D rotations to the linear section of the catheter being at the isocenter.

C. Treatment planning with the PLATO BPS using reconstruction images obtained by the C-arm

C1. Introduction

At our Department one of the most frequent application of the HDR brachytherapy is in treatments of the cervix carcinomas, performed with 2-5 fractions. The relative positions of the tandem and the ovoids are influenced by the patient anatomy. We experienced similar FSD geometries in different fractions, but small variations in geometry can modify the dose distribution significantly. We prepare treatment plan for each treatment fraction.

C2. Treatment planning of insertions with the FSD applicator

C2.1. The FSD applicator geometry during the treatment fraction and the inter-fractional variation

We investigated the possible change in FSD applicator geometry during the treatment fraction. We repeated the applicator reconstruction after finishing the dose delivery and we compared the dummy sources' co-ordinates inserted into the applicator. We also investigated the inter-fractional variations in FSD applicator geometries and the influence for the dose distribution.

C.2.2. Optimizing the dose distributions of the FSD applicators with different geometries

Using the PLATO BPS geometrical optimization method, the source's dwell times are varied to ensure uniform dose values to dose points in a given distance from the applicator.

We regard the FSD geometry ideal with 6cm active tandem length and with 2cm lateral distance between the ovoids and the tandem. The optimized dose distribution of the ideal arrangement is the reference dose distribution.

The insertion geometries with the FSD applicator can be divided into groups as follows. The ovoids' lateral separation can be symmetric, asymmetric or small. The sagittal position of the ovoids can be shifted in direction of the bladder or the rectum. The sagittal shift of the ovoids can result in under-dosed region or a hot spot on the organs at risk.

C.2.3 Improvement of the dose distribution of insertions with non-ideal FSD geometries

The sagittal dose distribution of the ideal FSD geometry is symmetrical. The FSD applicator with ovoids shifted towards the bladder shows dose distribution with an over-dosed region in the bladder's wall and under-dosed region in towards the rectum. The FSD insertion with ovoids shifted towards the rectum shows the reverse situation.

We investigated the dose distribution of different FSD geometries by defining two applicator points on the sagittal axis in a distance of 2cm from the origin. The co-ordinate system was fixed to the tandem. We improved the symmetry of dose profiles by shifting the active dwell positions around the tandem. In addition, we applied geometrical optimization.

C3. Treatments of the carcinoma of the endometrium

The other main application field of the HDR brachytherapy at our Department is the treatment of the endometrial carcinomas. In majority of these treatments are performed with modified Heyman packing method. We insert smaller number of Simon-Norman catheters (5-6), compared to other centres, and the heads of the catheters are inserted to the fundus uteri. The required dose distribution is achieved with dose optimization on dose points and geometry. In dose planning we take into account the uterine wall thickness. The geometrical arrangement of flexible catheters are different in each treatment fraction, therefore preparation of treatment plan for each fraction is needed. One part of the insertions showed regular geometrical arrangement. These insertions were suitable for dosimetric comparison using dose profiles and for comparison of the dose distribution of the rigid Y-shaped endometrial applicator. We also investigated the sagittal dose distribution with patient points defined on the sagittal uterine contour.

4. Results

A1. We use secondary capture images obtained by a mobile C-arm fluoroscopy unit in brachytherapy treatment planning. We convert the images to Dicom format for the PLATO BPS. We developed methods for obtaining reconstruction images with a non-isocentric C-arm and for the determination of the magnification factor.

A2. We assessed the reconstruction accuracy in FSD insertions with pairs of PA and PO images obtained by the C-arm and the PLATO BPS V13.7. We used the 'catheter description points method' and variable angle reconstruction with PO images in the range of 150-135º. The maximum error of the reconstructed tandem lengths was smaller (1.8mm), than the acceptance level (2.5mm) of the BPS.

A3. The use of the mobile C-arm located in the brachytherapy treatment room makes possible to perform the treatment planning and the dose administration with the same patient position.

A4. We checked five FSD insertions for possible applicator displacement under these circumstances. We repeated the reconstruction of the FSD applicators after finishing the treatment fractions. The maximum 3D difference in coordinates between the pre- and post-treatment reconstruction was 2.3 mm.

B1. We developed the MPF method for reconstruction of FSD applicators. The MPF method based on the known geometries of the tandem and the ovoid. The geometry of the actual FSD insertion is obtained by adaptation of the applicator's parts with translations and and rotations. The determination of the magnification factors are also incorporated.

B2. We tested the reconstruction accuracy with a tandem phantom placed into different positions. The largest 2D error was 1mm.

B3. We tested the MPF method with FSD insertions of various tandem and ovoids' geometries. The largest 2D error was 1.7mm.

B4. We tested two versions of the MPF program. In the first version we separated the fit process into two steps. In the first step we reconstructed the position of the tandem, while in the second step the ovoids using the magnification factors and the lateral rotation angle of the tandem, obtained by the first step. With the single-step version we reconstructed the tandem and the ovoids in the same process.

B5. We compared the 3D differences of the reconstructed applicator points: the tandem's tip, middle and proximal end, as well as the second marker in the right ovoid obtained by the two program versions agreed within 1.7 mm.

C1. The geometrical arrangements of the tandem and the ovoids in insertions with the FSD applicator were divided into groups. The lateral separation of the ovoids can be symmetrical or asymmetrical, or the distance between the left and right ovoids can be small, while the ovoids' sagittal position can be correct, or shifted towards the bladder or the rectum.

C2. After finishing the insertion of the applicator, the patient lies in the same position during taking reconstruction images, the treatment planning and administration of the dose. We have not experienced applicator displacement under these circumstances.

C3. We assessed the inter-fractional variations of the FSD applicator geometries during definitive treatment fractions. We experienced similar lateral ovoid separation, while the sagittal positions of the ovoids were oft different.

C4. Using geometrical optimization method in FSD insertion with non-ideal geometrical arrangements, we could improve the dose distribution close to the dose distribution of the ideal arrangement. We computed the optimized dose values to sagittal applicator points being in a distance of 2cm towards the bladder and rectum. In majority of cases the dose values to the applicator points were within ±1Gy, while in FSD insertions with narrow ovoids' separation, those were higher.

C5. The geometrical arrangements of Simon-Norman catheters for the endometrial treatments are various in different treatment fractions, while part of the insertions approximated the regular arrangement. We obtained lateral and axial dose profiles from the dose matrices calculated by the PLATO BPS, and compared with the profiles of the Y-shaped geometrical arrangements. The axial dose profiles of the multichannel arrangements showed 1.3-1.7 times higher dose to the patient points on the outer uterine contour and near the catheters' heads, compared to the dose values of the Y-shaped applicator.

C6. We obtained the required dose distribution with geometrical optimization using lateral dose points, being in a distance of the uterine wall thickness. We assessed the dose to patient points on the sagittal uterine contour with different uterine shapes and dimensions. We experienced relative under-dosed region at the fundus, while hot spot on the bladder's dorsal wall.

5. Conclusion

A. The sophisticated approach in biplane applicator reconstruction, the use of the Integrated Brachytherapy Unit with filmless treatment planning is not available in lot of institutions. The IBU concept involves, that the patient lies on a treatment table suitable for the insertion of the applicator, also for taking reconstruction images and for the dose delivery.

At our department we introduced the use a C-arm fluoroscopy unit as a localiser in treatment planning.

The main differences between our method and the referred ones are:

1. Our applicator reconstructions are based on pairs of PA and PO images, instead of the usual PA ad lateral ones. On PO images the shielding effect of the bony structures is smaller and in FSD insertions the ovoid overlap is avoided, the radio-opaque markers inserted into the applicator

are clearly visible.

2. In our reconstruction images the applicator appears on the centre of the image and we digitize the dummy source coordinates from the low distortion region of the image intensifier.

We experienced the following advantages:

1. The patient lies in the same position from the insertion of the applicator, while the therapy plan is prepared, until finishing the treatment session, minimizing the applicator displacement.
2. The treatment planning time was shortened using on-line images instead of the film development.
3. We prepare individual treatment plans for each FSD treatment fraction and also for more complex catheter arrangements, like the Simon-Norman catheters, while other centres shorten the treatment time using standard dose plans.
4. If it is necessary, the position of the ovoids in FSD insertion is corrected before the dose planning.

We experienced the following limitations using the C-arm:

1. The mechanical precision of the C-arm is smaller compared to the therapy simulator or an IBU.
2. The shielding of the metal parts of the dedicated treatment table limited the possible angles of the posterior oblique reconstruction images resulting in a suboptimal condition in applicator reconstruction.
3. For obtaining the reconstruction images with our method 3-4 exposures

are needed to find the isocenter.

4. The diameter of the fluoroscopy unit, applied at our institution is small (16cm).
5. The estimation of the relative position of the FSD applicator parts for checking the insertion and reconstruction of the ICRU patient points with the posterior oblique image needs more practice, than using lateral image.

B. For generation of treatment plans with a commercial brachytherapy planning system the magnification factors of the reconstruction images have to be determined previously. We developed a reconstruction method using multiparametric fit (MPF), that is suitable for reconstruction of FSD applicators and that utilizes pairs of posterior-anterior and lateral or preferably posterior oblique reconstruction images without the knowledge of the exact values of the magnification factors.

For the MPF method proper initial values for the parameters are needed. The range of the variation of the lateral and sagittal rotational angles is small, rarely exceeding ±10°, however, the tandem's tip can be rotated from 0 to 360°. In FSD insertions with retroverted tandem the initial geometry had to be changed for the initial geometry of the retroverted tandem. We tested two versions of the MPF program. The reconstructed marker coordinates obtained by the two program versions show good agreement, however, the two-steps fitting provides a slightly more accurate image reconstruction, usually, than the one-step program version.

We experienced the following advantages of the MPF method.

1. The method incorporates the determination of the reconstruction images' magnification factors, also for applicators showing inclination from the images' axis.
2. The most of the conventional methods reconstruct the dummy sources separately, while the MFPF method adapts the known geometry of the applicator's parts to the actual FSD insertion using translations and rotations.
3. In case of successful fit, the reconstructed catheter's length and the length of the catheter's sections are correct.
4. The MPF method is less sensitive for the distortion of the reconstruction images.
5. The tests showed that the accuracy of the MPF reconstruction method is acceptable for clinical use.

C. Recently, for the assessing of the brachytherapy dose distributions dose-volume histograms, based on sectional images are increasingly used. These investigations are performed in majority with standard applicators (tandem and ring), or only one of the treatment fractions is performed with treatment plans based on CT or MR images.

One of the possibilities for sparing the organs at risk is the increase of the distance between the organs and the applicator.

At our Department we decrease the dose to the organs at risk in FSD insertions of different geometries using geometrical optimization. With this method we also increase the symmetry of the sagittal dose distribution. We perform the modified Heyman packings with small number of Simon-Norman catheters. This method has the advantage, that the catheters are reconstructed in full length, while other centres reconstruct the catheters' tips. The dose distribution is optimized for the uterine wall thickness. The heads of the catheters are inserted to the fundus, resulting in higher doses on the fundus uteri, on the origin of the endometrial carcinomas.

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