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Dose distribution for gynecological brachytherapy with dose accumulation between insertions: Feasibility study

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ABSTRACT

PURPOSE: For gynecological treatments, it is standard to acquire CT images and preferably also MR images before each treatment to calculate the dose of the day. The dose of the complete treatment is calculated by adding the dose metrics of each fraction. It makes the conservative assumption that the same part of the organs at risk always receives the highest dose. The dose calculated this way often limits the prescription dose or the target coverage. We investigated the use of deformable image registration (DIR) as an alternative method to assess the cumulative dose for a treatment course.

METHODS AND MATERIALS: Rigid registration is preformed on CT images, followed by DIR. DIR can be based either solely on the three-dimensional images or combined with organ contours. To improve DIR in the pelvic region with low CT contrast, we propose (*1*) using contours drawn on CT or (*2*) modifying artificially the contrast in certain volumes. The dose matrix from fraction_n ($n > 1$) is deformed using a calculated deformation field.

RESULTS: The use of the contrast-enhanced images or of contour information helps to guide the DIR. However, because of the very high dose gradients involved in brachytherapy, the uncertainty on the accumulated dose remains of the order of 5−10%. Even for good contour matching, a small local error in the deformation can have significant consequences for the dose distribution.

CONCLUSIONS: Using DIR, based on image features and contours, allows to accumulate the dose from different brachytherapy fractions. A robust validation procedure should be developed.
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Keywords: Deformable registration; Gynecology dose accumulation

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Introduction

In brachytherapy, as in external beam radiotherapy (EBRT), image guidance plays an important role. For gynecological (GYN) treatments, it is standard to acquire at least CT images and preferably also MR images before each treatment and to calculate the radiation dose of the day on each set of images (1, 2). Then, the dose distribution to the target and to the organs at risk (OAR) is calculated for each fraction, and dose volume histogram (DVH) metrics are added up to obtain information for the full brachytherapy treatment, for example, the volume covered by the 100% isodose (V_{100}) for the target and the highest dose received by any 0.1 or 2 cc ($D_{0.1cc}$ or D_{2cc}) for the OAR (2). For the OAR, it makes the safe conservative assumption that the same part of the OAR always receives the highest dose. The dose calculated this way often limits the prescription dose to the target or the target coverage.

In this work, we propose to investigate an alternative method to assess the cumulative dose for a high−dose rate GYN treatment course; the use of deformable image registration (DIR) to track the deformations of the OAR from one fraction to the next and accumulate the dose of all the fractions. When using DIR for dose tracking, the implicit hypothesis is that the patient tissue moves but does

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not disappear. This is probably a correct approximation for the walls of the OAR but is much more questionable for the target. We consequently chose to limit this study to OAR deformations.

Several DIR studies were recently published for EBRT, for example, using DIR to deform structure contours for four-dimensional CT imaging or for repeated cone beam CT imaging to ease the organ segmentation (3−5). Others looked at accumulating dose recalculated on cone beam CT images acquired at each treatment fraction (6, 7). However, to our knowledge, only a few articles have been published concerning DIR applied to dose accumulation for brachytherapy (4,5,8−12) and those authors only use one DIR.

One of the problems regarding deformation in the pelvic region is the lack of CT imaging contrast compared with, for example, lung or head and neck tumors. To compensate for this, some authors have proposed model-based algorithms (13, 14) where they developed viscoelastic models for specific organs. These models exist, for example, for the liver (6, 15, 16), the lungs (17, 18), and the bladder (8, 19, 20). This kind of algorithm is often limited to the deformation of one organ or a few organs for which elastic properties can be obtained. The deformation can then be propagated to neighboring tissues to obtain the global deformation of the whole region, but this propagation is a source of large uncertainties. The use of those algorithms for brachytherapy, moreover, has to be adapted to take into account the presence of a rigid applicator that may modify the elastic properties of the abdomen region by introducing different boundary conditions. For low-image contrast regions, surface matching has been shown to yield adequate results (21) but is again limited to a few or even just one organ.

The validation of DIR, certainly in regions where there is only a limited amount of information available, is a difficult issue. This validation can be experimental (22−25) or based on patient images using structure contours or landmarks where they are available (26). It concerns, however, always a limited number of features (e.g., landmarks or contours) or is performed on a phantom, which has different characteristics than a human body and is not easily translated into a real clinical case. To our knowledge, completely satisfactory validation methods have not yet been proposed.

It has been shown that different DIR algorithms can provide very different deformations (27, 28). The present article provides an estimate of the influence of differences between different DIR methods on the deformed dose distribution for GYN brachytherapy. More specifically, it addresses the effect of the deformation uncertainty on the DVH metrics to compare it with the use of the recommendations from the Groupe Européen de Curiethérapie and the European SocieTy for Radiotherapy & Oncology (GEC/ESTRO) recommendations. As was already stated, the disappearance or appearance of material is a challenge for DIR, we chose consequently to limit our study to the deformation between fractions and not the deformation between brachytherapy and EBRT.

Methods and Materials

Deformation methods

CT images are acquired before each of the typically four brachytherapy fractions. Rigid registration to correct for gross alignment differences, followed by DIR, is then applied using the first fraction as reference image set using the REGGUI software package developed at the Université Catholique de Louvain-la-Neuve (29). Briefly, the purpose of the DIR process is to find the transformation Δ that optimizes an energy functional consisting of a metric M, which compares the fixed image f with the warped image $m\circ\Delta$, where m is the moving image. An additional regularization term $\Re$ is added that increases the energy functional when displacements become larger or physically improbable, penalizing those solutions.

$$\tilde{\mathit{\Delta}} = \arg_{\mathit{\Delta}}\min M(f,\, m\circ \mathit{\Delta}) + \Re(\mathit{\Delta})$$

The two methods considered in this study are the demons registration method (30) and the morphon registration method (31). The demons method is based on the matching of gray levels, whereas the morphon algorithm is based on the matching of edges and lines. For both, we follow an iterative and multiscale approach to increase speed, robustness, and accuracy (32). This approach based on a subsampled version of the images not only reduces the computational time but also allows the estimation of large displacements that could not be estimated in the final resolution because of noise and local minima in the optimization process. Starting with a coarse estimation of the displacement field, one can then improve the field estimation using finer resolutions (see Fig. 1). Demons and morphons were applied using eight scales, with a maximum of 20 iterations at each scale. In Fig. 1d is the displacement field associated with the transformation Δ and the symbol $\Diamond$ is introduced to express the warping of a moving image m by the displacement field D and is defined as

$$w(X) = [m \Diamond D](X) \triangleq [m \circ \mathit{\Delta}](X)$$

where $\circ$ is the common function “composition” and w is the result of the warping at co-ordinates X.

Additionally, REGGUI uses a diffusion-like Gaussian regularization of the displacement field, leading to smooth and realistic fields. The physical meaning of the displacement field is important when warping dose as dose accumulation is based on the hypothesis that each individual voxel in the image can be tracked. The regularization term is defined by a Gaussian function, with a variance that varied between 1.5 and 0.7 pixels.

Registration is usually an ill-posed problem as there is not enough information in the images to fully constrain the set of possible solutions. This is particularly true in the pelvic region where the CT image contrast is usually poor. Fortunately, additional information can be added by medical experts or image processing. Based on a priori

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