replanning [Tilly 2013]. Since the current deformable image registration (DIR) methods still fall short concerning anatomically correct deformations and therefore do not reach the required accuracy expectations, we have developed a tissue-dependent transformation model. With this we aim at improving the characteristic deformation behavior of rigid and soft tissue without the need of time-consuming tissue delineation.

**Material and Methods:** We adapted the Enhanced ChainMail (ECM) algorithm [Schill 1998], which was originally developed for surgical simulations, to CT-images by assigning each voxel of the image elastic properties according to its HU-value. The deformation, initialized by shifts of anatomical landmarks, is then propagated by adjusting the deformation limits for every individual element. In addition to deformation limits for stretching, contraction and shear between neighboring elements (voxels), we also introduced an element orientation, which allows for an initial rotation to decay within elastic material.

**Results:** The ECM algorithm has successfully been applied to phantom as well as real CT-images. Due to the simple deformation rules the algorithm takes less than two minutes for a high-resolution CT-image (dimension: 512 x 512 x 170), but still approximates the shape and geometry of the deformed image in a physically realistic manner. Since tissue parameters can be assigned based on HU-values, the deformation is adapted to different material properties without the necessity of segmentation of different organs. This is in contrast to finite element methods, which represent the state of the art in deformation accuracy [Brock 2006].

![Image](image_url)

**Fig. 1:** Rotation of a vertebra surrounded by soft tissue. The vertebra is automatically rotated rigidly, whereas the rotation decays in soft tissue as can be seen by the deformed grid cells.

**Conclusion:** This is one of the first applications of the ECM-based transformation model for DIR in radiotherapy. With the extension by inter-element rotation, the algorithm is now able to register deformed and locally rotated organs in CT-images without the requirement of time-consuming segmentation. On the long-term the ECM-algorithm will allow for fast and physically realistic registrations, promising to cope with the strict accuracy requirements in deformation detection for particle therapy.

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Virtual CT for adaptive prostate radiotherapy based on CT-CBCT deformable image registration

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**Purpose or Objective:** We present a deformable image registration (DIR) framework for adaptive radiotherapy treatments of prostate cancer (PCa). The objective is the generation of virtual CTs by warping the CT planning in an adaptive IGRT framework. Previous studies on the use of CBCT as a support for dose recalculation and re-planning decisions for head and neck cancer showed promising results. For the pelvic region, similar studies are not yet available, mainly due to limitations in CBCT image quality and in the overall field of view. We developed an algorithm in order to perform DIR, making specific efforts to overcome the poor signal-to-noise ratio that limits CBCT use for treatment planning purposes.

**Material and Methods:** The planning CT and 5 CBCT images of 2 PCa patients treated with ultra-hypofractionated IGRT at the European Institute of Oncology (Milan, Italy) were included in this study. The CT image resolution was 1.25x1.25mm2 in-plane and 2.5 mm in the cranio-caudal direction, whereas the voxel size of CBCT reconstruction was set to 0.39x0.39x2.0 mm3. The Insight Segmentation and Registration Toolkit (ITK) was used to implement the DIR framework featuring: (1) Mattes Mutual Information metric, with the advantage of rescaling the images internally while building up the discrete density function; (2) Regular step gradient descent optimizer, which sets the parameters in the direction of the gradient to calculate the step size; (3) The B-Spline interpolator to handle the deformable transformation of the images. In order to verify the proposed approach, the obtained Virtual CTs were compared with the corresponding CBCTs. For this purpose we applied an automatic approach to the scale invariant feature (SIFT) method, which extracts and matches features from each pair of the fixed and the transformed images, thus quantifying geometrical errors in Virtual images. SIFT allows DIR methods assessment through the evaluation of landmark residual errors.

**Results:** For each pair of CBCT and registered CT, 31 matching points were found on average (range 12-42). The resulting residual error along each anatomical axis had the same order of magnitude of the voxel size (0.39, 0.39, 2.0 mm along x, y and z, respectively) as seen in Fig.1.

![Image](image_url)

**Fig. 1:** Landmark distance residual errors distribution for patient 1 (left) and patient 2 (right).

**Conclusion:** The implemented DIR framework provides a registration accuracy within the voxel size. Our results point out the potential of using CBCT and DIR for IGRT in PCa patients. Future studies envision the implementation of DIR for dose recalculation and margin evaluation in adaptive IGRT of PCa patients, taking into account the existing limitations in the field of view. Acknowledgment: This study was
Feasibility of automatic contour propagation of spinal bone metastases for online MR-Linac treatment

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Purpose or Objective: Accurate identification of the clinical target volume and organs at risk remains one of the most observer-dependent and time-consuming processes in radiotherapy treatment planning. An online adaptive procedure at the MRI linear accelerator (MR-Linac) requires fast contouring to adapt the treatment plan to the daily anatomy. Automatic contouring software can be a helpful tool to speed up this process. The purpose of this study was to evaluate the feasibility of automatic contour propagation for online adaptive treatment of spinal bone metastases on the MR-Linac.

Material and Methods: Two healthy volunteers underwent an MR-scan twice of the lumbar spine with an interval of two months. The MR-scans were acquired on an Ingenia 1.5 T scanner (Philips, Best Netherlands) according to the clinical stereotactic spine protocol. The first MR-scan series contained a transversal mDixon scan with a Field of View (FOV) length of 30 cm, which is considered the reference. The second series contained, besides the same mDixon, a transversal T1 TSE and T1 VISTA both with a FOV of 20 cm. These scans were considered as the daily MRI. Ten contours were manually delineated on the reference; the whole vertebral compartments of thoracic 12 until lumbar 5, both kidneys, aorta and myelum (figure 1a). Automatic contouring software “Advanced Medical Image Registration Engine” (ADMIRE v1.12, Elekta, Stockholm Sweden), was used for MR-based deformable registration and contour propagation of all contours between the reference and the 3 daily MR-sequences. The processing time required by ADMIRE to create contours on each MR-sequence was scored. The contour propagation on different MR-sequences was evaluated visually. A scoring system with a scale from 1-3 was used for visual evaluation of all contours: contours clinical acceptable, according to the clinical guidelines (score 1), contours need some adjustments (score 2) and contours need major adjustments (score 3). All adjustments (score 2) were specified for location of the contour failure and the adjustment time.

Results: The mean processing time needed for automatic registration and contour propagation was 56 (range 35-89) seconds. The mean processing time decreased when a 20 cm length of FOV was used to 41 (range 35-47) seconds. In total, 98% of the automatically delineated contours were clinically acceptable (score 1) (figure 1b). In the remaining 2% small adjustments (score 2) were made at the border of a 20 cm FOV. No score 3 was observed. The additional time needed for manual adjustments was 28 seconds.

Conclusion: MR-based contour propagation using automatic contouring software is fast enough for an online treatment at the MR-Linac. A limited FOV is usable for contour propagation, which allows tailoring of the FOV to the target of each individual patient. These high numbers of clinically acceptable contours will need to be confirmed in an ongoing study, first on several volunteers and then on patients pathology.

Importance of true cord delineation in spine SBRT and rigid vs. deformable MRI-to-CT registration

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Purpose or Objective: Spine stereotactic body radiation therapy (SBRT) employs high doses per fraction. In this study, we assessed the importance of delineating the true cord (TC) for dose planning constraints, rather than using thecal sac (TS) as a surrogate. We also evaluated different MRI-to-CT registration methods for matching the MRI cord to the CT myelogram (CTM, here considered as the gold standard for TC visualization).

Material and Methods: Fifteen spine SBRT patients with both CTM and MRI scans were selected. The TS and TC were delineated according to RTOG protocols and the MRI contours were fused to the CT volume using either rigid or deformable image registration. To compare the performance of the rigid vs. deformable registration, Dice similarity coefficients and Hausdorff distances (largest distance from a point in one contour to the closest point in the other contour) were calculated. The importance of TC delineation was evaluated by comparing the TC and TS from the CTM by determining the minimum distance between any of the circumference points on the two structures, and the number of points that were closer than 1 mm (indicating that parts of the TC were close to the edge of the TS). For 3 fraction spine SBRT, we used this minimum distance to estimate the potential maximum dose that could be received by the TC if this is not delineated and constrained directly in treatment planning, given a TS maximum dose constraint of 21.9 Gy. We also estimated the subsequent risk of radiation myelopathy based on published dose-response model from a clinical spine SBRT series.

Results: The average Dice coefficient (± standard deviation) for the TS was 0.84 ± 0.06 for rigid and 0.81 ± 0.07 for deformable registration, and respectively 0.73 ± 0.10 and 0.67 ± 0.14 for the TC. For some patients rigid registration was superior and vice versa for others, no method was clearly superior.