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Multi-segmental spine image registration supporting image-guided interventions of spinal metastases

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ABSTRACT

Background: Radiofrequency ablation was introduced recently to treat spinal metastases, which are among the most common metastases. These minimally-invasive interventions are most often image-guided by flat-panel CT scans, withholding soft tissue contrast like MR imaging. Image fusion of diagnostic MR and operative CT images could provide important and useful information during interventions.
Method: Diagnostic MR and interventional flat-panel CT scans of 19 patients, who underwent radiofrequency ablations of spinal metastases were obtained. Our presented approach piecewise rigidly registers single vertebrae using normalized gradient fields and embeds them within a fused image. Registration accuracy was determined via Euclidean distances between corresponding landmark pairs of ground truth data.
Results: Our method resulted in an average registration error of 2.35 mm. An optimal image fusion performed by landmark registrations achieved an average registration error of 1.70 mm. Additionally, intra- and inter-reader variability was determined, resulting in mean distances of corresponding landmark pairs of 1.05 mm (MRI) and 1.03 mm (flat-panel CT) for the intra-reader variability and 1.36 mm and 1.28 mm for the inter-reader variability, respectively.
Conclusions: Our multi-segmental approach with normalized gradient fields as image similarity measure can handle spine deformations due to patient positioning and avoid time-consuming manually performed registration. Thus, our method can provide practical and applicable intervention support without significantly delaying the clinical workflow or additional workload.

1. Introduction

Due to the improvement of medical treatment and diagnostic procedures, life expectancy has steadily increased over the last decades. However, this lifetime gain promotes also age-related diseases like cardiovascular diseases, as well as cancer and cancer induced malicious metastases. Beside liver and lungs, bone metastases are the third most likely. Up to two thirds of the latter are located in the spine [1,2]. Spinal metastases could tremendously affect the quality of life by evoking vigorous pain by fractures, bruises, spinal cord and nerve root compressions or neurologic deficits [3]. Currently, the method of choice to treat painful vertebral metastases is external-beam radiation [4]. However, percutaneous minimally invasive therapies gain increasing reception as a promising alternative. Radio-frequency ablation (RFA) has been used to reduce lower back pain caused by facet osteoarithritis [5] or osteoid osteoma [6] and was introduced more recently to treat osseous spinal metastases [7].

Flat-panel CT and CT angiography are the most common imaging methods regarding image guidance during osseous RF ablations [8–10]. However, low dose protocols like intra-interventional Dyna-CT scans provide a reduced image quality compared to native CT or MR imaging and weak soft tissue contrast (see Fig. 1). Additionally, it manifests in decreased signal-to-noise ratio (SNR), beam-hardening and scatter artifacts, which hamper precise and reliable metastasis localisation during interventions. Due to the poor visibility of the spinal metastases during interventions, the radiologists have to infer their location from pre-interventionally acquired MRI data and mentally match those images with the intra-interventionally performed flat-panel CT scans. Thus, a precise localisation is only possible to a certain degree of accuracy. Moreover, each interventional image during the RFA is acquired in prone patient position, causing intervertebral joint movements and altered spine flexion compared to the diagnostic images. This aspect further increases the cognitive load of the radiologists for metastasis puncture, particularly if several metastases are treated in a

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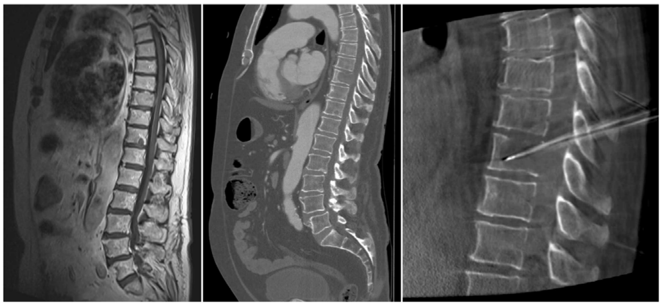

Fig. 1. Image modalities that have been used for image-guided interventions of spinal metastases. Sagittal and axial T_1-weighted, T_2-weighted and T_1-weighted contrast-enhanced (left) MR imaging sequences, as well as CT scans (middle) were acquired pre-interventionally. During interventions, flat-panel CT scans (right) support navigation and applicator placement. Artifacts due to low dose protocols, e.g. beam-hardening at the vertebral rim and from inserted metallic instruments aggravate precise metastasis localisation and puncture.

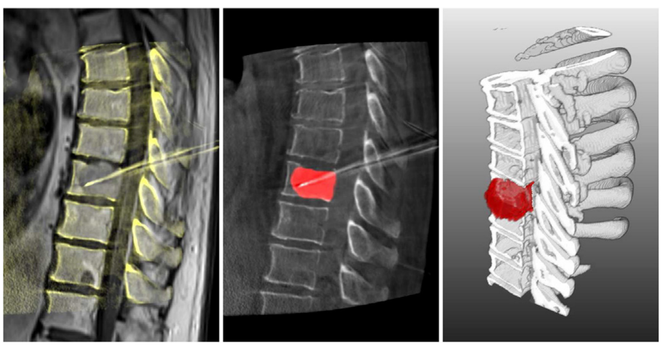

Fig. 2. Fusion of pre- and intra-operative images could become a significant improvement of the intervention routine. As a result of the image registration (left; background: MRI, overlay: Dyna-CT) a transformation matrix could be used to transfer and display pre-interventionally produced information like contoured metastases within the intra-interventional images (middle, right).

single procedure [11,12]. These limitations could be overcome by fusing diagnostic MR images with the intra-interventional scans in order to benefit from the typical MR high soft tissue contrast during interventions. Furthermore, additional image information generated during intervention planning, e.g. segmented metastases or optimized RFA applicator trajectories [13,14], can be displayed in the interventional images (see Fig. 2).

Some studies have been presented regarding image fusion of spine MR and CT imaging. Most of them used landmark-based rigid registration approaches [15–18]. Alternatively, rigid image fusion could be formulated as an optimisation problem using image similarity measures like mutual information (MI) [19–21] or normalized gradient fields (NGF) [22,23]. MI is seen as one of the most suitable similarity measures for multimodal image registration, however, images with sparse structural information, like low dose protocols of interventional flat-panel CT imaging, could yield problems with MI [24]. The most common limitations in fusion of diagnostic spinal MR and interventional flat-panel CT images are differences in patient positioning causing intervertebral joint movements and deformations of the spine structure. Globally rigid techniques like [15,19] cannot take this into account, therefore, piecewise rigid registration methods with previously segmented vertebral structures or defined region of interests (ROI) have been reported [16,17,21], partly with local rigidity embedded within a global deformation field [20].

Our work combines a multi-segmental registration approach with NGF as an image similarity measure, to cope with deformations of spine structures during RFA interventions of multiple metastases and to overcome limitations of reduced structural information due to low dose interventional imaging. For efficient and convenient applicability within the clinical workflow, the total procedure should not exceed 5 min and should require only minimal user interaction to be performed between the calibration of the navigation system and the metastasis puncture. The mean registration error should be less than 3 mm for being sufficiently precise to likewise enable applicator pathways through vertebral pedicles with mean diameters ranging from 3 to 10 mm (thoracic to lumbar) [25].

2. Materials and method

2.1. Image data

19 patients who underwent RF ablations of both, single or multiple vertebral metastases, were chosen retrospectively. For diagnostic purposes spine MR imaging was performed pre-interventionally, containing sagittal and axial native T_1- and T_2-weighted sequences, as well as a sagittal STIR (short tau inversion recovery) sequence to enhance oedemata typical due to cancerous and metastatic processes. If required, additional contrast-enhanced T_1-weighted sequences were performed. During the RFA intervention, flat-panel CT scans were acquired to calibrate the navigation system and to validate the final applicator position. We assembled an evalutation set consisting of sagittal native T_1-weighted or contrast-enhanced T_1-weighted MRI sequences and intra-interventionally acquired Dyna-CT scans of each patient. Additionally, we tested the influence of T_2-weighted sequences on our registration approach for five randomly chosen patients. The in-plane image resolution of the MRI data ranged from 0.47 mm to 1.25 mm (average 0.63 mm) and the slice spacing was 3.30 mm for all scans. The flat-panel CT scan resolution ranged from 0.22 mm to 1.10 mm (average 0.65 mm) in-plane and had a slice spacing ranging from 0.46 mm to 3.00 mm (average 1.28 mm). Additionally, segmentation of metastases was performed manually and was for demonstration purposes only (see Fig. 2).

2.2. Image registration

The presented registration approach was selected due to both the physical characteristics of the spine and the available multimodal images. In our main case of application, in which most patients were in advanced tumour stages and had several vertebral metastases, the intervention region was not limited to a single vertebra, but covered entire spinal segments. A multi-segmental, i.e., piecewise rigid registration procedure appeared to be the most suitable approach in order to accurately model the deformation of spine structures, caused by different patient positioning. Therefore, a global non-rigid image fusion problem was split into multiple local rigid registrations of individual vertebrae or spine segments. To initialize our method, the user had to mark each vertebra or spine segment which has to be registered in both modalities. Following this, regions cropped to single vertebrae or segments were transformed so that their centers coincided in the coordinate origin, taking into account the patient orientation and voxel spacing specified in the DICOM header. This lead to a coarse initial image registration. The anteroposterior length l of those regions was 10 cm, the laterolateral width equaled the MRI volume. Depending on the distance between each marker, we chose the craniocaudal height h. Each ROI is aligned parallel to the vertebral end-plates by rotating it by the orthogonal angle of the connecting line of two marker points (see Fig. 3–4).

Subsequently, a three level multi-resolution image-based rigid registration approach precisely registers each ROI with the interventional image combining normalized gradient fields (NGF) [22] as image similarity measure and a Quasi-Newton optimizer. Starting with a rather coarse image resolution, we refined the transformation subsequently on images of increasing resolution until full resolution was reached (downsampling factor was 0.63). NGF are based on a pointwise (continuous) or voxel-based (discrete) distance measure D of the angle