Registration of portal and hepatic venous phase of MR/CT data for computer-assisted liver surgery planning

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Abstract. The exact localization of intrahepatic vessels in relation to a tumour is an important issue in oncological liver surgery. For computer-assisted preoperative planning of surgical procedures high quality vessel models are required. In this work we show how to generate such models on the basis of registered CT or MRI data at different phases of contrast agent propagation. We combine well-established intensity-based rigid and non-rigid registration approaches using Mutual Information as distance measure with a masking strategy as well as intensity inhomogeneity correction for MRI data. Non-rigid deformations are modeled by multilevel cubic B-splines. Quantitative evaluations of 5 MRI and 5 CT image pairs show that the liver moves rigidly 7.1 (+/- 4.2) mm on average, while the remaining non-rigid deformations range from 2-3 mm. As a result we find that masked rigid registration is necessary and in many cases also sufficient. After non-rigid registration the matching shows no deviations in most cases.

Keywords: non-rigid registration; liver; computer-assisted surgery; preoperative planning.

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1. Introduction

Surgical removal of primary tumours and metastases from the liver is a potentially curative therapy. The location of the tumour in relation to the vascular system of the liver has a strong influence on the operability decision and resection strategy. High quality geometric computer models of the liver tissue as well as the vascular system may support the surgeon in planning and implementing liver resections. They can provide

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(a) (b) (c)

Fig. 1. Portal (dark grey) and hepatic (light grey) veins are displayed in the PV (a) and the HV (b) phase. A combination of portal veins from the PV and hepatic veins from the HV phase is visualized in c).

precise resection proposals [1] and guide intra-operative procedures [2,3]. A sufficient blood supply via the portal veins and blood drainage via the hepatic veins has to be ensured after tumour resection. The planning procedure is based on preoperative CT or MRI data under contrast agent injection. The problem is that portal and hepatic veins are imaged in two consecutive acquisitions: In the portal venous (PV) phase and in the hepatic venous (HV) phase of the contrast enhancement (see Fig. 1). Accurate registration of PV and HV phase has to be performed in order to compensate for different respiration states of the patient during image acquisition. The aim of this contribution is to investigate the amount of misregistration and how it can be improved by automatic intensity-based registration methods.

Several clinical applications and algorithms concerning the registration of CT or MRI data of the liver have been published. The applications range from radiosurgery [4], control of thermal ablations [5], localization of malignancies in combination with FDG-PET [6] to quantification of tumour volume change over time [7,8]. Intensity-based registration methods using Mutual Information (MI) as similarity measure allowing rigid or even non-rigid transformations prevail. In case of rigid transformations, in all referenced work [4-7] a liver mask is used to restrict the evaluation of the MI value on liver voxels. That means that the motion of the liver in relation to its surroundings has no influence on the registration result except for motion-dependent deformations of the liver itself.

Rohlfing et al. [4] as well as Park et al. [7] apply intensity-based non-rigid registration to correct for these liver deformations. Our non-rigid registration algorithm is similar to the multilevel B-spline technique of Rohlfing et al. [4], but in case of MRI data, an intensity inhomogeneity correction is applied beforehand.

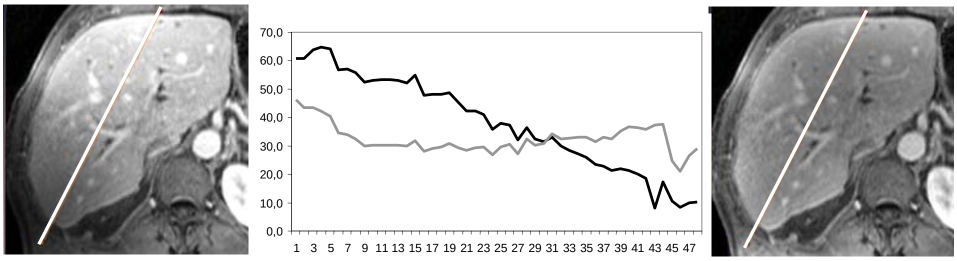

Fig. 2. MR image slice without (left) and with inhomogeneity correction (right). The graph in the middle shows a grey value profile of the original (black) and corrected (grey) image data. The position of the profile is visualized in the image slice.

2. Methods

A rigid and a non-rigid registration approach have been implemented using Normalized Mutual Information as the similarity measure. The rigid implementation is the standard multiresolution method of Studholme et al. [9] To improve the accuracy only voxels inside the liver were considered in the similarity measure (masking). This was easily possible because a segmentation of the liver in one phase was made for the planning anyway.

The intensity-based non-rigid registration algorithm is an implementation of the technique introduced by Rueckert et al. [10] and Rohlfing et al. [11]. The algorithm determines the set of parameters of a deformation T that maximizes the image similarity measure. The transformation model is a free-form deformation defined on a discrete uniform control point grid (CPG) with cubic B-spline interpolation between adjacent control points. The optimization of the similarity measure is done in a combined multiresolution (data pyramid) and multigrid (parameter pyramid) fashion in order to avoid local minima. In case of MR data it turned out that it was necessary to pre-process the images in order to reduce the intensity inhomogeneity using a method of Likar et al. [12] (see Fig. 2).

3. Results

We applied the rigid and non-rigid registration method to 5 contrast-enhanced MR and 5 contrast-enhanced CT data pairs of the liver. For MR imaging a VIBE sequence with 2.5 mm slice thickness was acquired. The CT data had a collimation of 5mm and a reconstruction interval of 2 mm. We used the transformed vessel centre lines of the portal veins to quantify deviations between rigid (masked and unmasked) and non-rigid registration (see Table. 1). Rigid registration with masking leads to significantly more accurate results than without masking. The RMS deviation between masked and

Table 1
The RMS distances in mm between differently transformed portal vein centre lines are listed. The first row specifies the movement of the centre lines between their original position and their position after masked rigid registration. In the second row, differences between rigid registration with and without masking are given. The last row quantifies the centre lines movements between masked rigid and non-rigid registration.

	CT1	***CT2***	***CT3***	***CT4***	***CT5***	***MR1***	***MR2***	***MR3***	***MR4***	***MR5***	***AVG***
Initial to rigid masked	9.2	1.4	1.3	3.2	12.3	4.6	7.1	10.0	11.0	11.1	**7.2 (+/- 4.2)**
Rigid to rigid masked	5.2	1.6	0.7	2.0	3.8	3.5	5.7	5.2	5.6	5.8	**3.9 (+/- 1.9)**
Rigid masked to non-rigid	3.0	1.6	1.4	1.6	2.8	1.5	2.4	1.9	3.0	2.3	**2.2 (+/- 0.6)**

unmasked registered centre lines was between 3.5 and 5.8 mm for the MR data and 0.7 to 5.2 mm for the CT data. The RMS deviation between masked rigid registration and the start position of the centre lines was 4.6 to 11.1 mm for the MR data and 1.3 to 12.3 mm for the CT data. In all cases masked rigid registration provides quiet accurate and better results than the not masked rigid registration. The remaining inaccuracies were determined by visual inspection of all slices with the intersecting vessel surface of the other phase and interactive measurement of the observed deviations. The deviations were in the range of 2-3 mm at some vessel segments. The RMS deviations between rigidly and non-rigidly registered centre lines were between 1.5 and 3.0 mm for the MR data and 1.4 to 2.8 mm for the CT data. In all 10 cases non-rigid registration further improves the accuracy. Only in one case of the MR data minor deviations for some vessel segments occur.

A combined presentation of the portal veins in the portal venous (transparent) and in the hepatic venous phase before and after registration is shown in Fig. 3. Three example slices of a portal venous phase with intersecting vessel surfaces of the hepatic venous phase are illustrated in Fig. 4 after masked rigid registration and after non-rigid registration.

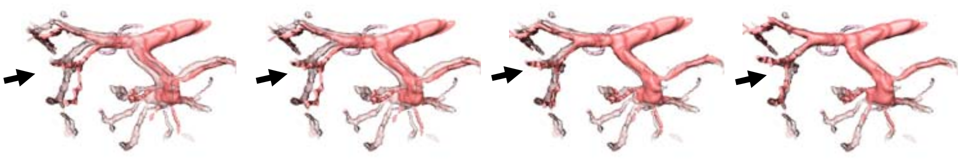

Fig. 3. Portal veins are extracted from PV phase (transparent) and SV phase (solid) of MR1**,** whereas SV phase is shown at original position (a), rigidly registered without masking (b) rigidly registered with masking (c) and non-rigidly registered (d).

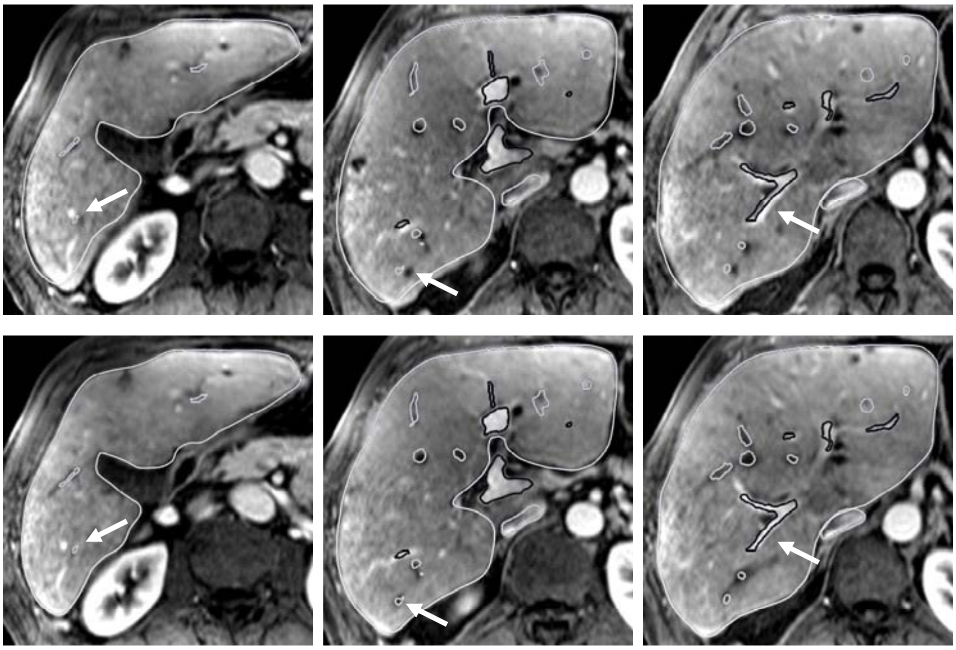

Fig. 4. Three different axial slices of the PV phase of data set MR4 with intersecting liver surface (white), vena cava (light grey), portal (black) and hepatic veins (light grey) of the SV phase. The upper row shows results after rigid registration (with masking) and the lower row after non-rigid registration.

4. Conclusions

In almost all cases (8 out of 10) at least rigid registration had to be performed to get satisfactory results. Up to 12 mm were the vessels moved by the masked rigid registration algorithm. Only in two cases of the CT data the vessels and also the liver surfaces were initially quiet well aligned (only 1.4 and 1.3 mm change by the masked rigid registration method). The masking of the liver significantly improves rigid registration. In all cases the remaining differences between model and reference vessels were not big, but the accuracy can be improved by non-rigid registration in the range of 2-3 mm. The B-Spline based parametric non-rigid registration algorithm provides robustly very accurate results. In case of MR data an important prerequisite for successful non-rigid registration is intensity inhomogeneity correction.

If very accurate models for liver surgery planning and/or intraoperative registration are needed B-spline non-rigid registration is a good choice to register portal and hepatic venous phases of CT or MR data.

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