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DOI:

[10.1007/978-3-030-33642-4_15](https://doi.org/10.1007/978-3-030-33642-4_15)

Document Version

Peer reviewed version

[Link to publication record in King's Research Portal](#)

Citation for published version (APA):

Drobny, D., Ranzini, M., Ourselin, S., Vercauteren, T., & Modat, M. (2019). Landmark-based evaluation of a block-matching registration framework on the RESECT pre- and intra-operative brain image data set. In L. Zhou, N. Heller, Y. Shi, D. Chen, X. S. Hu, Y. Xiao, R. Sznitman, V. Cheplygina, D. Mateus, E. Trucco, M. Chabanas, H. Rivaz, & I. Reinertsen (Eds.), *Large-Scale Annotation of Biomedical Data and Expert Label Synthesis and Hardware Aware Learning for Medical Imaging and Computer Assisted Intervention - International Workshops, LABELS 2019, HAL-MICCAI 2019, and CuRIOUS 2019, held in Conjunction with MICCAI 2019, Proceedings* (pp. 136-144). (Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics); Vol. 11851 LNCS). SPRINGER. https://doi.org/10.1007/978-3-030-33642-4_15

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Landmark-Based Evaluation of a Block-Matching Registration Framework on the RESECT Pre- and Intra-Operative Brain Image Data Set

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Abstract. In this paper, we describe the application of an established block-matching based registration method to the CuRIOUS 2019 MIC-CAI registration challenge. Directional and symmetric approaches with different parameters are evaluated to select the most suitable setting of this fully automatic and general registration method. The results can be used as a baseline, for example when evaluating methods specialised in ultrasound (US) to MRI registration or registration of different interventional US (iUS) data. This work is a continuation of our contribution to the CuRIOUS 2018 challenge. We provide a more extensive analysis of main parameters as well as add pre- to post-resection iUS registration to the previous MRI-iUS registration. The proposed approach achieves an average target registration error of 2.68 mm and 1.92 mm for the MR-iUS and the iUS-iUS task respectively.

Keywords: block-matching · symmetric registration · resection · brain shift · fully automatic · MRI · iUS.

1 Introduction

Brain tumour resection procedures can benefit from navigated surgery systems which allow displaying tumour segmentations, surgery plans, or regions of interest. The accuracy of the displayed information can be impaired by changes in the soft brain tissue. Intra-operative imaging techniques such as interventional ultrasound (iUS) can provide data of the current anatomy which can be used to update pre-operative images. However accurate image registration is required to establish meaningful correspondences of the pre- and intra-operative images.

The CuRIOUS 2019 MICCAI challenge aims at comparing state of the art registration methods in two tasks: aligning pre-operative MR images with iUS images before tumour resection (in continuation of the 2018 challenge [1]) and aligning iUS images before and after resection.

In this work, we evaluate a method which uses a block-matching approach to fully automatically solve both registration tasks. This registration method is well established and yields good results in different applications [2,3]. As this approach is not specialised to the registration challenge at hand, the results can provide a baseline when comparing to domain-specific approaches. We provide an analysis of important parameters of the registration framework and insight into its limitations. We finally demonstrate registration results for this data set that can be achieved by an out of the box approach.

2 Methods

Registration algorithms that align one image to a fixed reference image can introduce a directional bias, i.e. results and derived metrics can vary depending on which image is kept fixed and which is transformed. This has been shown, for example, in brain atrophy evaluation [8]. Symmetric approaches overcome this bias by generating a transformation that can be applied in both directions. Other desirable properties like improved capture range, higher accuracy and robustness of the symmetric approach were shown in [5]. The registration framework used for this application is published as part of the NiftyReg open-source software package (version 1.5.61) [4].

2.1 Block-Matching based registration

In the block-matching algorithm, first a set of correspondences of reference image and warped floating image blocks are established independently and then simultaneously used to determine the global transformation parameters by least trimmed squares (LTS) regression [6]. The blocks are determined by splitting the floating image into uniform blocks of four voxel edge length (default value). To improve robustness, only a percentage v of blocks with the highest variance of intensity values is kept in this step. Each of those blocks is compared to all reference image blocks that overlap with at least one voxel. The block with the highest absolute normalised cross-correlation (NCC) is selected as correspondence. The block matching approach is embedded in a multi-resolution scheme with ln levels. The registration is first computed on the $(ln - 1)$ -times down-sampled image. These results are used as an initialisation of the next finer resolution level. This procedure is repeated until the full resolution images are registered. The coarse-to-fine approach helps to avoid local minima and increases the capture range of the registration while enabling a speed-up of the computation.

2.2 Symmetric registration

Symmetric registration approaches avoid the need to choose which image to select as reference and floating image. Also, it avoids bias, introduced by non-symmetric methods otherwise. Performing both directions of registration at each iteration allows the resulting transformations to be averaged in log-space [5]. This averaged transformation can be used in one direction and its inverse in the opposite direction and can thus be considered bias-free.

2.3 Experimental set-up

The dataset used for this work was published as the RESECT database [7]. It contains 23 cases with pre-operative T2 FLAIR and T1-weighted MR images as well as intra-operative ultrasounds images at three time points of the procedure: after craniotomy and before opening the dura, during the tumour resection, and after resection. Each case is provided with landmark pairs, indicating the correspondence of anatomical landmarks in certain image pairs. Based on those landmarks, the mean target registration error (mTRE) provides a useful metric to describe the quality of the registration result.

In the context of the CuRIOUS 2018 challenge, we showed that the FLAIR MR images are more suitable for the multi-modal registration task compared to the T1-weighted MR images [1]. Accordingly, the experiments of this work focus on the FLAIR MR images as well. The possibility of combining information of both MR images is not being investigated, as the registration framework works on image pairs only. This year’s challenge extends the pre-operative MR to intra-operative US registration task by before and after resection iUS image registration. For both tasks of the challenge, the following three registration settings are investigated: either image used as reference image and the symmetric approach. For each setting, both rigid and affine transformations are evaluated. Furthermore, two important parameters of the registration algorithm—the number of levels of the pyramidal approach, ln , and the percentage of matched blocks, v —are varied. The values used for ln are 2, 3, and 4 and the values for v are 10, 25, and 100. All other parameters are kept as the default values. This totals in 54 configurations per registration task. Based on thresholding each US image with the background value, a mask is generated. Dilating this mask of the iUS image before resection by 20 mm provides an estimate of the search space in the MR image and is used as the MR image mask. The MR image is also cropped to the bounding box of the mask to reduce the image size. No further pre-processing or resampling of the image volumes was applied. The initial alignment of the images was derived from the image header information which was generated by tracking the US probe.

3 Results

The comparison of various registration settings for MR-iUS alignment is shown in Fig. 1. This shows that the choice of reference image has a significant impact

on accuracy. Using the MR image as reference leads to much larger mean target registration errors (mTREs) than the iUS image. The symmetric approach, which combines the two directed registrations, yields results close to the better directional one although almost always worse. The best results have a trimmed mean (i.e. ignoring outliers) around 2 mm while the worst result goes up to 60 mm.

In the comparison of the rigid and affine results of each experiment, the rigid transformation outperforms the affine approach in most cases. Only in the setting with the iUS image taken as reference and combined with low values of ln does the affine transformation provide better registration results than the rigid approach. Increasing the percentage of matched blocks moderately improves the average mTRE and reduces the standard deviation over all the experiments, at the expense of increased computational load. When increasing the number of pyramidal levels, ln , poor results become worse, especially for the affine registrations. This creates a bigger difference between rigid and affine registration for higher levels of ln , making the rigid ones more consistent.

The mTREs of the iUS-iUS registration task (Fig. 2) show a consistent pattern across all parameter settings of ln and v . Using the iUS image after tumour resection as reference leads to the best results with an average mTRE around 2 mm, while the other direction and the symmetric approach show very similar results around 5 mm to 6 mm. In this registration task, affine transformations increase the mTRE in most cases. Similarly to MR-iUS results, higher values of ln increase the impairment of using the affine transformation. Increasing v shows only negligible effects on the mTRE, except for the experiment with the highest ln : Here the lowest value of v significantly increases the mTRE of the affine registration using the iUS after resection as reference, while higher values of v yield results in the same magnitude of all other parameter settings.

Following the evaluation criteria of the CuRIOUS challenge, we select the setting that provides the lowest average mTRE across all available test subjects. Based on the results at hand, we chose the following parameters for both registration tasks: $v = 25$, $ln = 2$. While, for the multi-modal registration task, the affine transformation model yields better results, for the iUS-iUS task the rigid one is chosen instead. Examples of the registration results are visualised in Fig. 3 and show good alignment of structures in both registration tasks. To generate a reference registration which provides the best possible registration given the evaluation metric of mTRE, we computed the affine transformation that minimises the mean landmark distance. The mean TRE of this transformation is referred to as oracle. For both registration tasks, the mTRE of each test case for the rigid and affine registration with the selected parameters is displayed along with the initial landmark distance and the oracle result in Table 1 and Table 2.

The average run time of the affine registration for the MR-iUS registration task is 72 s with GPU utilisation (201 s on CPU only) and 23 s (89 s) for the rigid registration of the iUS-iUS task on a computer with AMD Ryzen Threadripper 1950X CPU and NVIDIA Quadro P6000 GPU.

Fig. 1. Boxplots of the mean TREs of all experiments of the MR-iUS registration task. The mTRE of each case is displayed as a dot on top of the boxplot.

Fig. 2. Boxplots of the mean TREs of all experiments of the iUS-iUS registration task. The mTRE of each case is displayed as a dot on top of the boxplot.

Fig. 3. Axial and sagittal views of the registration results in both tasks—MRI-iUS (left) and iUS-iUS (right)—for case 27. The top row is the initial alignment, the bottom row after registration. The MR FLAIR image is depicted in grey scale, the pre-resection iUS image in magenta, and the post-resection iUS image in green.

4 Discussion

In the two registration tasks of the CuRIOUS 2019 challenge, we observe a directional bias of the results, i.e. one direction outperforms the other one. As a consequence the symmetric approach which combines both directions underperforms. At the same time, the symmetric approach has the lowest standard deviation for the MR-iUS task and has a lower maximum TRE, i.e. the worst case is handled better.

One challenge of the multi-modal registration task is that iUS and MR images have fundamentally different image characteristics: voxel shape and size as well as the field of view are very different. Furthermore, the iUS images are affected by speckles and appear quite noisy. Those factors could explain the performance difference of the directional approaches. On the other hand, the mono-modal registration task shows similar directional bias. Here, the challenge lies in the tissue resection. In the pre-resection image, the tumour tissue is visible, but it has no correspondence in the post-resection image. When the pre-resection image is used as reference, blocks of the post-resection image with high variance are matched to it. The borders of the resected tissue are quite distinct in the post-resection images and are likely chosen for the block-matching. Those blocks do not have a correspondence in the pre-resection image and can thus impair the overall transformation estimation. This conclusion suggests that similar effects could take place in the mono-modal setting as well. Trying to find correspondences of US speckles in the MR image will most likely not provide a constructive match. The MR image is less noisy with clearer structures and is thus more suit-

able to determine the blocks to be matched. Noise reduction, specifically speckle reduction in the ultrasound images might reduce those effects. Different similarity measures than the used NCC might also improve the registration further. Improving the discrepancy between the directional approaches could yield an even better symmetric result whose advantages are currently held back by the bad performance of one directional registration in both tasks. The initial landmark distance is 5.37 mm for the MR-iUS task and 3.55 mm for the iUS-iUS task. Only a few cases have clearly higher mean distance and for these, two levels of the pyramidal approach have a sufficient capture range. Higher values of ln show little effect in the mono-modal task. For the multi-modal task, higher ln even worsen the alignment of many registration settings. If there are already difficulties in finding correct correspondences in the finer levels, coarser levels will not improve this. Increasing the percentage of matched blocks from 10% to 25% improves the mTRE over all settings. Increasing it further to match all floating image blocks does not show a clear advantage but increases the computational

Table 1. Mean TRE in mm per case for the MR-iUS registration task evaluated on all cases with landmark pairs provided for this task. The chosen setting is: reference US, affine, $ln = 2$, and $v = 25$.

case	initial	rigid	affine	oracle
1	1.82	1.70	1.72	1.07
2	5.68	5.32	2.90	1.13
3	9.58	3.40	1.48	0.77
4	2.99	1.52	1.56	0.98
5	12.02	9.90	3.47	0.94
6	3.27	1.87	1.87	0.78
7	1.82	1.42	2.45	1.26
8	2.63	2.51	2.59	1.08
12	19.68	19.16	16.37	0.94
13	4.57	3.54	2.18	0.96
14	3.03	1.50	2.11	1.00
15	3.21	2.39	2.46	1.30
16	3.39	1.95	1.61	0.91
17	6.39	1.90	2.11	1.04
18	3.56	1.28	1.45	0.76
19	3.28	2.22	2.99	0.83
21	4.55	1.78	2.00	0.75
23	7.01	4.04	1.66	0.71
24	1.10	1.63	1.32	0.75
25	10.06	6.91	1.34	0.90
26	2.83	1.33	1.50	0.98
27	5.76	2.09	1.80	1.03
mean	5.37	3.61	2.68	0.95
stddev	4.17	3.97	3.04	0.16

Table 2. Mean TRE in mm per case for the iUS-iUS registration task evaluated on all cases with landmark pairs provided for this task. The chosen setting is: reference US-after, rigid, $ln = 2$, and $v = 25$.

case	initial	rigid	affine	oracle
1	5.80	1.34	2.04	0.97
2	3.65	4.63	5.44	1.62
3	2.91	1.34	7.81	0.68
4	2.22	0.91	2.13	0.56
6	2.12	3.07	4.06	1.25
7	3.62	2.61	3.20	1.47
12	3.97	1.65	1.63	1.10
14	0.63	0.60	0.61	0.45
15	1.63	0.90	0.87	0.72
16	3.13	3.12	2.87	1.09
17	5.71	1.83	2.29	0.97
18	5.29	2.29	2.32	1.16
19	2.05	1.81	3.90	0.89
21	3.35	1.87	1.20	0.81
24	2.61	1.06	1.93	0.64
25	7.61	2.84	5.76	0.92
27	3.98	0.71	0.62	0.47
mean	3.55	1.92	2.86	0.93
stddev	1.70	1.04	1.93	0.32

time. A value of 25% for v thus seems a good choice. Despite these limitations, overall good registration results can be achieved by using this registration framework with mostly default parameters. The initial average landmark distance of 5.37 mm and 3.55 mm was reduced to 2.68 mm and 1.92 mm for the MR-iUS and the iUS-iUS task respectively.

Acknowledgments This work is supported by the UCL EPSRC Centre for Doctoral Training in Medical Imaging [EP/L016478/1], the Wellcome/EPSCRC Centre for Interventional and Surgical Sciences [NS/A000050/1], the Wellcome/EPSCRC Centre for Medical Engineering [WT 203148/Z/16/Z] and EPSRC [NS/A000027/1]. We gratefully acknowledge the support of NVIDIA Corporation with the donation of the Quadro P6000 used for this research. This research was supported by the NIHR BRC based at GSTT and KCL.

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