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A novel tool for monitoring and assessing the outcome of thermal ablations of hepatic lesions

Abstract: This paper presents a proof-of-concept intervention monitoring and outcome assessment tool for thermal ablative strategies like microwave ablation of hepatic tumours. For this purpose, simulated 3D+t temperature maps of the ablation progress are combined with liver MR imaging, as well as corresponding segmentations of the lesion and other relevant anatomical structures. The proposed tool mainly consists of a monitoring and validation part, each comprising 2D and 3D visualisations and various modifiable settings. With the aid of the monitoring features, the heat propagation during the ablation progress could be visually tracked, while the validation part of the tool provides the radiologist with comprehensible and detailed feedback to assess the treatment result. Hence, it could enable an immediate validation of the ablation progress and support interventional decision-making. For evaluation purposes, we used an exemplary patient case to demonstrate the benefits of the proposed prototype. This tool could represent a crucial step towards a suitable computerassisted and more accurate workflow of thermal ablations, with benefits for both, patients and radiologists.

Keywords: MRI thermometry, hepatic tumours, thermal ablations, treatment monitoring, treatment outcome assessment

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1 Introduction

Regarding non-resectable primary and metastatic hepatic lesions, percutaneous microwave ablation represents an efficient, tissue-sparing and gentle treatment technique [1]. In terms of treatment success of such thermal ablative interventions, the most important factor is the coverage of the

lesion including a minimal ablative margin (MAM) of approx. 5 mm by the resulting necrosis zone [2]. A robust estimation of the necrosis was found to be one of the most predictive factors regarding tumour recurrence [2, 3]. However, current clinical practice relies mostly on side-by-side comparison of pre- and post-interventional images with simple measurement tools [1]. This promotes rather subjective assessments and significant inter-reader variability [4]. Various works tried to address these limitations by (semi-)automatic fusion of pre- and post-interventional images and a more direct comparison of lesion and necrosis [1, 3].

In contrast, interventional MR thermometry represents a strategy to monitor the progress and intra-interventionally assess the treatment success of thermal ablative techniques [5, 6]. Due to near-real-time imaging and conversion into temperature maps, the radiologists could visually track the heat propagation and therefore, estimate the accomplishment of the treatment goal. Applying the temperature maps to different 'cell death prediction (CDP) models' result in necrosis zone predictions, that enable a direct and immediate assessment of the treatment outcome. Such temperature mapdefined necrosis zones were found to be of convincing predictive power compared with follow-up imaging examination results [5, 6]. Hence, visual and quantitative feedback of the ablation process during the intervention could enhance interventional decision-making. Furthermore, it could reduce the necessity of corrective interventions due to avoidable residual tumour fractions prevent disproportional overablation or complications due to heating of nearby risk structures.

With this in mind, the aim of this work was to contribute a prototype of a combined monitoring and treatment outcome validation tool for thermal ablative interventions, especially of hepatic tumours and metastases. In contrast to most of the related work, the proposed tool combines the monitoring and validation aspects and is additionally designed to support and incorporate 3D+t temperature maps, as well as 2D+t MR thermometry slices. Therefore, the presented tool could provide the radiologist with more accurate visual and quantitative feedback regarding the ablation progress and its

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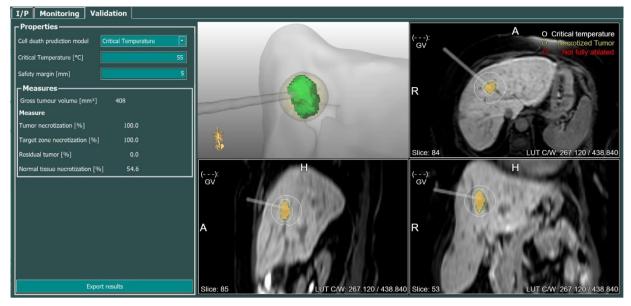


Figure 1: Shown is the validation section of the tool's graphical user interface (GUI), where the user is provided with intuitive bicolour-coded visualisations of the treatment result in 2D and 3D, as well as with corresponding measures (left box). The user can choose between different CDP models and modify their key parameters.

final results. The primary focus was on accessible and intuitively comprehensible visualisations and display of associated measures to monitor and assess the outcome of thermal ablative interventions.

2 Materials and Methods

The proposed tool was prototypically implemented in MeVisLab [7]. Due to the tool's focus on visualisation features and that 3D+t MR thermometry imaging itself is still subject of current research, we replaced it with simulation data for the time being. Accordingly, we used a straightforward and rather simple simulation by a t-times incremental summation of 3D Gauss filtered (kernel size v) images, resulting in a temperature map of size $(x,y,z) \times t$. The initially binary image of t=0 was an empty volume except for a user defined starting point, which represented the applicator needle tip. The characteristics of the Gauss filter ensured a uniformly spherical propagation. By taking into account segmented vessel structures, highly simplified heat sink effects could additionally be simulated [8].

2.1 The proposed tool

The presented tool consists of three main parts, which differ in their underlying purpose and are structured in different tabs within the tool (see Fig. 1): the first part consists of DICOM import functions and pre-processing methods to produce correspondence of the input image volumes in terms of uniform size and spacing (see Fig. 1, tab 'I/P'); the second part

represents the monitoring support; and the third section is for the treatment outcome assessment.

After importing and aligning the required image volumes, i.e., liver MRI planning datasets with corresponding binary segmentation masks as well as the MR thermometry images, the user switches to the monitoring section. In contrast to the future clinical application using near-real-time 3D+t MR thermometry image data, we processed simulated 3D+t temperature maps. But it remains alike, that the user can track the temperature propagation starting from the applicator tip chronological step by step through, both 2D and 3D visualisations (see Fig. 2). Depending on the ablation progress, colour-coded temperature maps and derived iso-temperature contours could be displayed as overlays on the original liver MR image. Furthermore, the priorly segmented lesion is displayed with an adjustable MAM. Besides the visual feedback of the ablation progress in the image viewers, the display of various quantitative parameters, like tumour coverage, elapsed ablation time, induced energy or the portion of necrotised healthy tissue, could help the radiologists with keeping track and to determine the time of achieving the treatment goal.

The third part of the proposed tool focuses on the assessment of the treatment result. The primary objective here is to automatically determine whether or not individual voxels and associated regions can be labelled as fully necrotised based on information derived from the temperature maps. The decision is made with the aid of CDP models. There are different approaches, e.g., CEM43, Arrhenius Damage Integral or Critical Temperature [5, 6]. Since we simulated the heat

propagation at this stage, without information on some of the crucial parameters required for example for the Arrhenius Damage Integral (e.g., accurate ablation time or induced energy), we have chosen the Critical Temperature approach for our feasibility demonstration. This model leads to a voxelwise binary decision depending on whether a critical temperature threshold was exceeded. Thus, we could define a binary ablation zone, which was matched with the lesion segmentation and the corresponding MAM. Subsequently, 2D and 3D visualisations with bicolour labelling, i.e., green for fully necrotised and red for residual tumour volume are displayed in the image viewers (see Fig. 2), as well as additional quantitative results, like the crucial tumour coverage measurement are stated. This ensures straightforward and intuitive assessment of the treatment result through image-based and numerical feedback. For adjustment purposes, various parameters can be modified, e.g., the MAM, the CDP model and related parameters like the temperature threshold of the Critical Temperature model. Finally, the binary ablation zone images can be exported as DICOM files and the quantified treatment results as csv-files.

3 Results and Discussion

Due to the proof-of-concept stage of the prototype, no comprehensive user studies have been carried out so far. Therefore, to evaluate the proposed tool and its features, it is suitable to refer to the requirements for clinical applicability defined by our clinical partner. The required feature range must cover the following:

- 1. DICOM image import and pre-processing
- Display of all relevant structures (lesions, risk organs, vessels)
- Real-time monitoring of the ablation progress (visual, quantitative)
- 4. Computer-assisted assessment of the treatment outcome
- 5. Export/record of the treatment results

So far most of the related work solely focussed either on the treatment outcome validation part [1, 3] or on retrospective assessments of the accuracy of MR thermometry-based intervention monitoring [5, 6]. To the best of our knowledge, the proposed tool is the first to combine both aspects in a single framework for intra-interventional support. Most commonly, the treatment results are assessed by comparing lesion and necrosis zone segmentations by matching pre- and post-interventional images [1, 3]. In contrast, due to the incorporation of MR thermometry data the presented tool

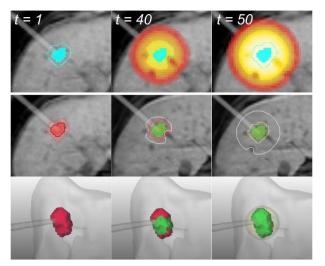


Figure 2: Shown are visualisations of three time points during the ablation process. The top row images were taken from the monitoring part and display the lesion with MAM (blue) as well as superimposed temperature maps including iso-temperature zones. Both bottom rows originated from the validation part of the tool and visualise the treatment result that would have been achieved by the respective ablation time. A CDP model (critical iso-temperature contour in white) decides whether voxels are classified as necrotised (green) or not (red). Only if the complete area within the MAM is fully necrotised the MAM turns green.

could promote direct and immediate assessments and thus, support decision-making during the interventions, without the need to wait for follow-up imaging. Providing features for visual and quantitative monitoring of the ablation progress could not only result in a more accurate lesion ablation with optimised sparing of healthy tissue, but also in the avoidance of subsequent interventions due to incomplete tumour control. Furthermore, due to the implemented CDP models, automatically derived necrosis zones are defined and used to visually and quantitatively support treatment outcome assessments by the radiologist. Existing limitations of 2D MR thermometry-based approaches regarding the accuracy of necrosis zone predictions could be addressed with our tool, which was specially designed to incorporate 3D volumetric image data [5, 6].

In terms of the priorly defined requirements to ensure a clinical benefit, our proposed tool covers all of the specified functions (requirement 1 to 5), except for the current limitation of a missing interface for a direct incorporation of near-real-time MR thermometry data (e.g., Siemens' Access-I integration). Due to the proof-of-concept stage of the prototype and the lack of suitable study data, we replaced it with retrospective simulations of the heat propagation. Furthermore, the segmentation of relevant structures (requirement 2) as well as image fusion procedures for registering the morphologic and MR thermometry images that exceed rigid approaches (requirement 1), still have to be performed outside the framework, but should reasonably be integrated in the future.

3.1 Exemplary patient case

For demonstration purposes we applied an exemplary patient case. A T₁-weighted liver MR planning image volume of the hepatobiliary phase with corresponding binary segmentation masks of the liver, lesion (size of 408 mm³) and some surrounding vessels were used as input. All images were resampled to the size 1283. The user specified the applicator needle tip and therefore, the starting point of the heat propagation. The latter was simulated for 50 time steps (could correspond, e.g., to a total ablation time of 15 min with every 18 s a new generated 3D temperature map). The propagation speed v was roughly 1°C per time step and voxel. The measures to assess the treatment result dependent on the ablation progress can be seen in Table 1. In this example, the target lesion would have to be ablated for ~13.5 min until full tumour coverage was achieved. However, the whole area within a MAM of 5 mm would take about 1.5 min longer to be fully ablated, especially due to the simulated heat sink effect near vessel structures (see Fig. 2). In the end, the treatment goal of full tumour coverage including a MAM of 5 mm would have been achieved, although, approx. 55 % of the necrosis zone consisted of healthy tissue outside the MAM.

Table 1: Resulting validation measures dependent on the ablation progress. TN – necrotised tumour fraction, NMAM – necrotised tissue fraction within a MAM of 5 mm, RT – residual tumour fraction, NHT – necrotised healthy tissue fraction beyond a MAM

Measure	Time point t					
	1	30	35	40	45	50
TN [%]	0	6.6	55.5	83.6	100	100
NMAM [%]	0	2.4	25.3	55.8	89.2	100
RT [%]	100	93.4	44.5	16.4	0	0
NHT [%]	0	0	0.3	11	30.4	54.6

4 Conclusion

This work presents a prototype tool to support thermal ablative interventions by visualising and quantifying the ablation progress and by providing valuable feedback to support the assessment of the treatment results. For this purpose, the proposed tool combines suitable 2D and 3D visualisations including segmentation masks, colour-coded temperature maps with corresponding iso-temperature contours as well as comprehensible and intuitive bicolour representations of the treatment result. In combination with quantitative feedback, the proposed tool could support the radiologist in intra-

interventional decision-making and lead to more accurate ablation results.

In future work, the direct incorporation of near-real-time MR thermometry data will enable advanced studies regarding the accuracy of necrosis prediction, as well as detailed usability studies.

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