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Original paper

Investigation of the XCAT phantom as a validation tool in cardiac MRI tracking algorithms

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ABSTRACT

Purpose: To describe our magnetic resonance imaging (MRI) simulated implementation of the 4D digital extended cardio torso (XCAT) phantom to validate our previously developed cardiac tracking techniques. Real-time tracking will play an important role in the non-invasive treatment of atrial fibrillation with MRI-guided radiosurgery. In addition, to show how quantifiable measures of tracking accuracy and patient-specific physiology could influence MRI tracking algorithm design.

Methods: Twenty virtual patients were subjected to simulated MRI scans that closely model the proposed real-world scenario to allow verification of the tracking technique's algorithm. The generated phantoms provide ground-truth motions which were compared to the target motions output from our tracking algorithm. The patient-specific tracking error, e_p, was the 3D difference (vector length) between the ground-truth and algorithm trajectories. The tracking errors of two combinations of new tracking algorithm functions that were anticipated to improve tracking accuracy were studied. Additionally, the correlation of key physiological parameters with tracking accuracy was investigated.

Results: Our original cardiac tracking algorithm resulted in a mean tracking error of 3.7 ± 0.6 mm over all virtual patients. The two combinations of tracking functions demonstrated comparable mean tracking errors however indicating that the optimal tracking algorithm may be patient-specific.

Conclusions: Current and future MRI tracking strategies are likely to benefit from this virtual validation method since no time-resolved 4D ground-truth signal can currently be derived from purely image-based studies.

1. Introduction

Magnetic resonance imaging (MRI)-based tracking strategies for the use in emerging MRI-guided radiotherapy systems have demonstrated the ability to precisely localize and follow organ and tumor position in real-time scenarios [1,2]. Ideally, these tracking applications would utilize MRI sequences that can acquire time-resolved target volumes in real-time (4D). However, this is often restricted due to the complexities of 4D-MRI [3]. A number of recent studies utilize real-time interleaved orthogonal 2D cine-MRI slices [4–7] to provide real-time information about the target position in an effort to compensate for the lack of real 4D MRI data. Template matching [8,9] is a common localization technique where a previously acquired volume-of-interest is matched to a target image, in this case fast acquired 2D MRI planes. Other localization strategies utilizing orthogonal MRI focus on automatic feature extraction for motion prediction [10,11].

A recent study by Ipsen et al. [12] suggested that a non-invasive treatment of atrial fibrillation (AF), the most common cardiac arrhythmia with millions of patients worldwide [13], could be facilitated by using an MRI linear accelerator (MRI-linac) with real-time image guidance. Despite the spatial and temporal limitations of 4D-MRI for this purpose, a guidance method incorporating a cardiac tracking algorithm was developed. Similar to previous approaches [2,8] the target, i.e. the left atrium (LA), and its 3D position during the proposed radiosurgery is detected through template matching of a pre-treatment target volume to orthogonal real-time planes [14]. Orthogonal real-time planes are used in an effort to provide adequate positional information in all anatomical planes (i.e. sagittal, coronal, axial). The

Abbreviations: AF, atrial fibrillation; AP, anterior posterior; DICOM, Digital Imaging and Communications in Medicine; ECG, electrocardiogram; FLASH, fast low-angle shot; LA, left atrium; LR, left right; MRI, magnetic resonance imaging; MRI-linac, MRI linear accelerator; SI, superior inferior; TrueFISP, fast steady-state free precession; XCAT, 4D digital extended cardio torso

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temporal acquisition times of the real-time planes are more appropriate than that of complete 3D MRI volumes when tracking complex cardiac and respiratory motion. The template matching calculates similarity between the target volume image and the real-time planes to assign 'best-match' 3D positions during the proposed treatment. To account for the rapid target deformations caused by the heartbeat, an electrocardiogram (ECG) surrogate and a multi-phase template were incorporated into the method. The ECG signal determines which pre-treatment template will be used in the matching process.

New tracking strategies, such as our cardiac tracking algorithm, could directly improve treatment quality due to their ability to visualize internal moving organs in real-time with superior soft-tissue contrast and without using ionizing radiation. However, in a clinical scenario the economic and time-related burdens on specialists, patients and departments do not always allow rigorous testing of every new method on real patient data. It would be beneficial to assess the accuracy of a specific tracking technique and investigate the influence of different anatomical parameters on the approach before moving towards clinical implementation and patient studies. This is particularly relevant in developing MRI integrated radiotherapy units [15,16] where a number of image-guided treatment scenarios have been proposed [7,17]. Physical phantoms could be an alternative but are restricted in their modeling of realistic patient physiology, especially reproducible deformation, and fabrication cost. The previously described lack of real-time volumetric MRI data increases the challenge of validating the accuracy of MRI tracking strategies in general since a time-resolved ground-truth can merely be approximated.

Digital phantoms allow simulation of realistic patient anatomy and physiology. They also provide a desirable tool in exploring and developing novel image interpretations studies because of the known and quantifiable 4D phantom anatomy. A number of digital phantoms have been developed for use in medical imaging analysis [18–22]. Organ-specific digital phantoms [21,22] are generally designed for a specific image analysis investigation, restricting their use as a tool in tracking validations of multi-organ systems. In contrast, the 4D digital extended cardio torso (XCAT) phantom [19,20] has the ability to model a wide range of patient anatomies, provides a realistic interaction of multiple organs and a multitude of simulated imaging modalities. These design features of the XCAT phantom, described in detail in the literature [19,20], make it a suitable validation tool for various tracking applications. The XCAT phantom has been used periodically in experimental investigations, e.g. to simulate realistic cardiac MRI on a virtual patient cohort of 40 digital phantoms [23], for the modeling of regional heart defects caused by ischemia with incorporation of a finite-element model [24] and in respiration-focused modeling applications. The respiration-focused modeling applications include the verification of reproducible patient-specific diaphragm and chest motion traces for lung cancer radiotherapy [25], the validation of novel 4D-MRI techniques which image respiratory motion [26] and an analysis of audiovisual biofeedback and gating on thoracic-abdominal 4D computed tomography [27].

In Ipsen et al. [14] the XCAT phantom was first utilized to validate the MRI cardiac tracking algorithm by comparing the developed method's target trajectories with a ground-truth trajectory output from the XCAT phantom. Here, we now describe in detail the implementation of the XCAT phantom to validate and assess our cardiac tracking techniques and show how this quantifiable measure of tracking accuracy and patient-specific physiology could influence and improve MRI tracking algorithm design.

2. Methods and materials

2.1. Virtual patient dataset

To cover a range of different patient anatomies we generated a virtual dataset of 20 patients by using different XCAT phantom parameter sets and utilized the digital phantom's ability to control anatomical and physiological parameters, in addition to its MRI simulation capabilities. Six specific anatomical parameters of the XCAT's initialization file were anticipated to strongly influence algorithmic tracking robustness and were varied across the 20 virtual patients. These were LA volume, heart rate, respiratory rate and cardiac respiratory motion broken into its three constituent components – superior inferior (SI), anterior posterior (AP) and left right (LR). The three motion-related parameters (heart rate, respiratory rate and respiratory motion) can be manipulated directly in the XCAT parameter initialization file while the LA volume was controlled indirectly by either scaling the entire phantom or scaling the heart only. Both scaling factors were varied for all 20 virtual patients in the XCAT parameter initialization file

To date, only healthy volunteers have been included in our cardiac tracking research [12,14]. For comparability, the virtual dataset was designed to replicate this digitally. Anatomical parameters of the virtual patients were randomly generated based on distributions (mean and sample standard deviation) from our previous studies [12,14], and taken from literature when appropriate data was unavailable. The reference values and sources are shown in Table 1. The individual XCAT patients' parameters are shown in Table 2.

Table 1
Reference values and sources for the physiological parameters of the 4D extended cardiac-torso (XCAT) virtual study.

Parameter	Reference value (mean ± SD)	Reference source
LA max-diastolic volume (ml)	103 ± 30	Hudsmith et al. [28]
Heart rate (bpm)	58.3 ± 10.3	ECG data from our scanned volunteers [12,14]
Respiratory rate (cycles per min)	13.5 ± 1.5	Ganong and Barrett [29]
LA respiratory motion LR (mm)	3.1 ± 1.1	Ipsen et al. [14]
LA respiratory motion AP (mm)	5.8 ± 3.5	Ipsen et al. [14]
LA respiratory motion SI (mm)	16.5 ± 8.0	Ipsen et al. [14]

Table 2
Individual physiological parameter values of the 20 4D extended cardiac-torso (XCAT) virtual patients.

Patient	Maximal LA volume (ml)	LA respiratory motion			Heart rate (bpm)	Respiratory rate (cycles per min)
		AP (mm)	LR (mm)	SI (mm)		
1	73.1	14.0	1.2	27.0	65	14.4
2	88.6	10.1	2.7	16.7	66	15.2
3	104.8	1.0	4.9	15.6	75	13.1
4	92.1	8.5	2.1	25.5	59	13.9
5	104.0	6.5	5.2	9.6	68	11.5
6	79.5	8.5	2.6	12.0	54	15.5
7	102.2	7.2	1.2	14.8	42	10.8
8	77.3	2.7	4.0	11.8	64	13.0
9	69.0	6.8	2.7	23.1	69	16.5
10	103.5	7.4	3.5	23.5	64	12.0
11	119.8	5.8	2.5	8.4	48	13.2
12	55.2	7.1	3.3	16.9	50	11.6
13	89.7	2.9	3.9	9.3	56	13.0
14	122.6	14.7	4.2	15.5	54	10.5
15	49.4	1.8	2.5	17.2	79	14.6
16	94.6	6.4	4.5	26.7	78	13.6
17	103.5	8.8	3.9	11.9	64	12.5
18	82.7	0.7	2.1	22.9	48	12.7
19	90.9	4.7	2.6	4.6	55	13.8
20	71.0	11.1	3.3	19.2	60	15.6