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Deformable respiratory motion correction for hepatic rotational angiography

Alexandra Klugmann[a,1], Bastian Bier[a,1], Kerstin Müller[b], Andreas Maier[a], Mathias Unberath[a,c,*]

[a] Pattern Recognition Lab, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany
[b] Radiological Sciences Lab, Stanford University, United States
[c] Computer Aided Medical Procedures, Johns Hopkins University, United States

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ABSTRACT

Cone-beam rotational angiography enables 3D imaging of the hepatic vasculature and is considered beneficial for guidance of transcatheter arterial chemoembolization procedures. Respiratory motion during the rotational acquisition challenges state-of-the-art reconstruction algorithms as intra-scan motion leads to inconsistencies causing substantial blurring and streaking artifacts in uncompensated reconstructions, suggesting the need for motion correction.

We propose an automated method for respiratory motion estimation and compensation based on registration of an initial 3D arterial model to vesselness enhanced 2D projection images. Centerline points of the arterial tree are modeled as B-splines over time, the control point positions of which are optimized using α-expansion moves on graph cuts. This approach naturally allows for the estimation of 3D rigid translations as well as non-rigid deformations.

Applied to a pre-clinical and a clinical acquisition, the proposed methods resulted in notable reductions in reprojection error and increased vessel sharpness that are reflected in less streaking and blurring artifact compared to the uncompensated case, implying superior vessel contrast. As the proposed methods are generic, future work will investigate their applicability to related rotational angiography imaging protocols, such as coronary angiography.

1. Introduction

Transcatheter arterial chemoembolization (TACE) is a minimally invasive, catheter-based bridge therapy for hepatocellular carcinoma (Llovet et al., 2002) and metastatic liver tumors (Brown et al., 2006; Virmani et al., 2007). TACE relies on intra-arterial injection of small particles, such as ethiodized oil, cancer medication or gold particles, to artificially occlude vessels that feed the tumor with oxygenated blood (Wang et al., 2018). Consequently, accurate knowledge of feeding vessels is key for successful treatment (Virmani et al., 2007; Iwazawa et al., 2009). These vessels are traditionally identified based on 2D fluoroscopy images, i.e., digital subtraction angiography (DSA) (Virmani et al., 2007), that are acquired with interventional C-arm angiography systems. Unfortunately, 2D images suffer from the effects of projective simplification, such as foreshortening and overlapping, that complicate diagnostic assessment.

Modern C-arm scanners, however, are motorized and allow for the acquisition of multiple fluoroscopy images while the X-ray source and detector rotate on a circular orbit around the patient (Zeng, 2010). During X-ray acquisition, the vasculature is selectively contrasted by intra-luminal injection of a contrast agent. This imaging protocol is commonly referred to as cone-beam CT (CBCT) or rotational angiography and allows for 3D reconstruction of the vascular anatomy. Clinical studies comparing CBCT to DSA for identifying feeding vessels suggest that providing physicians with the accurate 3D vascular anatomy is potentially beneficial (Iwazawa et al., 2009; Miyayama et al., 2009; Pung et al., 2017).

However, obtaining high quality reconstructions of the hepatic vasculature from rotational angiography is still challenging due to intra-scan motion that leads to image artifacts in the reconstructed 3D image volumes. The liver is strongly affected by respiratory motion due to its anatomical proximity to the diaphragm that drives diaphragmatic breathing. Hepatic motion due to respiration is largest along the cranial–caudal patient axis (5–25 mm) but has components in anterior–posterior (1–12 mm) and in left–right (1–3 mm) direction (Von Siebenthal, 2008).

* Corresponding author at: Computer Aided Medical Procedures, Johns Hopkins University, United States.
E-mail address: unberath@jhu.edu (M. Unberath).
[1] These authors have contributed equally.

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A common way to circumvent intra-scan respiratory motion is requiring patients to hold their breath (Unberath et al., 2017a,b,c; Tognolini et al., 2010a,b). Due to the relatively long acquisition time of about 6 s for a single CBCT scan, residual respiratory motion from imperfect breath-hold is a common corruption mechanism that leads to double edges, streaking, and blurring in uncompensated 3D reconstructions. Consequently, motion correction strategies have to be devised to achieve acceptable image quality.

In literature, many approaches are known that seek to assign motion phases to the acquired images. Assuming that multiple respiration cycles are observed, the phase information can be used to extract consistent images, so-called *bins* or *gates*, that are input to 3D reconstruction algorithms. The phase assignment can be performed using external devices (Geimer et al., 2016), such as respiration belts (Wilms et al., 2014). However, this requires the use of additional equipment that has to be synchronized to the acquired data. To overcome this limitation, other approaches extract surrogate signals from the acquired projection images directly. These approaches usually exploit that diaphragm motion is highly correlated with respiratory motion (Von Siebenthal, 2008; Balter et al., 2001). Sonke et al. (2005) use the Amsterdam shroud to derive a surrogate signal by horizontally aligning the diaphragm position in all images. These approaches are elegant, as they avoid explicit motion compensation.

Unfortunately, they are not applicable in CBCT angiography since the observed motion patterns are not periodic. When motion compensation is applied, the diaphragm position can be used to directly estimate respiratory motion of the liver. This course of action is particularly well suited for the upper parts of the liver and motion estimation along the cranial–caudal direction (Balter et al., 2001). In an animal model, Schäfer et al. show that compensation using the projection domain diaphragm displacement is possible. The method handles large displacements but requires sophisticated segmentation of the 3D anatomy, i.e. the ribcage and the diaphragm, in an uncompensated reconstruction (Schäfer et al., 2012). Bögel et al. (2013) automatically track the diaphragm contour in the projection image sequence and use a motion-corrected triangulation approach on the diaphragm vertex to estimate 3D motion patterns via thin-plate-spline interpolation that are used to compensate for respiratory motion. While this method does not require segmentation in 3D, the estimated motion is valid only within a narrow target region around the diaphragm. More recent, Sindel et al. (2015) extended this approach by tracking not only the motion of the diaphragm but also a vessel bifurcation to achieve a more reliable motion estimation within the liver. Whilst achieving substantial improvements in reconstruction image quality, the method requires manual tracking of the bifurcation over the complete sequence, making its application cumbersome and time consuming.

2. Materials and methods

In this work, we propose a novel method to compensate for residual respiratory motion in rotational angiography acquisitions. The main contribution of our method is a 2D/3D registration of the contrasted hepatic vasculature. To this end, the 3D vessel tree, extracted from an uncompensated reconstruction, is forward projected and registered to the 2D projection images. Motion is expressed using a B-spline-based motion model, which is able to account for both rigid translational and non-rigid motion. We evaluate the method on two datasets: a porcine model and a clinically acquired dataset. Evaluation is performed qualitatively and quantitatively, using the reprojection error as well as the vessel sharpness.

An overview over the proposed method is shown in Fig. 1. The algorithm uses the stack of acquired projections of the contrast enhanced hepatic vasculature that contains intra-scan motion. Before starting the motion estimation using 2D/3D registration, the projection data has to be preprocessed. To this end, the 2D images are reconstructed in a first step in order to obtain a motion-corrupted reconstruction (Step 1).

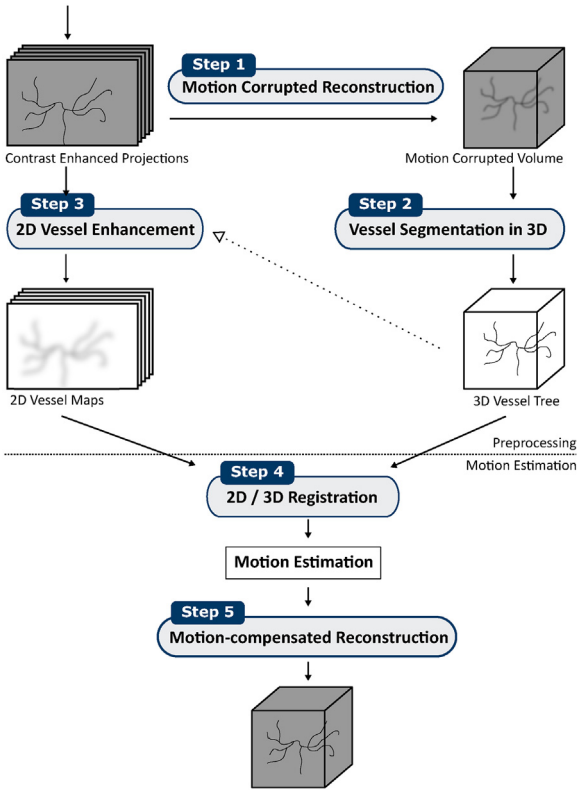

Fig. 1. Illustration of the processing pipeline for respiratory motion-compensated 3D reconstruction.

Afterwards, the 3D vessel tree is segmented from this volume (Step 2) and projected onto the 2D images to define the vessel regions. Within these regions, we apply vessel enhancing filters to the acquired 2D projection images (Step 3). Finally, motion is estimated by registration of the 3D vessel tree to the 2D vessel maps (Step 4), yielding the intra-scan motion estimate. By incorporation of this estimate in the reconstruction, a motion-compensated reconstruction is obtained (Step 5).

2.1. Data

The data used in this work are from a rotational cone-beam C-arm angiography acquisition. In such a setup, the X-ray source and detector are mounted on a C-shaped gantry that rotates around the patient on a circular trajectory. While acquiring projection images of the liver from different angles an iodine-based contrast agent is injected into the hepatic vasculature that selectively contrasts the vessel lumen.

In this work, two sequences were acquired using the same imaging protocol that consist of 396 projection images acquired over 200° on a circular source trajectory over approximately 6 s. Each projection image has 620 × 480 pixels with an isotropic pixel size of 0.616 mm. During acquisition, contrast agent was injected with a power injector (Medtron, Saarbrücken, Germany) into the hepatic artery. All reconstructions are performed on a voxel grid of 448 × 448 × 448 voxels with an isotropic voxel size of 0.5 mm.

The first dataset (D1) is taken from an animal study on a porcine model. This dataset shows substantial respiratory motion that is also observable in projection domain. The second dataset (D2) shows a clinical dataset scanned during breath-hold. In this case, we observe residual respiratory motion only that still decreases image quality and diagnostic value.