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Constrained Bayesian Streak Artifact Reduction Approach for Contrast Enhanced Computed Tomography Imaging of the Intervertebral Disc

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Abstract— **A promising approach for the study of progressive herniation damage of the intervertebral discs under flexion/extension motions as well as compressive loads is the use of contrast-enhanced computed tomography (CECT). One of the biggest limitations of using CECT is the presence of significant streak artifacts in the acquired tomograms, due primarily to the contrast agent injected into the intervertebral disc. To address this issue, a novel constrained Bayesian approach to streak artifact reduction in CECT imagery is introduced in this paper. The problem of artifact reduction is formulated as a constrained Bayesian estimation problem in projection space, and a non-parametric Parzen window estimation approach is employed to estimate the underlying posterior distributions. Experimental results show that the proposed approach provides significant artifact reduction while preserving the intervertebral disc regions to allow for clear visualization of progressive intervertebral disc damage.**

I. INTRODUCTION

Low back pain is amongst the most common disorders experienced by individuals living in industrialized countries [1]. One of the leading causes of low back pain is progressive intervertebral disc damage, where the shock absorbing capabilities normally provided by the intervertebral discs for the individual vertebrae is significantly reduced. It was found in different studies [2], [3] that the major factors associated with intervertebral disc damage are flexion/extension motions as well as compressive loads. Therefore, the study and quantification of intervertebral disc herniation under flexion/extension motions combined with a compressive load can have great potential for furthering our understanding of how such factors can influence and result in low back pain.

While early work in non-destructive methods for studying progressive intervertebral disc damage involved the use of x-ray radiography, it was found in a number of studies that the results produced using such methods exhibit noticeable discordance with the results produced using gold standard destructive dissection methods [4], [5]. As such, alternative non-destructive approaches for studying intervertebral disc herniation damage have been investigated in recent years. Of the methods investigated, one of the most promising approaches for studying intervertebral disc herniation damage was found to be the use of contrast-enhanced computed tomography (CECT). To study intervertebral disc herniation damage via CECT, a radio-opaque contrast agent is injected into the intervertebral disc prior to being scanned using a CT acquisition system. An example CECT slice in the axial plane of the intervertebral disc and the surrounding vertebrae is shown in Fig. 1. As seen in Fig. 1, the intervertebral disc can be clearly discriminated from the surrounding region as saturated bright regions as a result of the contrast agent, making it easier to identify the intervertebral disc. Furthermore, CECT provides greater resolution and material density sensitivity than conventional x-ray radiology, as well as little image distortion. As such, given all these benefits, CECT has shown strong potential for providing better visualization of intervertebral disc herniation damage under flexion/extension motions as well as compression loads in a non-destructive manner.

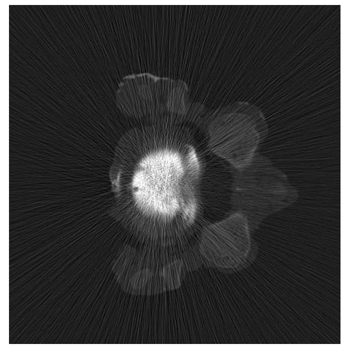

Fig. 1. CECT slice in the axial plane of the intervertebral disc and surrounding vertebrae.

Despite the potential advantages of using CECT for studying progressive intervertebral disc herniation damage, one of the major challenges that prevent such a technique from seeing widespread use is the presence of significant streak artifacts in the acquired data, as shown clearly in Fig. 1. Such prominent streak artifacts is a result of the radio-opaque contrast agent that was injected into the intervertebral disc to enhance the contrast of the disc in the CECT data. Since the contrast agent possesses high material density, the transmitted radiation hitting a detector is reduced to the point where no transmission level is observed, thus violating the basic assumption of CT image acquisition that the transmitted radiation by the acquisition device is observed by all detectors at every position [6]. Such prominent streak artifacts significantly degrades the quality of the CECT data, making it very difficult to visualize and isolate the intervertebral disc to study the morphological changes of the intervertebral disc as a result of progressive herniation damage. Therefore, methods for reducing such streak artifacts are necessary for the widespread proliferation of CECT in progressive intervertebral disc herniation damage.

The problem of reducing streak artifacts in CT data due to dense materials has been tackled using a variety of different

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methods, which can be generally divided into two main groups: i) non-iterative interpolation, and ii) iterative reconstruction. In non-iterative approaches [7], [8], the regions affected by dense materials in projection space is identified and treated as missing data. An interpolation scheme is then employed to fill in the missing data, and the completed data in projection space is then used to reconstruct the CT data. While computationally efficient, such approaches make strict assumptions about the missing data being highly related to the surrounding data used to interpolate these missing regions. This results in poorly reconstructed data, particularly when dealing with large regions of dense materials such as the contrast enhanced intervertebral disc regions we wish to study. In iterative approaches [9], [10], the regions affected by dense materials are also identified in projection space, and iterative reconstruction strategies are applied to better reconstruct the data based on additional prior knowledge. Such methods provide better reconstructions than existing non-iterative linear methods, but are significantly more computationally expensive. Furthermore, such methods have been primarily designed and tested for reducing streak artifacts due to small metal implants such as dental filling and hip protheses, and as such have not had its performance validated for large dense material regions that dominate the data like contrast enhanced intervertebral disc regions.

The main contribution of this paper is a constrained Bayesian approach to streak artifacts in CECT imagery of intervertebral discs. The problem of streak artifact reduction is formulated as a constrained Bayesian estimation problem in projection space, and is subsequently solved in a non-iterative manner via a non-parametric Parzen window estimation approach for learning posterior distributions. Such an approach aims to significantly reduce streak artifacts while preserving the underlying intervertebral disc regions, which is important for accurate study of progressive intervertebral disc herniation damage.

II. Materials and Methods

The following CECT acquisition protocol was used to study progressive intervertebral disc herniation under flexion/extension motions combined with compressive loads in a non-destructive manner. First, a solution containing a mixture of 0.15 mL blue dye and 0.4 mL radio-opaque contrast agent (Omnipaque$^{\text{TM}}$, General Electric Company, USA) was injected into the intervertebral discs of excised porcine spinal units. A servo-hydraulic system was then used to apply repeated flexion/extension motions as well as compression loads to the spinal units, thus causing intervertebral disc herniation damage in a controlled manner [11]. CECT scans were then acquired at three different points in time: i) prior to application of load, ii) after application of sufficient load cycles for partial intervertebral disc damage, and iii) after additional load cycles that have been hypothesized to exacerbate intervertebral disc herniation damage. The underlying CECT data has an effective voxel size of 0.2mm×0.2mm×0.2mm.

Given the acquired CECT scans, the following procedure was used to reduce streak artifacts in the underlying data. First, the regions affected by the injected radio-opaque contrast agent in the projection space are detected automatically via a combined multi-scale level set segmentation and projection space transform strategy, which is described in Section II-A. A constrained Bayesian estimation strategy is then used to estimate the streak artifact-free projection data, with an inverse projection space transform then applied to reconstruct the streak artifact-free CECT data, as described in Section II-B.

A. Detection of contrast agent affected regions in projection space

The first step of the proposed streak artifact reduction algorithm is to detect and identify the contrast agent affected regions of the CECT data in projection space. To accomplish this goal, a two step procedure is employed: i) identify the contrast enhanced intervertebral disc regions in the spatial domain to construct a corresponding binary map identifying these regions, and ii) perform a projection space transform on the binary map to identify the contrast agent affected regions in projection space. To identify the contrast enhanced intervertebral disc regions in the spatial domain, the multi-scale segmentation approach proposed in [12] was employed, which can be described as follows. Let the CECT data u_0 be represented as a piece-wise smooth function of material density that can be well approximated using a set of smooth functions u_i defined on a set of regions R_i defining the the contrast enhanced intervertebral disc regions and the surrounding regions covering plane domain R. The corresponding iterative bilateral scale-space representation L can be defined at each scale $t = 1, 2, ..., N$ as

$$L_t(\underline{x}) = \frac{\sum\limits_{\psi} w_p(\underline{x},\psi) w_s(\underline{x},\psi) L_{t-1}(\underline{x})}{\sum\limits_{\psi} w_p(\underline{x},\psi) w_s(\underline{x},\psi)} \tag{1}$$

where $L_0 = u_0$, t and ψ denotes the scaling parameter and a local neighborhood, respectively, and w_p and w_s denote Gaussian photometric and spatial weights on $\underline{x}$, respectively,

$$w_p(\underline{x},\psi) = \exp\left[-\frac{1}{2}\left(\frac{\|L_{t-1}(\underline{x}) - L_{t-1}(\psi)\|}{\sigma_p}\right)^2\right] \tag{2}$$

$$w_s(\underline{x},\psi) = \exp\left[-\frac{1}{2}\left(\frac{\|\underline{x} - \psi\|}{\sigma_s}\right)^2\right] \tag{3}$$

Going from the coarsest scale $t = N$ to the finest scale $t = 0$, the estimate of R at a particular scale $t-1$ can be found by minimizing the Mumford-Shah energy functional for L_{t-1} using the set of smooth functions u_i related to the estimate of R at adjacent scale t as the initial condition,

$$\hat{R}_{t-1} = \arg\min_{R_{t-1}} \left[\alpha \oint\limits_{R} (u - L_{t-1})^2 \, d\underline{x} + \oint\limits_{R-\Gamma} \|\nabla u\|^2 \, d\underline{x} + \beta\,|\Gamma|\right]. \tag{4}$$

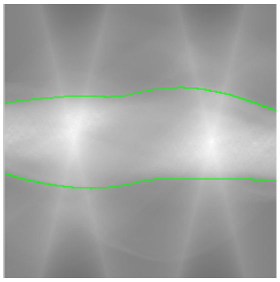

Fig. 2. Example of identified contrast agent affected regions in projection space.

where Γ denotes the boundary between regions, $|\Gamma|$ denotes the total arclength of Γ, and α and β control the penalty terms. As such, the results propagate from the coarsest scale $t = N$ to the finest scale $t = 0$, giving us the final segmented regions $\hat{R} = \hat{R}_0$. A binary map $b(\underline{x})$ indicating the intervertebral disc regions (i.e., $b(\underline{x}) = 1$ iff $\underline{x} \in$ intervertebral disc) can then be determined in the CECT data as the segmented regions with intensity distributions similar to the known distribution of the injected contrast agent under CECT imaging [12]. Finally, the contrast agent affected regions Q in the projection space can be found by applying the forward projection space transform $\mathcal{P}$ on $b(\underline{x})$, resulting in $B(\underline{s}) = B(d, \theta)$, and identifying the non-zero elements,

$$\underline{s} \in Q \text{ iff } B(\underline{s}) > 1. \quad (5)$$

An example of the identified contrast agent affected regions in projection space is shown in Fig. 2.

B. Constrained Bayesian estimation

Based on the segmented contrasted intervertebral disc regions obtained during the segmentation process, the second step of the proposed streak artifact reduction algorithm is to estimate the streak artifact-free projection data, then apply an inverse projection space transform to obtain the streak artifact-free CECT data. To accomplish this goal, rather than treat the contrast agent affected regions in projection space as missing data, we instead treat it as degraded data and thus allowing us to formulate the problem of estimating the streak artifact-free projection data $u_a(\underline{s})$ as the following constrained Bayesian estimation problem,

$$\hat{u}_a(\underline{s}) = \arg_{\hat{u}_a} \min \left\{ E\left(\|\hat{u}_a(\underline{s}) - u_a(\underline{s})\|_2 \,|u_0(\underline{s})\right)\right\}, \quad (6)$$

subject to the fidelity constraint

$$\|u_a(\underline{s}) - u_0(\underline{s})\| \le \epsilon \quad \forall \underline{s} \in Q \quad (7)$$

Since the underlying goal of the proposed algorithm is specifically to reduce the streak artifacts in the CECT data as opposed to tackling other forms of phenomena that have minimal impact on the visualization of intervertebral disc damage in CECT, a reasonable assumption is to let $\epsilon = 0$. What this allows us to do is derive an analytical solution for $\hat{u}_a(\underline{s})$ as

$$\hat{u}_a(\underline{s}) = \begin{cases} \int u_a(\underline{s})\, p\left(u_a(\underline{s})\,|u_0(\underline{s})\right) du_a(\underline{s}), & \underline{s} \in Q \\ u_0, & \text{otherwise} \end{cases} \quad (8)$$

The posterior distribution $\hat{p}\left(u_a(\underline{s})|u_0(\underline{s})\right)$ used in Eq. 8 is determined via a non-parametric Gaussian Parzen window estimation approach based on samples taken from the surrounding $J \times J$ neighborhood in projection space:

$$\hat{p}\left(u_a(\underline{s})|u_0(\underline{s})\right) = \frac{p^*\left(u_a(\underline{s})|u_0(\underline{s})\right)}{\int p^*\left(u_a(\underline{s})|u_0(\underline{s})\right) du_a(\underline{s})}, \quad (9)$$

where p^* is defined as

$$p^*\left(u_a(\underline{s})|u_0(\underline{s})\right) = \prod_j exp\left[-\gamma(\tilde{u}_a(j) - u_0(j))^2\right]. \quad (10)$$

where j denotes the j^{th} sample in the local neighborhood, γ is the relaxation factor, and $\tilde{u}_a$ is an initial estimate of u_a obtained by applying median filtering on u_0. Based on testing, a 15×15 neighborhood and $\gamma = 30$ was found to produce strong results.

Based on the estimate of the streak artifact-free projection data $u_0(\underline{s})$, an inverse projection space transform $\mathcal{P}^{-1}$ is used to obtain the streak artifact-free CECT data $u_a(\underline{x})$.

III. Experimental Results

To evaluate the effectiveness of proposed constrained Bayesian (CB) streak artifact reduction method, three sets of CECT data were processed, with each set consisting of 16 slices. The proposed CB method was implemented in MATLAB and tested on an Intel Pentium 4 3 GHz machine with 1 GB of RAM. For comparison purposes, a traditional non-iterative linear interpolation (LI) method and a state-of-the-art iterative constrained optimization (CO) method [10] were also tested.

Representative CECT slices from the three test sets are shown in Fig. 3. While all three methods are effective at reducing streak artifacts in the CECT data, it can be clearly observed that the LI method performs the poorest of the three tested methods, with the morphological characteristics of the intervertebral disc regions largely degraded and unusable for visualization of intervertebral disc herniation damage. The state-of-the-art CO method performs significantly better than LI, but still exhibits noticeably structural degradation and artifacts on certain regions. The proposed CB method provides the best streak artifact reduction while also exhibiting the fewest morphological artifacts in the intervertebral disc regions. These results clearly indicate the potential for the proposed CB method in significantly improving the visualization of mechanical damage to the tissues of the annulus fibrosus that has allowed the nucleus pulposus to progress in the disc herniation process.

IV. Conclusions and Future Work

In this paper, we introduced a novel approach to streak artifact reduction in CECT data to improve visualization of progressive intervertebral disc herniation damage. The contrast agent affected regions are identified automatically via a combined multi-scale level set segmentation and projection space transform strategy, and the streak artifact-free data is obtained via a constrained Bayesian estimation approach. Experimental results show the proposed approach provides

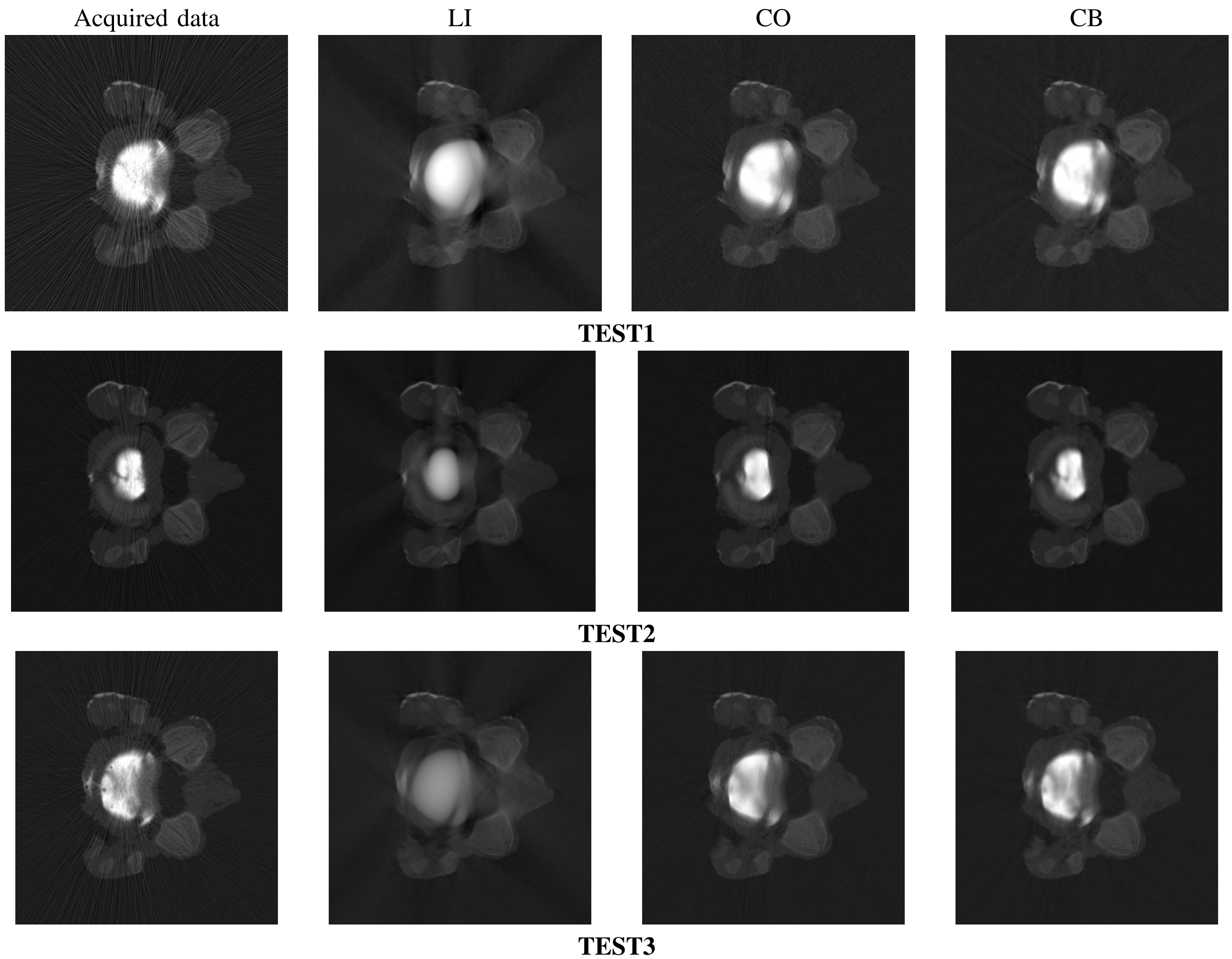

Fig. 3. Representative CECT slices from the three test sets.

strong streak artifact reduction while preserving the morphological details of the intervertebral disc regions, making it will suited for improved visualization of progressive intervertebral disc herniation damage. Future work involves the integration of the proposed streak artifact reduction scheme into a 3D intervertebral modeling framework to create a comprehensive framework for free-form visualization of intervertebral disc damage.

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