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Simultaneous Label Fusion With Vessel Preserving for Bone Removal in CT Angiography Scans

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***Abstract*— When visualizing vessels with CT angiography scans, the arteries are often obstructed by bones. Traditional methods require an additional non-enhanced scan to acquire a bone mask which is then subtracted from the original CTA scan. In this study, we present an automated bone removal method using only contrast enhanced scans based on simultaneous label fusion. We build an atlas database where each atlas is paired with a bone label and a vessel label. After the atlases are mapped to a subject, we propose a vessel preserving scheme to protect possible vessel areas from bone removal by simultaneous label fusion. Seven clinical data sets were used for validation and the results showed that this method can achieve consistent and thorough bone removal with maximal vessels preservation.**

I. INTRODUCTION

CT angiography (CTA) has been demonstrated to be an accurate and cost-effective way to visualize arteries and veins with minimal radiation [1]. The resulting CTA scans are often visualized using maximum intensity projection (MIP) or volume rendering. However, in a CTA scan, the maximum intensity normally occurs in bones and obstructs the vessels. Therefore, it is essential to remove the voxels that represent the bones in CTA scans image before vessels can be visualized properly.

Due to the structural complexity of bones, for example the skull or vertebrae, manual elimination of bones can be both tedious and time-consuming, if not virtually impossible. To automate this process, a common approach is to use a non contrast enhanced (non-CE) scan to create a bone model for the same subject, and subtract it from the enhanced scan. This method is called digital subtraction angiography (DSA) and is shown to be a robust method if the small motion between the two scans is compensated properly [2], [3].

One drawback of the DSA method is that it requires an additional CT scan with extra scanning time and radiation to the patient. Moreover, as the non-CE scan is not included in the routine clinical workflow, it may not be feasible to get such scan retrospectively. Alternative methods have been proposed for CTA scans only, including simple thresholding and region growing methods[4], level set based methods [5], and classifier based methods[6]. In this study, we propose to solve the automatic bone removal problem based on multiple atlas label fusion[7], where a series of atlas image and the corresponding label image is registered and transformed to the subject. Then, a label aggregation or propagation is performed to summarize the labels from the multiple atlases, including global atlas selection methods [7], [8] and patch based label propagation [9]. After the bone labels from atlases are aggregated, to prevent unwanted vessel removal in the proximity of bony structures, we propose a novel vessel preserving technique that performs simultaneous label fusion for both bones and vessels. Preliminary experiments are performed on seven datasets showing that our method performs consistently well on various subjects.

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II. SIMULTANEOUS LABEL FUSION FOR BONE REMOVAL

In this section, we demonstrate in detail our proposed bone removal algorithm based on simultaneous label fusion with vessel preserving. The rest of this section will be organized as follows. In section II-A, we discuss the construction of the atlas database. Bone labeling based on multi-atlas label fusion is presented in section II-B. Finally, we propose our vessel preserving scheme for simultaneous label fusion in section II-C.

A. Construction of Atlas Database

The collection of atlases is the fundamental building block of a multi-atlas based system. In this study, we have collected CT scans from 7 subjects, each with one non-CE scan and one CTA scan with contrast enhancement. Denote the atlases as $A_i = \{I_i, B_i, V_i\}$, $i = 1 \dots 7$, where I_i is the CTA image, B_i and V_i are the corresponding bone and vessel label, respectively. Specifically, $B_i(x,y,z) = 1$ indicates that the voxel at the z^{th} slice, y^{th} row and x^{th} column is labeled as bone, while 0 indicates otherwise. We define V_i similarly.

For each pair of contrast enhanced and non-enhanced CT scans, we apply a piece-wise linear registration and connectivity analysis with two thresholds to label bony structures in the CTA scans [10]. The obtained bone label image (B_i) is then subtracted from I_i to acquire the DSA image of the original scan, which can be used as ground truth for performance evaluation.

Using an additional non-enhanced reference scan provides accurate bone labeling for atlases. After bone removal, the vessels now represent the highest intensity values in CTA images. Therefore, applying a threshold will perform fairly well in acquiring the vessel labels. To further eliminate noises in vessel label images, connected component is applied and only the largest component is kept [11]. Note that since we are constructing labels for the atlas database, we apply some manual tuning of parameters and editing of the results when necessary. When a new subject image arrives for bone removal, no manual editing is required and the system is fully automated.

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B. Multi-Atlas Bone Labeling

Once an atlas is constructed, it can be viewed as a classifier that provides a map from a coordinate (x,y,z) to a label $B_i(x,y,z)$. Therefore, the classification of a new subject I using the i^{th} atlas can be done by finding the transformation R_i such that $I \simeq R_i \circ I_i$. In this study, we acquire this transformation by a diffeomorphic non-rigid registration using a variational approach [12].

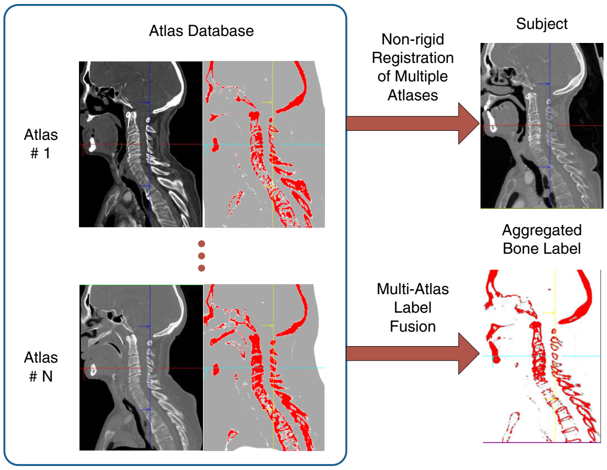

Fig. 1. Illustration of the bone labeling process based on multiple atlas label fusion.

As illustrated in Figure 1, the bone labeling process using multiple atlases consists of the following steps:

- **Registration Step**. In this step, each atlas is registered to the subject image, while the transformation is also applied to the corresponding label image to obtain the prediction as $B_i' = R_i \circ B_i$.
- **Label Aggregation Step**. In this step, the predictions made by multiple atlases are summarized to obtain the final label prediction B. In this study, we propose to use a simple voting scheme for label aggregation. We first calculate the sum of all label prediction B_A as $B_A = \sum_{i=1}^{7} B_i'$. Then, B is obtained as:

$$B(x,y,z) = 1 \Leftrightarrow B_A(x,y,z) \geq \alpha,$$

where α can be viewed as the effective number of votes to make a prediction, and is set to be 2 in this study.

C. Vessel Preserving Scheme

Due to the partial volume effect in CT images, bones may not be removed completely and the remaining bony structures would obstruct vessel visualization. Constrained dilation [11] is then performed on the aggregated bone label B such that a more thorough bone removal can be obtained. The dilation constraint t is defined such that a voxel value can be set to zero only if the voxel value is higher than t.

Though effective, the constrained dilation brings another problem: the unexpected removal of vessels. In the head-neck region, there are quite a few vessels that are in the close proximity of bones. An example is the vertebral artery as illustrated in Figure 2. As we can observe from the figure, the vertebral artery is tightly surrounded by the cervical vertebra that a small bias in the registration and dilation would result in the unwanted remove of the vessel.

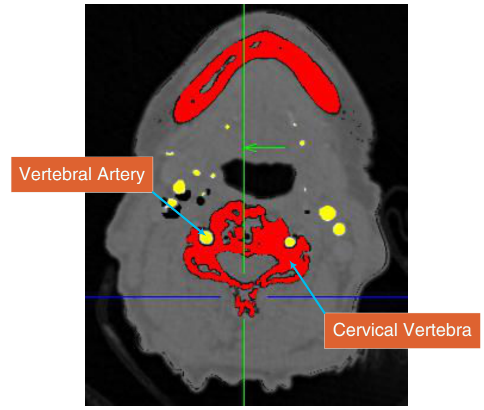

Fig. 2. An example of the vessels (vertebral artery) that are in the close proximity of bones, bringing challenge to the constrained dilation. This example is taken from axial view of the neck, where red regions indicate bones and yellow ones indicate vessels.

In this study, we propose to utilize the vessel label information in the atlas database to perform vessel preserving. Similar to using the transformed bone labels to remove bones, we use the transformed vessel labels ($V_i' = R_i \circ V_i$) to construct a "safe zone" such that the voxels within this area cannot be altered during the bone removal. That is to say, we aim to construct a vessel preserving area V such that if $V(x,y,z) = 1$, the bone removal will not take place in this voxel. Similar to the bone label aggregation, we first calculate the sum of all vessel label prediction V_A as $V_A = \sum_{i=1}^{7} V_i'$. Then, V is obtained as:

$$V(x,y,z) = 1 \Leftrightarrow V_A(x,y,z) \geq \beta,$$

where β can be viewed as the effective number of votes to trigger vessel preservation, and is set to be 2 in this study. An overview of incorporating vessel preservation into the constrained dilation is presented in Figure 3.

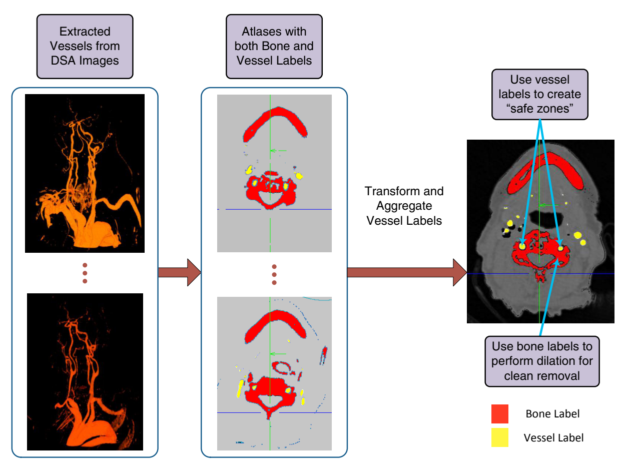

Fig. 3. Illustration of the vessel preserving method.

By combining the multi-atlas label fusion and vessel preserving into a simultaneous label fusion method, we have constructed a fully automated bone removal system that requires only CTA. The workflow of this system is presented in Algorithm 1.

Algorithm 1 Automatic Bone Removal by Multiple Atlas

Input: Atlases $A_i = I_i, B_i, V_i$, subject image I

Output: Subject image I with bone removed

1: For each atlas image I_i, register to I to obtain the transformation R_i.

2: Transform the bone and vessel labels to obtain the aggregated labels as:

$$B_A = \sum_i R_i \circ B_i, \quad V_A = \sum_i R_i \circ V_i$$

3: For each voxel in I, set $I(x,y,z) = 0$ (bone removal) when all of the following is satisfied:

- **Bone Dilation**: For all voxels (x_0, y_0, z_0) in the r_d radius of (x,y,z), at least one of them satisfies $B_A(x_0, y_0, z_0) \geq \alpha$
- **Vessel Preservation**: $V_A(x,y,z) < \beta$
- **Dilation Constraint**: $I(x,y,z) > t$

4: 4. Perform connected component to further reduce noise.

III. EXPERIMENTAL RESULTS

In this study, CTA scans and corresponding non-CE scans from 7 patients were acquired with Siemens CT scanners. All 7 subjects are male, with ages ranging from 40 to 84. The dimension of each slice is 512 × 512, and the numbers of slices vary from 750 to 924. The voxel spacing is 0.49 mm while the slice spacing is 0.4 mm. A leave-one-out approach is used to evaluate the performance of our system. For each subject, we use the remaining 6 subjects as atlases to apply our method for bone removal. The DSA scan (obtained using two CT scans) of this subject is then used as the ground truth to evaluate the results.

Fig. 4. Visual evaluation of our proposed bone removal system, subject 1. The left figure is obtained by CE and non-CE scan subtraction (considered as ground truth in this work), and the right image is obtained using our proposed method.

In Figure 4 to 7, we use four subjects as illustrative examples, and compare the vessel visualization results after bone

Fig. 5. Visual evaluation of our proposed bone removal system, subject 2. The left figure is obtained by CE and non-CE scan subtraction (considered as ground truth in this work), and the right image is obtained using our proposed method.

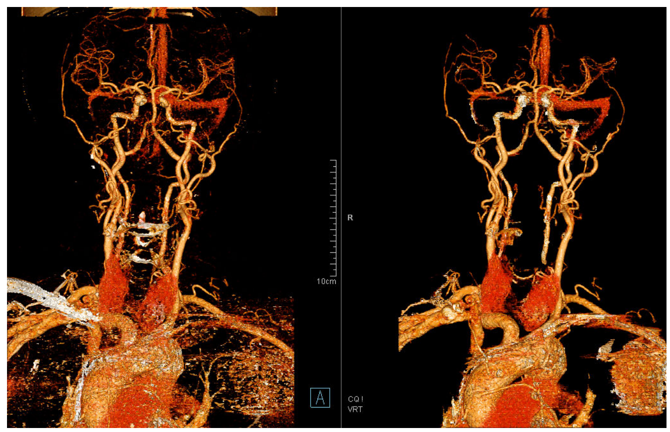

Fig. 6. Visual evaluation of our proposed bone removal system, subject 3. The left figure is obtained by CE and non-CE scan subtraction (considered as ground truth in this work), and the right image is obtained using our proposed method.

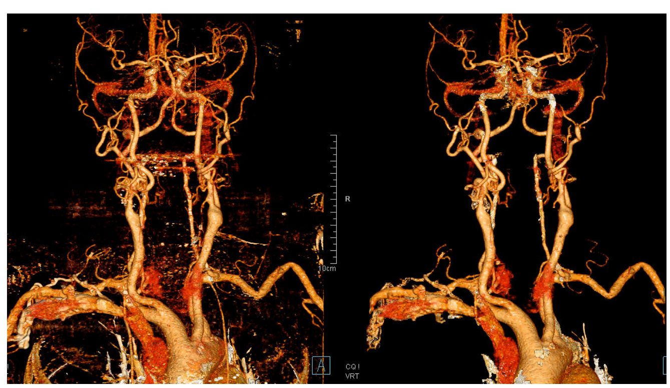

Fig. 7. Visual evaluation of our proposed bone removal system, subject 6. The left figure is obtained by CE and non-CE scan subtraction (considered as ground truth in this work), and the right image is obtained using our proposed method.

removal using the DSA method and our proposed method. As we can see from the figures, using only the contrast enhanced scan, we can obtain very comparable results as the DSA method, where an additional non-CE scan is needed. All the major vessels, including the challenging vertebral arteries that are surrounded by the cervical vertebrae, are preserved quite well. Furthermore, with the help of the connected component technique, our results are in general less noisy than the DSA method. On the other hand, some small vessels may be missing due to the connected component step. We would like to emphasis here that since there are no "true labels" for the test subjects, and since our goal is to preserve and inspect the major vessels, visual inspection is more appropriate for our current experimental settings.

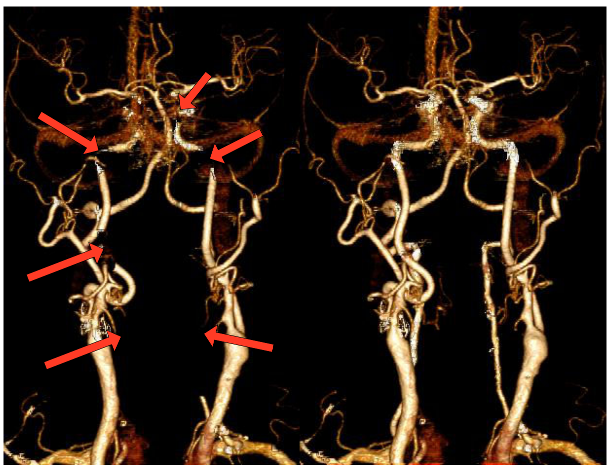

Fig. 8. Illustration of the effectiveness of our proposed vessel preserving method. We remove the vessel preserving component while keeping the rest of the bone removal algorithm untouched; and the result is placed in the left figure. The result with vessel preserving technique is shown on the right figure for comparison.

To demonstrate the effectiveness of our vessel preserving method, we remove the vessel preserving component in our algorithm and repeat our bone removal method with all other parameters set to be the same. The comparison is made in Figure 8. As is evident from the figure, without the protection of the vessel preserving technique, the vertebral arteries are completely removed, as well as several segments of other major vessels.

IV. DISCUSSIONS AND CONCLUSION

In this paper, we present a novel automated bone removal algorithm using only contrast enhanced CTA scans. We use multiple atlas based label fusion for bone labeling and removal, and propose a vessel preserving scheme such that the vessel labeling information in the atlases is utilized to protect the vessel area from unwanted removal. Using a leave-one-out evaluation method on a dataset with 7 subjects, we show that our method achieved the same performance as the traditional DSA method, where an additional non-CE scan is required. In this preliminary work, the "ground-truth" labeling in atlases are actually not perfect, and manual editing would be needed in our future work to further improve the labeling quality.

Meanwhile we would also like to mention that in this preliminary study we only focus on bone removal accuracy; and ideas such as registering the atlases to a template offline to acquire the aggregated label images beforehand may improve the speed of this system. Meanwhile, a patch-based label fusion approach [9] may also improve computational efficiency and/or the labeling accuracy. Furthermore, as we accumulate a much larger atlas database in the future, we can potentially build multiple databases for different patient groups (children, adults etc.); and dedicate specific database for different studies.

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