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AUTOMATIC SEGMENTATION OF SPINAL CORD IN CT IMAGES

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Abstract — Accurate segmentation of the spinal cord in computed tomography (CT) images is an important task in many related studies. In this paper, we propose an automatic segmentation method and apply it to our highly challenging image cohort that is acquired from multiple clinical sites and from the CT channel of the PET-CT scans. To this end, we adapt the interactive random- walk solvers to be a fully automatic cascaded pipeline. The automatic segmentation pipeline is initialized with robust voxelwise classification using Haar-like features and probabilistic boosting tree. Then, the topology of the spinal cord is extracted from the tentative segmentation and further refined for the subsequent random-walk solver. In particular, the refined topology leads to improved seeding voxels or boundary conditions, which allow the subsequent random-walk solver to improve the segmentation result. Therefore, by iteratively refining the spinal cord topology and cascading the random-walk solvers, satisfactory segmentation results can be acquired within only a few iterations, even for cases with scoliosis, bone fractures and lesions. Our experiments validate the capability of the proposed method with promising segmentation performance, even though the resolution and the contrast of our dataset with 110 patient cases (90 for testing and 20 for training) are low and various bone pathologies occur frequently.

Index Terms — Image landmark detection, image segmentation, random walk, spinal cord, topology.

I. INTRODUCTION

Image segmentation is a fundamental issue in biomedical imaging. Segmenting structures from medical images and reconstruction of a compact analytic representation of these structures is difficult. This difficulty is due to the sheer size of the data sets and the complexity and variability of the anatomic shapes of interest. As manually segmenting the structures is a time-consuming task for physicians. Many research and clinical studies require the automatic segmentation of the spines, which is capable of facilitating disease diagnosis, treatment, and statistical analysis/evaluation. An obvious disadvantage is that an exhaustive process, where the results are hardly repeatable. Hence clinicians are discouraged to use these in routine diagnosis. It is important to observe that an efficient, precise medical image segmentation system should necessarily add to the model some level of intrinsic knowledge about the problem. Segmentation is the process that separates an image into its important features (primitives) so that each of them can be addressed separately. In other cases where simpler anatomical regions with a very distinguishable shape must be identified an algorithm can perform this task. Image segmentation is currently used into several medical imaging applications that involve diagnosis or treatment. Traditionally the segmentation process is done manually on a slice-by-slice base. Nowadays usually high-resolution CT data are used (60 to 120 slices).

Therefore the overall manual segmentation process could last several minutes. In this work we present an algorithm that can be used for the accurate automatic segmentation of the spinal cord in three dimensions from CT images. For example, the segmentation of the spine provides spatial reference to locate and identify other neighbouring anatomical structures in abdomensand chests, thus contributing to the understanding of the full-body scan essentially. In terms of image registration, the segmented spines provide important features that are helpful to the correct alignment of corresponding anatomical structures across individual subjects. Furthermore, it becomes easier to conduct disease-oriented analysis given the segmented topologies/shapes of the spines.

In the meantime, based on the segmentation of the spinal canal, the entire spinal cord can easily be delineated, making it possible to count radiotherapy dosages which are crucial to the normal functions of the nerve tracts. To this end, a lot of efforts have been devoted to the segmentation of the spine and its related structures from multi-modal imaging acquisitions. Accurately segmenting the spinal canal facilitates the computer-aided detection process of anomalies, such as epidural masses on CT scans. In general, most conventional methods require user inputs to certain extent for the segmentation of the spinal cord in CT data. It is not easy to apply these automatic methods to large-scale image cohorts, as human interaction is often tedious and costs high. The inconsistency among human experts also challenges the quality of the segmentation results.

A. Spinal condition and necessary of segmentation

A herniated disc describes the condition when the intervertebral disc is injured and its contents are bulge or protrude into the spinal canal. The terms slipped disc, ruptured disc, bulging disc, disc protrusion, and extruded disc, among others, all mean herniated nucleus pulposus (herniated disc), which is the proper medical term. Diagnostic system needs protrusion of the disc into canal region. That can be measured by describing the canal region, which needs canal segmentation. A lower back problem that puts pressure on a nerve to the leg, such as a herniated disc, can cause leg symptoms, either on its own or along with low back pain. Leg symptoms can include pain, numbness, and/or tingling, usually below the knee and/or weakness in one leg. Weakness and/or numbness in both legs, alongwith loss of bladder and/or bowel control, are symptoms of caudal equine syndrome, a serious condition in which the bundle of nerve roots at the end of the spinal cord are squeezed. This results in reduced spinal canal region. A thoracolumbar spine fracture is an injury that results from a broken bone in the thoracic or lumbar region of the spine. There are four different types of fractures: compression fracture, burst fracture, chance fracture and fracture/dislocation. The most common causes of thoracolumbar fractures are falls, motorized vehicle accidents, and sports activities. Severity of the fracture is estimated based on the vertebral boundary.Spinal metastases occur in 90% of prostate, 75% of breast, 45% of lung, and 30% of renal terminal cancer patients. To effectively quantify the impact of metastatic tumor involvement in the spine, accurate segmentation of the vertebrae is required. In many vertebrae with lytic involvement, the tumor may breach the cortical shell of the vertebral body, in which case semi-automated techniques such as thresholding or region growing have difficulty in defining the boundary between tumor tissue and the surrounding soft tissue. Potential solutions to automate the segmentation of metastatically involved vertebrae are the level set methods. Segmentation of spinal cord is desirable in many studies because it facilitates analysis, diagnosis, and therapy planning related to spines. Segmentation of spinal cord provides helpful references to quantify the facet angle. Here we present an approach for automatically segmenting the spinal cord from CT images with low-resolution and low-contrast images. Scoliosis is a three - dimensional (3D) deformity of spine that is characterized by its lateral curvature. Radiographic technique involves identifying the end vertebrae of the curve. Manual definition of required end vertebrae are time consuming and imprecise. Automatic determination of the detailed vertebral shape could enable more powerful quantitative tool for diagnosis of scoliosis. That can be achieved by providing knowledge about the segmented object through active contour models. In numerous medical imaging modalities, the boundaries of anatomical structures cannot be detected by algorithms that only use edge or region information. Reasons for this probleminclude significant signal loss, noise, and non- uniformity of regional intensities. These problems are ever present for images acquired in spine inter vertebral disc etc., where the boundary detection problem is further complicated by the presence of Confusing anatomical structures.

Alternative automatic solutions mostly follow the *top-down* design, by recognizing related anatomical structures from the large scales to small. In this way, the spine can finally be localized with the helps from other neigh boring anatomies. However, the robustness of these top-down methods are challenged if certain anatomical structure is missing in a specific image due to limited superior-inferior coverage. In particular, our patient population has a large portion of unhealthy subjects where various bone/spine pathologies can often be observed. The *top down* strategy may not generalize well to these diseased/outlier cases. This motivates us to exploit more flexible and robust data-driven *bottom-up* method in this paper.

Meanwhile, it is worth noting that our task to segment the spinal cord is extremely difficult concerning the data, which

Will be handled in the method and experimental sections.

1) We acquire a total number of 110 CT scans of individual Patients from eight different clinical sites for this study. The cohort of the CT images is among the largest in the literature.

2) The images in our collection vary significantly in terms of the acquisition configurations, including superior-inferior coverage, sizes, spatial resolutions, etc. This variation strongly challenges the robustness of the automatic segmentation methods.

3) All images are acquired from the CT channels of the PET-CT scanners. Therefore, the quality (e.g., signal-noise-ratio, tissue contrast) of the images is relatively lower compared to regular CT acquisitions. Also, regular CT scans of the spines are often acquired with intravenous (IV) contrast. However, for our data, no contrast is involved.

4) We recruit patients and aim to verify the proposed method upon real clinical data setup. All patients are affected by diseases (common to PET-CT imaging patient population), which introduce uncontrollable impacts to the shapes/appearances Of the spines. For example, typical slices of two patients are provided in Fig. 1(a) and (b), respectively. It is observable that, in Fig. 1(b), a disease (i.e., scoliosis) severely affects and then twists the spine in the lateral (left right) axis direction, resulting in a significant abnormality. Though facing the aforementioned technical challenges, we have successfully developed a novel method to segment the spine cord from the large-scale cohort of diverse CT images. Our automatic segmentation method relies on the iterative refinement of the topology of the spine, which provides contextual guidance to improve the segmentation of the spinal canal gradually. In particular, we describe the topology of the spine by its medial line, which can be extracted and refined from the tentative segmentation of the spinal cord. Seeding voxels are sampled according to the refined spine topology, and further fed into the random-walk solver to update the segmentation of the spinal cord. By iteratively applying the above scheme, we are able to cascade several random-walk solvers, and attain highly robust and accurate segmentation of the spinal cord in CT images.

In general, the major contributions of our work consist of the following three aspects.

1) A fully automatic method is proposed for the segmentation of the spinal cord in CT image. The method is successfully validated upon one of the largest and most challenging datasets ever reported in the literature.

2) We utilize the iterative random-walk solvers to flexibly fill in the spatial occupancy of the spinal cord. The topology of the spinal cord, which is extracted and refined from the tentative segmentation, behaves as the regularized context information for the refinement of the segmentation.

3) The topology of the spinal cord is initially determined from the discriminative learning of the training images. Then, subject-specific geometric/appearance constraints are applied for the refinement of the topology of each testing subject under consideration.

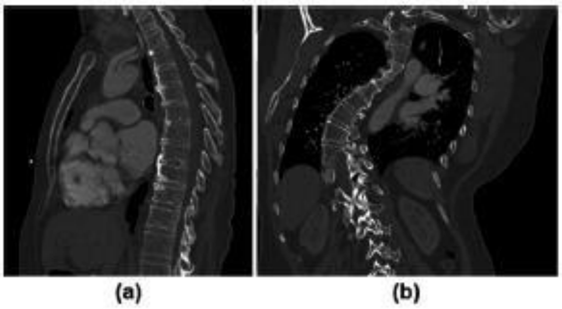
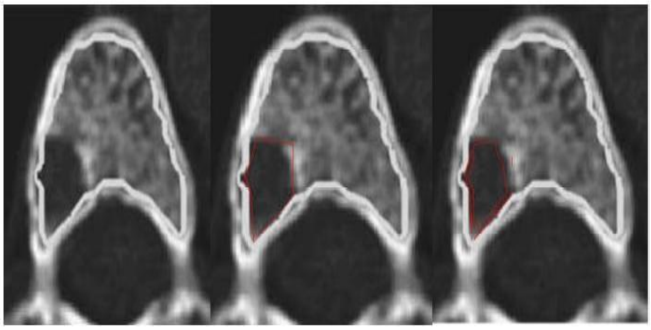


Fig. 1. The views of the spines of two individual patients. In (a) the shape of the spine is relatively normal. However, in (b), the disease (i.e., scoliosis) affects the appearance of the spine significantly by introducing a twist alongside the lateral axis. The views are sagittal and coronal in Fig. 1(a) and (b), respectively.

II. METHOD

We treat segmenting the spinal canal as a typical binary segmentation problem. Let p(x) denote the probability of the voxel x being foreground (i.e., inside the spinal cord) and p'(x) the probability for being background (i.e., outside the spinal cord), respectively. In general, we have $p(x)+p'(x)=1$ after proper normalization. The binary segmentation of the spinal cord then be acquired by applying a confidence threshold to the map of p(x) within the entire image space. For example, if $p(x) > p'(x)$, the voxels x is naturally regarded as being part of the foreground. On the contrary, if $p(x) < p'(x)$, then x belongs to the background. Note that the to-be-estimated p(x) is *de-factor* a posterior probability, which is conditioned on the observation (of the features) upon the voxel x .

The probability map can be generated in different ways. For example, by providing foreground and background seeding voxels automatically, we can acquire the probability map through the random-walk solver as in our method. The seeding voxels are determined according to the iteratively refined topology of the spinal cord. Specifically, to initiate the random-walk-based segmentation, we start from the supervised *voxelwise classification* to identify a small set of voxels, which are assigned with very high classification confidences and thus most likely to be foreground. The identified voxels act as positive seeds and are fed into the *random-walk solver* to generate a conservative binary segmentation with relatively low sensitivity but also low false-positive (FP) error. Concerning the fact that the spinal cord are generally tubularstructures even though their shapes vary significantly across the patient population, both geometric and appearance constraints that are Anatomically meaningful are then enforced to extract and to refine the topology of the segmented spinal cord. The refined topology, which is continuous and smooth, thus leads to the updated placement of the seeding voxels, which in turn increases the sensitivity in segmenting the spinal cord via random walk. By iteratively feeding the improved seeding voxels to the *cascaded random-walk solvers* , we have successfully built an automatic pipeline that yields satisfactory segmentation of the spinal cord. Details of our method will be provided as follows. For easy



understanding, the flowchart of our method, as well as explanations to its key steps, is shown in Fig. 2.

We categorize our method as being a *bottom-up* solution, which is significantly different from the conventional *top-down* methods. Specifically, we identify a set of seeding voxels where the tentative segmentation is mostly reliable, instead of detecting the anatomical objects of much larger sizes (e.g., organs near the spine). The seeding voxels are initially detected through appearance-based discriminative learning and then updated according to the (tentative) spine topology. The segmentation result, as well as the spine topology, can be improved in subsequent iterations. In this way, the segmentation of the spinal cord can accumulate or propagate from a few (seeding) voxels, until reaching satisfactory result throughout the entire image space. The below figure shows that the segmentation of bone metastase

III. CONCLUSION AND DISCUSSION

In this work, an automatic method to segment the spinal cord from highly varying CT images is proposed. With initial seeding voxels that are provided by PBT-based voxelwise classification, we introduce the topology constraints into the segmentation via random walk. Our iterative optimization has successfully enhanced the capability of a single random-walk solver in dealing with tubular spinal cord, in that the boundary conditions (i.e., the placement of the seeding voxels) can be iteratively improved to provide better segmentation results.Our large-scale evaluation shows that the proposed method is highly accurate and robust even if the datasets are very diverse and challenging.

Due to limited accesses to state-of-the-art methods, rigorously fair comparisons can hardly be conducted. Though we compared our method with four other methods reported in the literature, it is worth noting that the comparisons were based on different datasets that were used by individual papers. State-of-the-art methods typically reported failures when segmenting certain *outlier* images. However, it is worth noting that our method has been successfully validated on all 90 testing images. That is, no failure case has been generated through the proposed method. Concerning the challenges caused by our large-scale cohort of diverse images, we argue that our method is very robust and accurate for the segmentation of the spinal cord.

Although our method has demonstrated its robust and accurate segmentation capability upon the large-scale dataset, we are aware that the proposed method could be challenged in certain situations.

- Our images are collected from Siemens Biograph PET-CT scanners with no IV contrast. Although no inclusion/exclusion protocol has been used for the collection of the images, the variation within the dataset (i.e., patient age, pathology, scanning protocol) could still be limited. The performance of the proposed method upon other large-scale datasets is not investigated yet.
- We have assumed relatively homogeneous appearances for foreground voxels, such that individual segments of the extracted medial line can be refined into a single one. In clinical practice, however, there are certain diseases (e.g., calcified vertebral foramen) which may introduce inhomogeneous appearances into CT images of the spine. In this case, our method could possibly fail.
- Our images are acquired from adult patients only. For paediatric patients whose spine sizes may vary from adults, our method has not been validated yet.
- Our method could possibly well handle spine appearance anomalies (including lumbarisation, sacralisation, disc degeneration, bone spurs, surgical spinal-fusion, etc.). We only have very simple assumption regarding the appearance of the bones, i.e., with relatively high intensities for bone voxels especially on the boundaries. However, the exact effect of spine appearance anomalies cannot be investigated at this moment, as no such images are available in our dataset.

In general, we conclude that the proposed method can well handle our large-scale dataset, which is collected from clinical routines of multiple sites.

There are two directions in our future work. *First*, we will improve the speed performance of our method. In our current implementation particularly, the computation of each randomwalk solver in the cascaded pipeline is independent. In fact, only boundary conditions of two consecutive random-walk solvers change during the segmentation process. Therefore, we would be able to reduce the redundancy in computation, e.g., by using the method reported.

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