Automated Multidetector Row CT Dataset Segmentation with an Interactive Watershed Transform (IWT) Algorithm: Part 2—Body CT Angiographic and Orthopedic Applications

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The preceding manuscript describes the principles behind the Interactive Watershed Transform (IWT) segmentation tool. The purpose of this manuscript is to illustrate the clinical utility of this editing technique for body multidetector row computed tomography (MDCT) imaging. A series of cases demonstrates clinical applications where automated segmentation of skeletal structures with IWT is most useful. Both CT angiography and orthopedic applications are presented.

KEY WORDS: 3D Segmentation, computed tomography, body imaging

BACKGROUND

Segmentation of the bone for three-dimensional (3D) rendering of computed tomography (CT) angiography datasets remains a challenge despite advances in hardware and software. When 3D rendering was in its early stages, datasets were manually edited slice by slice. However, this is time consuming and prone to error, depending on the level of skill and education of the individual selecting the vasculature in each axial image. Such limitations have prompted investigation of computerized editing tools, particularly for the large number of axial sections produced by multidetector row computed tomography (MDCT). Compared to manual editing, automated segmentation resulted in a greater than 60-fold decrease in interaction time in one study.¹ Numerous programs have been evaluated, varying with respect to speed, memory requirements, and degree of automation.¹⁻⁷

The purpose of this paper is to demonstrate the utility of a fast, automated editing tool, an Interac-

tive Watershed Transform (IWT) technique, for segmenting body multidetector row computed tomography (MDCT) volumes.⁸⁻¹¹ The principles of the IWT are described in the preceding article. This manuscript reviews clinical applications of the technique for 3D rendering of MDCT in the chest, abdomen, pelvis, and extremities.

METHODS

Removal of bone for computed tomography angiography (CTA) with maximum intensity projection (MIP) algorithms is essential (Fig. 1). MIP algorithms select the highest attenuation voxels and do not display the anatomy with the proper 3D relationships to separate high-density structures. As such, inclusion of the osseous structures in MIP

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Fig 1. Coronal oblique volume renderings (a–c) and MIP renderings (d, e) from an intravenous (IV) contrast-enhanced MDCT dataset of the right shoulder and proximal upper extremity in a 41-year-old woman with upper extremity trauma and increasing pain. The obliquity used to depict the subclavian artery precludes visualization of the brachial artery behind the humerus (a) with VR. IWT segmentation (b, d) separates the osseous structures from the vasculature to optimize vessel viewing with either VR (c) or MIP (e).

displays can hinder evaluation of the vasculature. Using either volume rendering (VR) or MIP, clip planes can be applied to remove slabs of data, improving evaluation of centrally located vascular structures in a 3D volume. However, this may not be completely effective for separating vessels closely apposed to bone. Additional limitations of clip plane editing arise in regions where the relationship between arteries and bones do not conform to the flat surface of a plane (Fig. 2). Automated editing with the IWT algorithm quickly segments the osseous structures in these settings.

Specific anatomic regions benefit most from IWT segmentation, as illustrated by this series of cases. In 2003, Sebastian¹² reported that watershed techni-

ques were prone to oversegmentation, requiring the development of markers. The IWT technique presented here provides for such refinement through the placement of bone markers or nonbone markers, as described in the preceding technical note.

RESULTS

Clinical Applications

Chest Applications Clip plane editing often suffices to evaluate the aorta and pulmonary arteries. However, for vessels located close to the sternum or chest wall, such as coronary arteries, IWT

Fig 2. Follow up of aorto-iliac and left iliac to superior mesenteric artery bypass surgeries. a. Coronal MIP from an IV contrast-enhanced MDCT with slab editing to remove the posterior pelvis and spine. Because of spinal curvature, the lumbar vertebral bodies were not removed by clip plane editing. b, c. Automated segmentation in b removes the spine and pelvis (c). The bypass grafts are much more clearly visualized, although the three-dimensional relationships are not accurately displayed, owing to this limitation of MIP rendering.

segmentation can extract the sternum and ribs to facilitate visualization in the coronal plane (Fig. 3).

Abdomen Applications The proximity of the abdominal aorta to the spine is problematic for coronal viewing of MIP renderings (Fig. 4). Application of a clip plane can often remove the spine; however, in cases where the lumbar spine is curved (Fig. 2), this may not be adequate. Editing with the IWT algorithm is well suited for patients with aortic tortuosity and spinal curvature (Fig. 5).

Whereas most major abdominal aortic branches originate from the anterior aorta, the

renal arteries arise from the lateral surface and overlay the spine at their origins. Accordingly, vertebral bodies usually obscure the renal artery origins on coronal MIP renderings, unless obliquities are used. Removal of the spine with the IWT algorithm facilitates renal artery evaluation with MIP (Fig. 6).

Pelvis and Extremities Display of the iliac arteries and run-off vessels is optimized with a coronal orientation. However, the adjacent pelvic (Fig. 7) and leg bones (Fig. 8) preclude visualization of the arterial structures with MIP. Similarly, in the upper extremity, coronal viewing is impeded by the

Fig 3. Coronary MDCT angiography. Coronal color-coded volume renderings of the chest from an IV contrast-enhanced MDCT. Sternum and ribs preclude evaluation of the heart in a. In b, the automated segmentation is applied to remove the bones. The heart, coronary arteries (arrow) and thoracic arteries are displayed in c.

Fig 4. Middle aortic syndrome. Using a coronal MIP display (a–c) for this IV contrast enhanced MDCT dataset, the aorta is only visualized after automated segmentation with the IWT (b), revealing severe narrowing of the abdominal aorta at the level of the renal arteries (c).

skeletal structures, using both volume rendering and MIP (Fig. 1). Removal of the bones facilitates assessment of these arteries for pathology.

In the hands and feet, the small arteries do not conform to the flat surface of a plane, and clip planes are not well suited for bone segmentation in this region. The IWT can be used to remove the bones for enhanced evaluation of arterial structures (Fig. 9).

Orthopedic Applications Isotropic datasets from current generation MDCT scanners result in 3D renderings with high resolution, which should

improve efficacy for identifying small bone erosions and measuring fracture gaps with 2D and 3D rendering. Selective removal of bones enhances 3D volume-rendered viewing of surfaces, particularly in joint articulations. The information provided from surface viewing is valuable for both diagnosis and presurgical planning in the setting of arthropathy and fracture.^{13,14} Using the IWT, bone markers can be applied to a volume-rendered display to segment the femur from the acetabulum, enabling evaluation of either the femoral head or the acetabulum (Figs. 10 and 11). Multiple markers can be applied to separate the bones of the hands and feet (Fig. 12). This is potentially

Fig 5. Endovascular stent graft evaluation. Severe spinal curvature and aortic kinking do not prevent successful segmentation of the aortoiliac system (b) and spine (c) of a volume rendered IV contrast enhanced MDCT dataset. Bilateral internal iliac artery aneurysms (b) are present.

Fig 6. A 60-year-old woman being evaluated as a potential renal donor. Coronal MIP renderings from an IV contrast-enhanced MDCT dataset (a–c) require automated segmentation of the spine to adequately visualize the renal artery origins. Bilateral renal artery fibromuscular dysplasia is identified, more severe on the left side.

useful to inspect surfaces for articular erosions or to evaluate fractures. Furthermore, segmentation is required in kinematic studies of the carpal bones when instability is suspected.¹²

DISCUSSION

A variety of approaches to solve the bone removal problem are found in the literature. These can be roughly categorized into automated^{2–5} and interactive techniques.^{1,2,6,7} To date, a fully automated

approach fails to exist that provides fast and high-quality results without requiring manual refinement in many cases.^{4,5} Alyassin and Avinash² describe a simple method based on fast morphological operations and image filters, similar to the work by Fiebach et al.,³ where global thresholds can be adjusted to separate bones from vessels. More interactive approaches^{1,6,7} often provide a higher specificity at a lower speed. Moore's technique⁶ involved thresholding and dilation, followed by subtraction of the skull. For the novice, segmentation required 26 minutes; however, shaded surface renderings of segmented vasculature could be created in under 10 minutes by experienced operators.⁶ The technique proposed by Raman,¹

Fig 7. Right common iliac artery occlusion. Coronal MIP display from an IV contrast-enhanced MDCT dataset (a) cannot be used to evaluate the arterial run-off without segmentation of the bones, as performed to create b. This case shows the utility of the IWT for rapid segmentation of a large dataset, to produce a diagnostic display.

Fig 8. Patient with pain and coolness involving the right foot. **a.** Posterior coronal MIP from a contrast enhanced MDCT dataset, with automated IWT segmentation selecting the skeletal structures that obscure visualization of the arteries in this viewing orientation. **b.** Posterior coronal MIP status-post automated segmentation. The section of occluded right popliteal artery is now apparent.

Fig 9. Patient with wrist cellulitis and clinical concern for abscess. **a.** Posterior coronal VR from a contrast-enhanced MDCT dataset nicely depicts the normal arterial anatomy of the hand and wrist. The complex interrelationships of vessels and bone in the wrist and hand would make clip plane editing to segment the bones difficult. **b, c.** After automated segmentation of the volume rendering, the bones can be extracted (**b**), facilitating evaluation of the arterial vasculature, or the vasculature can be removed from the display (**c**). Despite the tortuosity of these small vessels, only a few tiny arteries near the distal phalanges remain unsegmented (arrows in **c**).

Fig 10. Acute right pelvic fracture. Coronal volume rendering of the hips and pelvis. A bone marker is applied to the left femur (a), resulting in successful segmentation to display the pelvis (b) or proximal femur (c).

requiring a click on each pair of bones and vessel to be separated, can be seen as a trade-off between generality and accuracy, although in large datasets a considerable amount of interaction is required. Other rapid segmentation techniques include the contiguity-based, seed-growing technique described

by Fiebach.³ Fully automated segmentation could be performed in less than 30 seconds for a chest, abdomen, or head CT. Bone segmentation was rated as good or excellent for 86% of axial images reviewed. However, inaccuracies were noted in anatomic regions where vessels were located adjacent to bone.³

A variety of segmentation methods to selectively remove bones are described in the computer science literature.^{12–14} Sebastian¹² and Wang¹³ categorize these techniques as intensity-based (which includes manual segmentation and thresholding techniques based on pixel density), edge-based (which identifies contours to separate structures), region-based (seed-growing techniques that select similar pixels), deformable models and watershed segmentation. Limitations of single techniques include inaccurate depiction of cancellous bone, undersegmentation (inability to separate closely apposed bones like the femur and acetabulum in the setting of joint space narrowing or the carpal bones; failure to capture a bony structure) and oversegmentation.^{12–14} Owing to such limitations, investigators have pursued hybrid techniques that incorporate several algorithms.^{12–14}

The case series presented here illustrates the anatomic regions where bone segmentation is most critical for 3D CT angiography, including the aorta, renal arteries, and extremities. Whereas editing with IWT is an efficient method of improving the diagnostic capacity of a 3D-rendering, errors can still arise when vessels are located in close proximity to bone (Fig. 13). In our experience, the most common segmentation error is actually undersegmentation of the ribs (Fig. 6), which can be easily corrected by applying bone markers if necessary.

For orthopedic imaging with 3D volume rendering, the percentage classifier segmentation technique enables selective display of the bones by adjusting the transfer function to only incorporate the highest attenuation voxels in the 3D display. Segmentation with VR is sufficient for a range of musculoskeletal applications. The utility of IWT for 3D VR of skeletal structures is the capacity to visualize bone surfaces that are traditionally not accessible to the viewing eye. Specifically, the surface of the bone within a joint cannot be seen unless the bone is segmented from its articulation, accomplished through placement of markers on selective bones (Figs. 9 and 10).

Fig 11. Same patient as Figure 10. The comminuted right pelvic fracture involves the acetabulum. Using a bone marker (a) on an oblique volume rendering, the right proximal femur is removed, providing an exceptional view of the fractured acetabulum (b).

CONCLUSION

In conclusion, we present a set of common visualization applications in MDCT where bone segmentation is useful and demonstrate the utility of the IWT technique for those applications. The technique has potential to further improve interpretation of 3D-rendered multide-

tector CT datasets, particularly in regions where clip plane editing is limited. Future investigations will need to evaluate the diagnostic accuracy for separating the vasculature from very closely approximated bony structures and for extracting bones from joints, particularly in the setting of comminuted fractures or joint space narrowing.

Fig 12. 50 year old man with clinical concern for foot abscess. Using the IWT bone markers, the talus and 4th metatarsal are selectively removed from the remainder of the skeletal anatomy on these coronal volume renderings.

Fig 13. 33-year-old man status post gunshot wound. A series of coronal color-coded volume renderings from an intravenous contrast-enhanced MDCT of the calf are shown before (a) and after (b–d) automated segmentation. Images c and d reveal that the IWT has oversegmented a section of normal artery that is closely apposed to bone.

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