Three-Dimensional (3-D) Segmentation of Knee Cartilage from 3.0 T MR Images using a Graph-Cuts Technique

H. Shim[1,2], S. Chang[3], C. Tao[1], J. Wang[1], and K. T. Bae[1]

[1]Department of Radiology, University of Pittsburgh, Pittsburgh, PA, United States, [2]School of Electrical Engineering, Seoul National University, Seoul, Seoul, Korea, Republic of, [3]Department of Radiology, Washington University, St. Louise, MO, United States

Introduction

Osteoarthritis (OA), which is a common cause of disability, is associated with degradation of articular cartilage. Quantitative evaluation of knee cartilage requires segmentation of the cartilage which is challenging and laborious. For instance, manual delineation of cartilage boundaries by an expert often results in several hours per case and is subject to analyst bias and error. Hence, we have developed a semi-automated approach based on a graph-cuts algorithm [1] for efficient and reproducible segmentation of knee cartilage from high-resolution 3T MR images. We also evaluated the performance of our semi-automated graph-cuts method and compared it to the performance of the conventional manual delineation segmentation method.

Material and Methods

MR image sets from eight subjects were selected from the double-echo and steady-state (DESS) MR right knee images in the Osteoarthritis Initiative (OAI) database. These subjects were chosen with consideration of OA severity. The MR images had 140x140 mm^2 field of view, 384x384 matrix size, 160 slices, and 0.36x0.36x0.70 mm^3 voxel resolution. The semi-automated segmentation method was completed in two steps (Fig. 1): placement of 'seeds' (i.e., curvilinear marks) over specific anatomical regions by an observer (Fig. 2b) and automated segmentation by computer. While the first step relies on the expert's perception and knowledge of knee anatomy, the second step takes advantage of the reliability of the computer. Since the seeds placed on a slice are propagated to adjacent slices with decreasing thickness (Fig. 2c), the observer may place seeds on every fifth to tenth slice. These two processes can be iterated, until the observer is satisfied with the segmentation result (Fig. 2d). For the manual segmentation by boundary delineation, every 3rd slice was sampled from the original dataset to generate a smaller dataset (384x384x53 voxels), because manual boundary delineation on every slice is exceedingly time-consuming. Two observers reviewed every slice of this smaller image dataset and manually delineated the boundaries of the cartilage of the femur, tibia, and patella with an electronic pen.

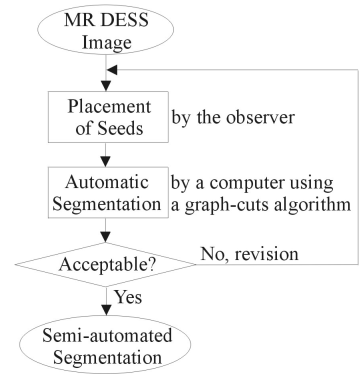

Fig. 1 The overall workflow:

Results and Discussion

The manual and semi-automated segmentation methods were evaluated and compared for their efficiency and inter-observer reproducibility. Efficiency was determined by segmentation processing time. The mean (±SD) manual segmentation time, which was based on processing only one-third of the original dataset, was 164(±47) min for observer 1 and 124(±26) min for observer 2. On the other hand, the mean (±SD) semi-automated segmentation time was 57(±12) min for observer 1 and 35(±5) min for observer 2, which means that the semi-automated method is approximately ten times more efficient than the manual method ($P<0.001$). The reproducibility of two methods was determined by means of the Dice Similarity Coefficient (DSC), which measures how closely two segmentation results match when they are superimposed onto each other. The mean (±SD) inter-observer DSC (superimposing segmentation by observer 1 over that of observer 2) was 87.8(±1.3)% for the manual delineation and 94.3(±1.1)% for the semi-automated segmentation. This implies that the semi-automated segmentation was significantly more reproducible between the two observers than the manual delineation ($P<0.001$). This trend was also confirmed by the qualitative evaluation in which cartilages (manual and semi-automated) segmented by observers 1 and 2 were displayed in different colors (Figs. 3). Non-overlapping superimposed volume fragments (in blue and red) were more apparent with the manual than with the semi-automated segmentation volumes. This is because a large portion of the segmentation operation was performed algorithmically by the computer based on the graph-cuts algorithm. This algorithmic process is consistent and not subjected to inter-observer variations. Thus, minor variations (e.g., variations in the location and size of seeds) between the two observers in the placement of seeds in the semi-automated method did not affect the segmentation outcome. In comparison, the manual segmentation method, which depends 100% on the subjective determination of cartilage boundaries by an observer, is more laborious and variable with reduced inter-observer reproducibility. Any variations in manual boundary delineation will likely affect the precise quantitative measurement of knee cartilage since the cartilage is very thin (only 1.3-2.5 mm in healthy subjects). In conclusion, we have developed an efficient, reliable semi-automated graph-cuts method for the segmentation of knee cartilage from high-resolution 3T MR imaging of the knee. The semi-automated method was significantly more efficient (approximately 10–folds for segmenting cartilage on every slice) and more reproducible than a manual boundary delineation method.

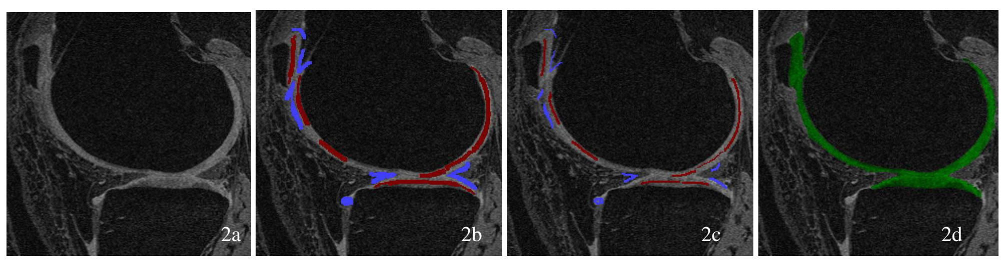

Fig. 2 (a) an original slice, (b) placement of seeds (i.e., red and blue curvilinear marks) (c) propagation of the seeds in (b) to an adjacent slice, (d) segmentation by a graph-cuts technique colored in green.

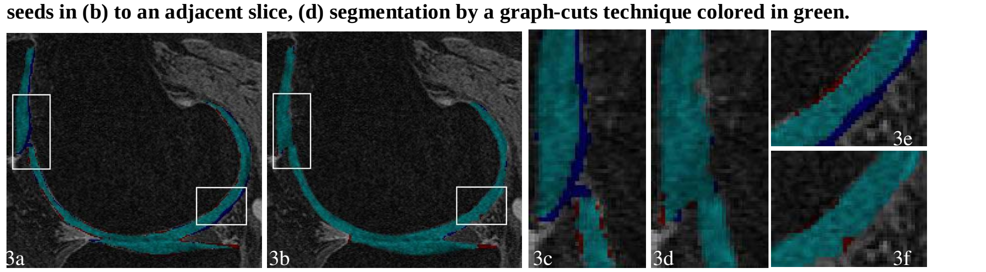

Fig. 3 Comparative representation of the inter-observer reproducibility of the manual method and semi-automated method: (a) the superimposition of the two manual results where the observer 1 result was colored in red, the observer 2 result was colored in blue, and the overlapped result was colored in cyan, (b) the superimposition of the two semi-automated results colored in the same way, (c, e) enlargements of the boxes in (a) having more fragments which are persistently red and blue, (d,f) enlargements of the boxes in (b) having much less blue and red regions, which means higher inter-observer reproducibility of the semi-automated than the manual method.

References

[1] Boykov et al., ICCV:105-112 (2001);