

Automated Anatomical Likelihood Driven Extraction and Branching Detection of Aortic Arch in 3-D Chest CT

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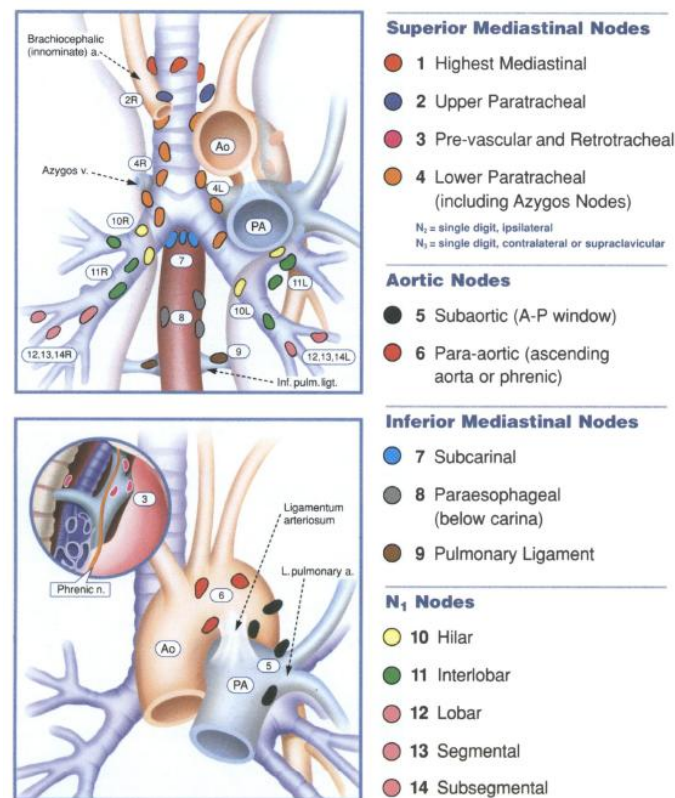
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Motivation

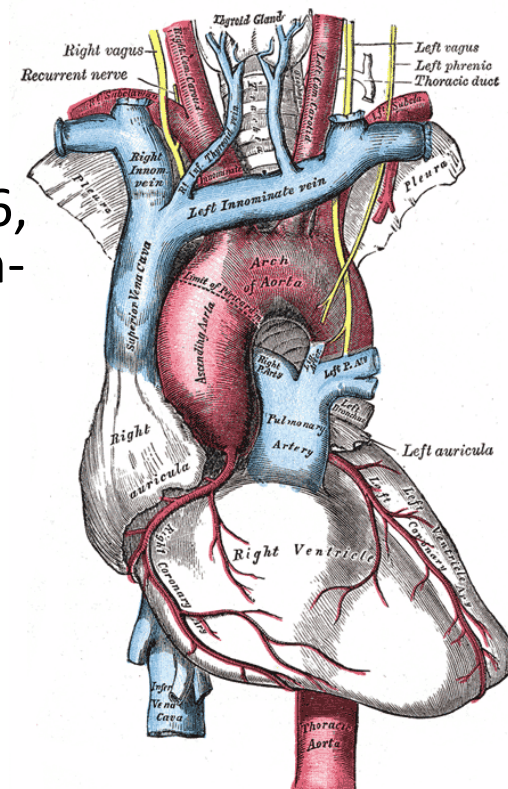
- Reduction of physicians' work load during diagnosis and treatment planning, e.g. for
 - Definition of mediastinal anatomy or lymph node stations for lung cancer staging
 - Planning of transbronchial needle aspiration
- Inter-patient registration
- Mediastinal atlas generation



[Mountain and Dresler: Chest 1998]

Related Work

- Aortic arch segmentation:
 - Mainly on contrast enhanced CT [Kovács2006, Peters2008]; usually not working well on non-contrast CT
 - Model-based methods [Kitasaka2002, Taeprasartsit2007] promising (also for non-contrast CT), but limited to cases similar to the model(s)
- Branching detection:
 - No prior work



- Kovács, T., Cattin, P., Alkadhi, H., Wildermuth, S., Székely, G.: Automatic segmentation of the vessel lumen from 3D CTA images of aortic dissection. In: Bildverarbeitung für die Medizin. (2006)
- Peters, J., Ecabert, O., Lorenz, C., von Berg, J., Walker, M.J., Ivanc, T.B., Vembar, M., Olszewski, M.E., Weese, J.: Segmentation of the heart and major vascular structures in cardiovascular CT images. In: SPIE Medical Imaging. (2008)
- Kitasaka, T., Mori, K., Hasegawa, J., Toriwaki, J., Katada, K.: Automated extraction of aorta and pulmonary artery in mediastinum from 3D chest X-ray CT images without contrast medium. In: SPIE Medical Imaging. (2002)
- Taeprasartsit, P., Higgins, W.E.: Method for extracting the aorta from 3D CT images. In: SPIE Medical Imaging. (2007)

Method – Overview

- Preprocessing
 - Image smoothing by median filtering
 - Lung, airways (up to main bronchi), and carina extraction [Hu2001, Feuerstein2009]
 - Aortic arch segmentation
 - Aortic arch delineation by circular Hough transforms
 - B-spline fitting to a Euclidean distance (likelihood) image
 - Branching extraction
 - Parallel projection of boundary of segmented aorta
 - Likelihood driven branching assignment
- Hu, S., Hoffman, E.A., Reinhardt, J.M.: Automatic lung segmentation for accurate quantification of volumetric X-ray CT images. IEEE Transactions on Medical Imaging 20(6) (2001) 490-498
- Feuerstein, M., Kitasaka, T., Mori, K.: Automated Anatomical Likelihood Driven Extraction and Branching Detection of Aortic Arch in 3-D Chest CT. In: Second International Workshop on Pulmonary Image Analysis. (2009)

Aortic Arch Segmentation

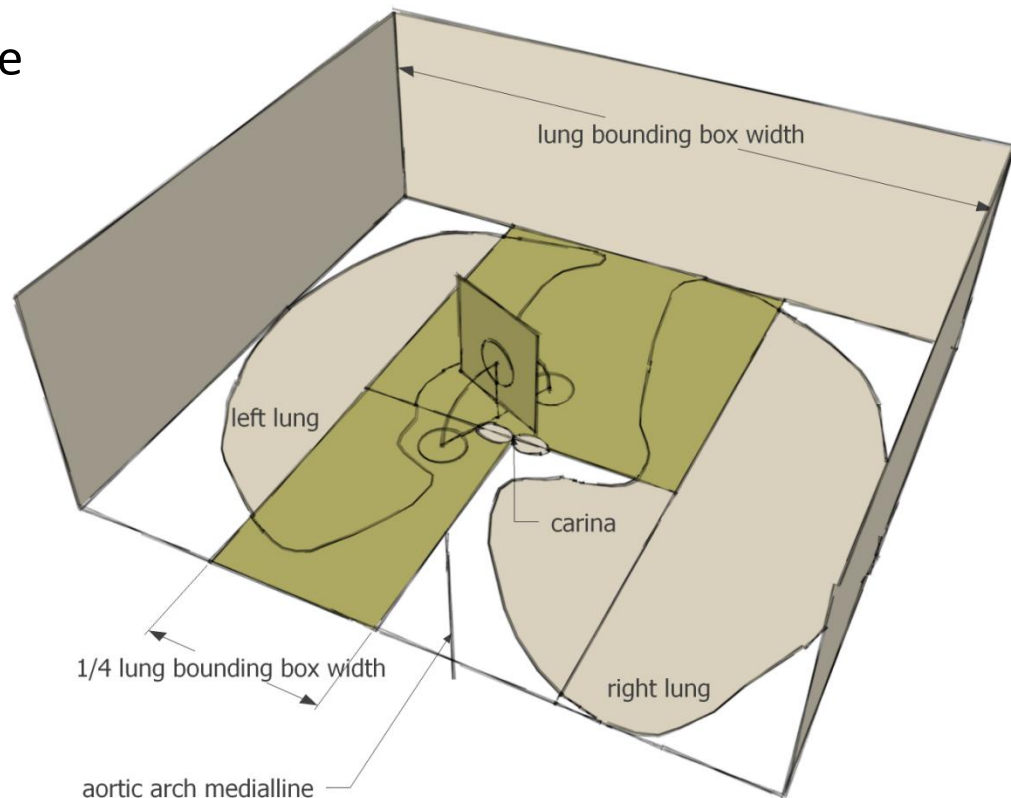
Circular Hough Transform

- Search for 3 Hough circles intersecting the ascending, descending, and upper part of the aortic arch (in khaki colored search regions)
- Voting for Hough circle through ascending aorta (to exclude inferior vena cava and brachiocephalic trunk):

$$a = \arg \max_{i=1..n} \left(\frac{h(\mathbf{x}_i)}{\max_{i=1..n}(h(\mathbf{x}_i))} \cdot \frac{r(\mathbf{x}_i)}{\max_{i=1..n}(r(\mathbf{x}_i))} \cdot \frac{d_{car_{max}} - d_{car}(\mathbf{x}_i)}{d_{car_{max}}} \right)$$

- Voting for Hough circle through upper part (to exclude left pulmonary artery):

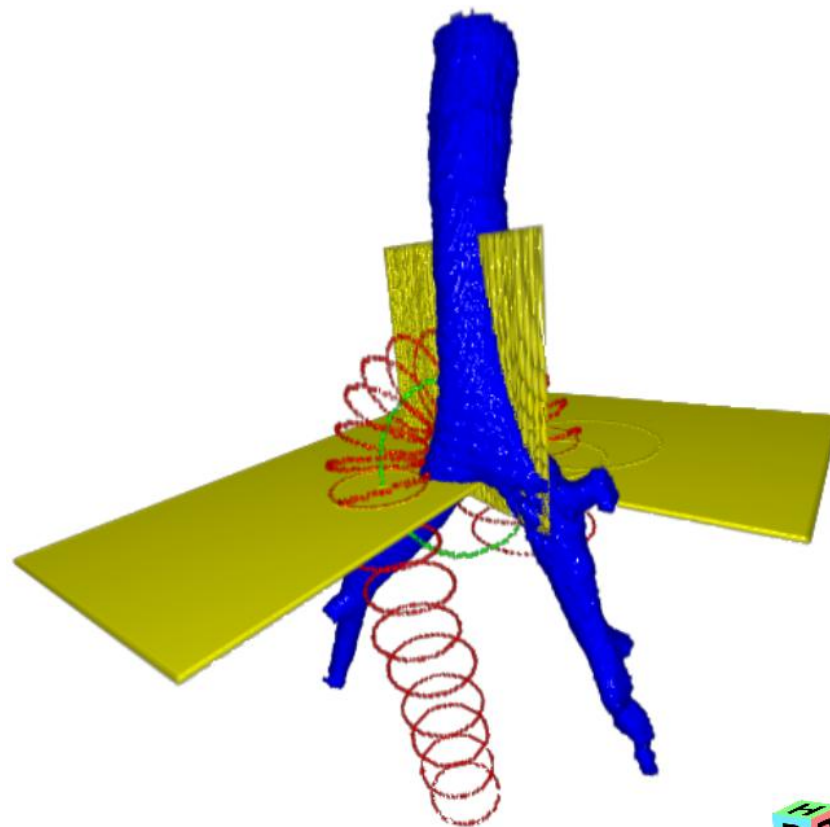
$$u = \arg \max_{i=1..n} \left(\frac{h(\mathbf{x}_i)}{\max_{i=1..n}(h(\mathbf{x}_i))} \cdot \frac{r(\mathbf{x}_i)}{\max_{i=1..n}(r(\mathbf{x}_i))} \cdot \frac{d_{cen_{max}} - d_{cen}(\mathbf{x}_i)}{d_{cen_{max}}} \right)$$



Aortic Arch Segmentation

Circular Hough Transform

- Analog to [Kovács2006]
 - Search for more Hough circles in oblique slices reconstructed along the circle (green) through the centers of the 3 initial Hough circles
 - Extension of search for ascending and descending aorta in axial slices

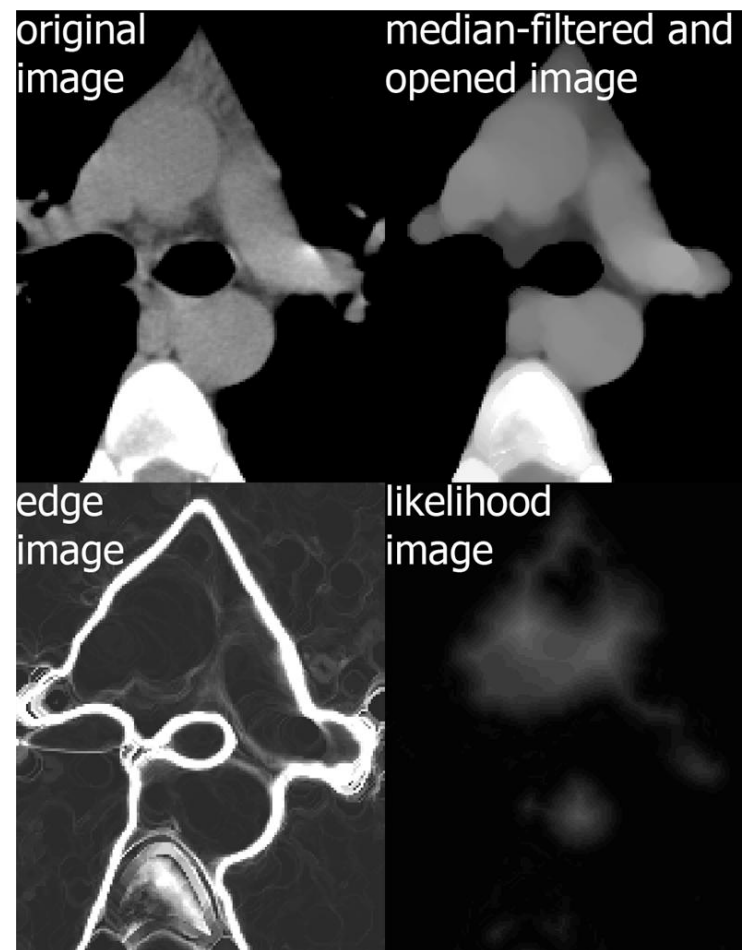


- Kovács, T., Cattin, P., Alkadhi, H., Wildermuth, S., Székely, G.: Automatic segmentation of the vessel lumen from 3D CTA images of aortic dissection. In: Bildverarbeitung für die Medizin. (2006)

Aortic Arch Segmentation

B-Spline Fitting to Likelihood Image

- Likelihood (Euclidean distance) image generation
 - Morphological opening (spherical)
 - Gradient magnitude image computation
 - Edge detection in gradient magnitude image, only leaving voxels with high standard deviation within spherical neighborhood in the opened image
 - Application of Euclidean distance transform to edge image to obtain likelihood image (masking out lung voxels)



Aortic Arch Segmentation

B-Spline Fitting and Recovery

- B-Spline Fitting

- Generation of NURBS curve from Hough circle centers
- Fitting NURBS curve to likelihood image by minimizing:

$$\arg \min_{\mathbf{P}_i} \left(-\frac{1}{m} \sum_{j=1}^m d_L^2 \left(N \left(\frac{j}{m} \right) \right) \right), \text{ where } N(u) = \sum_{i=1}^k R_{i,p} \mathbf{P}_i$$

- Vessel Lumen Recovery

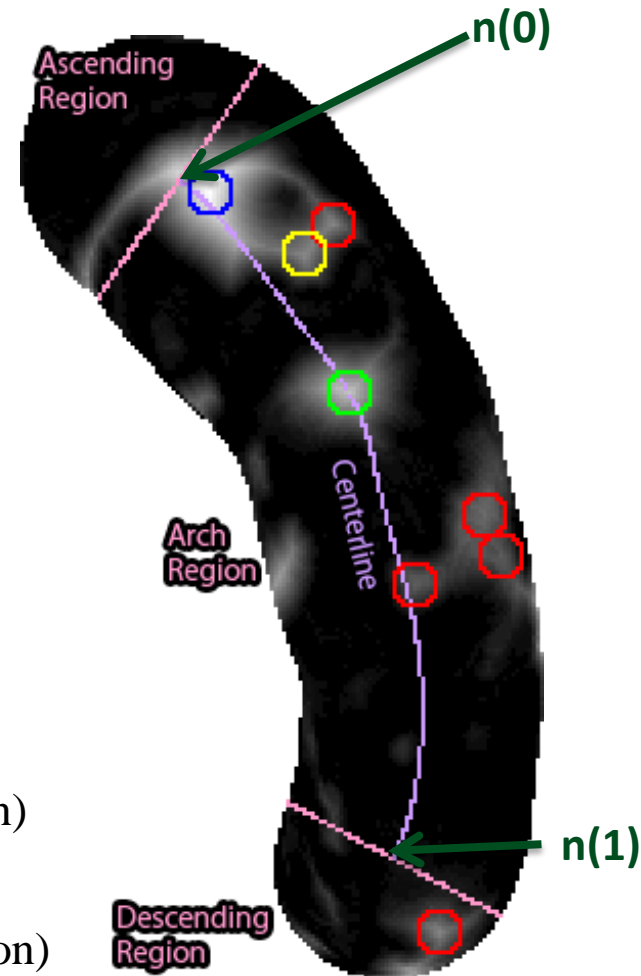
- Inverse Euclidean distance transform
- Spherical growing, until standard deviation of all sphere voxels exceeds a threshold

Branching Extraction

Parallel Projection

- Parallel projection (in z direction, starting at the carina) of
 - Centerline of the aortic arch
 - Likelihood image voxels corresponding to the 3D boundary of the segmentation (“2D likelihood image”)
- Computation of the distance of each pixel to the boundary of the 2D projection (“boundary distance image”)
- Approximation of a B-spline $n(u)$ to the centerline
- Definition of search regions: ascending, arch, and descending region

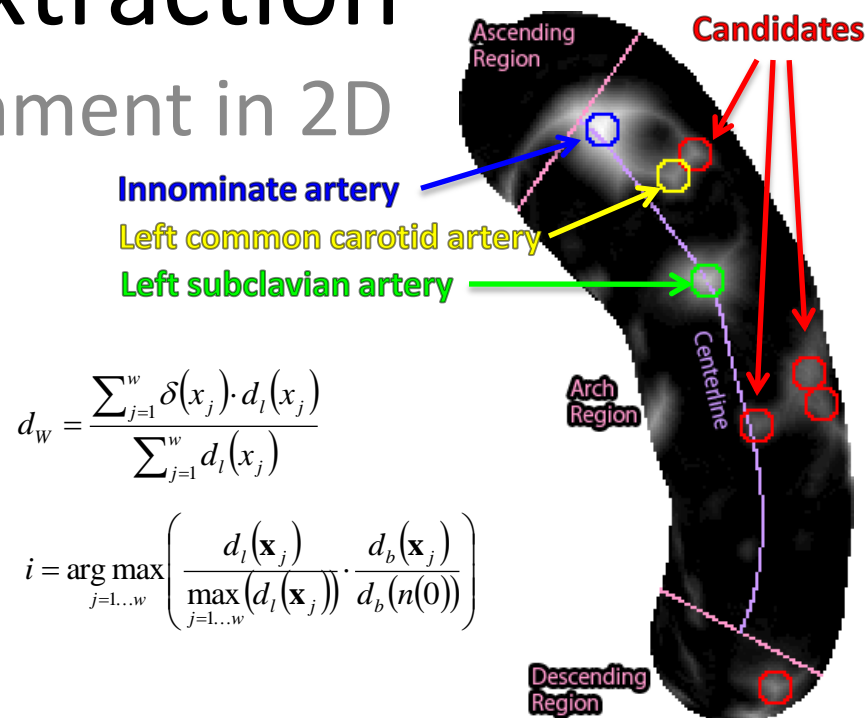
$$\delta(\mathbf{x}) = \begin{cases} -|n(0) - \mathbf{x}| & \text{if } f(\mathbf{x}) = 0 & \text{(ascending region)} \\ l_n(0, f(\mathbf{x})) & \text{if } 0 < f(\mathbf{x}) < 1 & \text{(arch region)} \\ l_n(0,1) + |n(1) - \mathbf{x}| & \text{if } f(\mathbf{x}) = 1 & \text{(descending region)} \end{cases}$$



Branching Extraction

Branching Assignment in 2D

- Local maxima search in 2D likelihood image
- Innominate artery
 - Choose most likely candidate within average weighted distance d_w
 - If it is inside the ascending region, update it to i (to take care of left innominate vein)
- Left subclavian artery
 - about one third the arc length of the centerline curve away from the innominate artery
- Left common carotid artery
 - halfway between the innominate and left subclavian artery



$$d_w = \frac{\sum_{j=1}^w \delta(x_j) \cdot d_l(x_j)}{\sum_{j=1}^w d_l(x_j)}$$

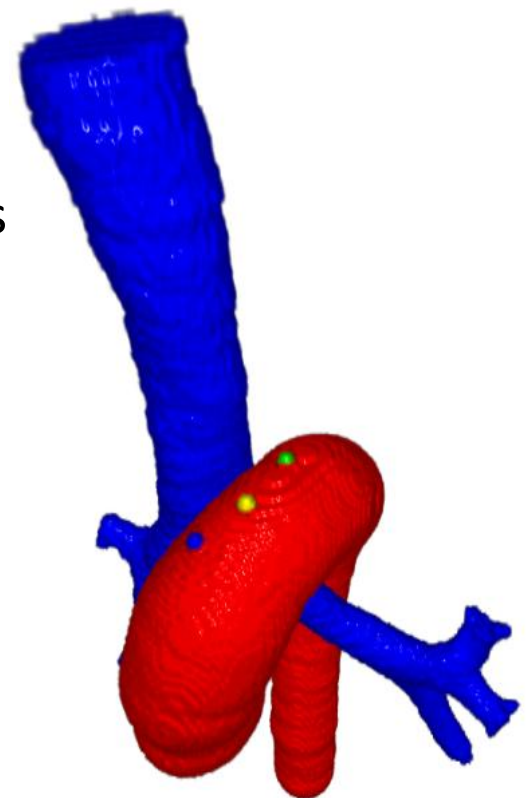
$$i = \arg \max_{j=1 \dots w} \left(\frac{d_l(\mathbf{x}_j)}{\max_{j=1 \dots w} (d_l(\mathbf{x}_j))} \cdot \frac{d_b(\mathbf{x}_j)}{d_b(n(0))} \right)$$

$$s = \arg \max_{j=1 \dots v} \left(\frac{d_l(\mathbf{x}_j)}{\max_{j=1 \dots v} (d_l(\mathbf{x}_j))} \cdot \frac{d_b(\mathbf{x}_j)}{d_b(n(f(\mathbf{x}_j)))} \cdot \left(1 - \frac{|l_n(0, \frac{1}{3}) - d_i(\mathbf{x}_j)|}{l_n(0, \frac{2}{3})} \right) \right)$$

$$c = \arg \max_{j=1 \dots u} \left(\frac{d_l(\mathbf{x}_j)}{\max_{j=1 \dots u} (d_l(\mathbf{x}_j))} \cdot \frac{d_b(\mathbf{x}_j)}{d_b(n(f(\mathbf{x}_j)))} \cdot \left(1 - \frac{|d_s(\mathbf{x}_j) - d_i(\mathbf{x}_j)|}{d_s(\mathbf{x}_j) + d_i(\mathbf{x}_j)} \right) \right)$$

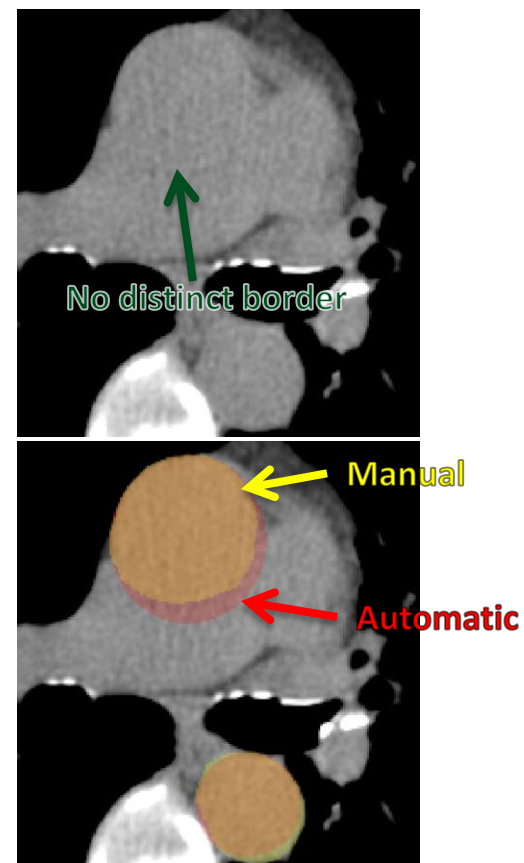
Evaluation

- 10 contrast enhanced and 30 non-contrast chest CTs of various hospitals, scanners, and acquisition parameters.
- Comparison to manual segmentations/extractions
- Results (averaged over all 40 data sets):
 - Preprocessing
 - Runtime: 68 s
 - Aortic arch segmentation
 - Runtime: 74 s
 - Sensitivity: 95%, Specificity: 99%, Jaccard index: 92%
 - Minimum distance (between boundaries): 0.4 mm
 - Branching detection
 - Runtime: 12 s
 - Distance to manually selected branchings: 2.0 mm
 - TP: 114, FP: 0, FN: 3 (total)



Discussion

- Slight overlaps and mis-extractions when
 - Cardiac motion or calcifications induce imaging artifacts
 - The pulmonary artery, superior vena cava, or other tissue is adjacent to the aorta
- Misdetection of a few branchings in the absence of a distinct local likelihood maximum
 - When the left common carotid artery was too close to one of the others
 - In the presence of calcifications or imaging artifacts
- Future work: Adaption of algorithm to four artery branchings (no such case in our 40 test data sets, but 4.6% of a larger study [Nelson2002])



• Nelson, M.L., Sparks, C.D.: Unusual aortic arch variation: Distal origin of common carotid arteries. *Clinical Anatomy* 14 (2001) 62-65

Conclusion

- Stable and fully automated aortic arch and branching extraction in both non-contrast and contrast enhanced chest CT
- Extension and improvement of current state of the art
- Quantitative evaluation on a large number of datasets
- Support of physicians' diagnosis and treatment planning
- Provision of valuable landmarks for
 - further segmentation of the aortic branches
 - intra- and interpatient registration of the mediastinum
 - mediastinal atlas generation

Thank you for your attention!

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