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

Marco Feuerstein\textsuperscript{a}, Takayuki Kitasaka\textsuperscript{b,c}, Kensaku Mori\textsuperscript{a,c}

\textsuperscript{a} Graduate School of Information Science, Nagoya University
\textsuperscript{b} Faculty of Information Science, Aichi Institute of Technology
\textsuperscript{c} MEXT Innovation Center for Preventive Medical Engineering, Nagoya University
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

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

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):

\[
a = \arg \max_{i=1\ldots n} \left( \frac{h(x_i)}{\max(h(x_i))} \cdot \frac{r(x_i)}{\max(r(x_i))} \cdot \frac{d_{\text{car}} - d_{\text{car}}(x_i)}{d_{\text{car}}_{\text{max}}} \right)
\]

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

\[
u = \arg \max_{i=1\ldots n} \left( \frac{h(x_i)}{\max(h(x_i))} \cdot \frac{r(x_i)}{\max(r(x_i))} \cdot \frac{d_{\text{cen}} - d_{\text{cen}}(x_i)}{d_{\text{cen}}_{\text{max}}} \right)
\]
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

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:

\[
\arg \min_{p_i} \left( -\frac{1}{m} \sum_{j=1}^{m} d_L^2 \left( N \left( \frac{j}{m} \right) \right) \right), \text{ where } N(u) = \sum_{i=1}^{k} R_{i,p} P_i
\]

• 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

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

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

\[
i = \arg \max_{j=1..w} \left( \frac{d_l(x_j)}{\max_{j=1..w} d_l(x_j)} \cdot \frac{d_b(x_j)}{d_b(n(0))} \right)
\]

\[
s = \arg \max_{j=1..w} \left( \frac{d_l(x_j)}{\max_{j=1..w} d_l(x_j)} \cdot \frac{d_b(x_j)}{d_b(n(f(x_j)))} \cdot \left( 1 - \frac{|l_n(0, \frac{1}{3}) - d_l(x_j)|}{l_n(0, \frac{2}{3})} \right) \right)
\]

\[
c = \arg \max_{j=1..w} \left( \frac{d_l(x_j)}{\max_{j=1..w} d_l(x_j)} \cdot \frac{d_b(x_j)}{d_b(n(f(x_j)))} \cdot \left( 1 - \frac{|d_s(x_j)-d_l(x_j)|}{d_s(x_j)+d_l(x_j)} \right) \right)
\]
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])

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!

Acknowledgements:

• All our colleagues at Mori Group
• JSPS postdoctoral fellowship program for foreign researchers
• Grant-in-Aid for Science Research funded by JSPS
• Grant-in-Aid for Cancer Research funded by the Ministry of Health, Labour and Welfare, Japan
• Program of formation of innovation center for fusion of advanced technologies "Establishment of early preventing medical treatment based on medical-engineering for analysis and diagnosis" funded by MEXT