Feature extraction and quantification to explore human vasculature

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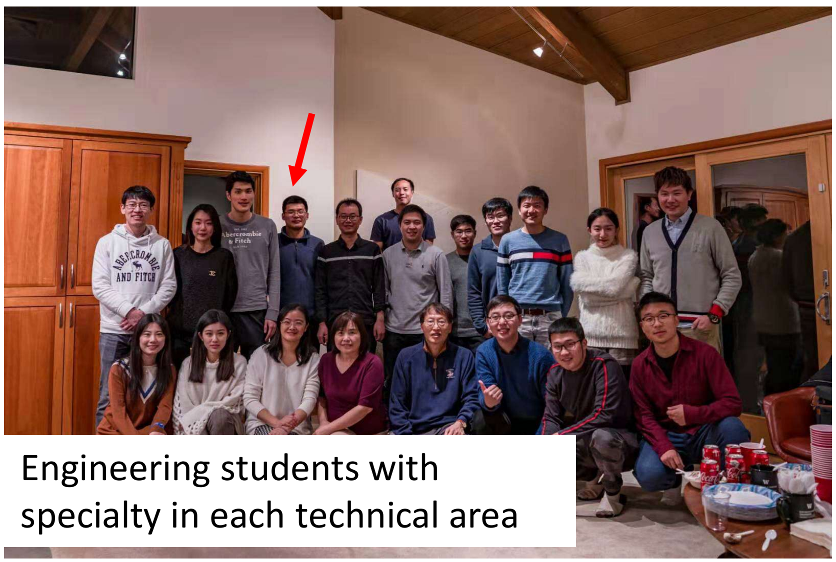
Introduction of myself and my groups

- A 5th year Electrical Engineering PhD student receiving funding from a Radiology lab
- Productive medical researcher with AI/Imaging background
  - 23 publications (13 as first author)



Engineering students with specialty in each technical area

Information Processing Lab
Department of Electrical and Computer Engineering

- MR physicists
- Research scientists
- Medical reviewers
- Radiologists
- Neurologists
- Vascular surgeons
- MR operators
- Statisticians

Vascular Imaging Lab
Department of Radiology

Introduction of my advisors

Dr. Jenq-Neng Hwang

- Professor of Department of Electrical & Computer Engineering
- Associate Chair for Global Affairs and International Development

Research interests

- Machine learning
- Computer vision
- Multimedia network

We are good at XXX techniques

Compare with SOTA

No innovations from medical people

To graduate/find a job you need to do XXX

Research interests

- Magnetic Resonance Imaging
- Vulnerable Plaque/Vessel Wall Imaging and Analysis
- Cardiovascular Disease Analysis and Investigation

We have plenty of data

How about the performance on another dataset

Those IEEE papers only work on their own data

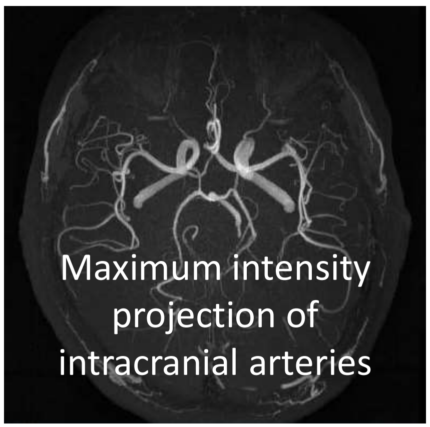
We should do XXX to get funding

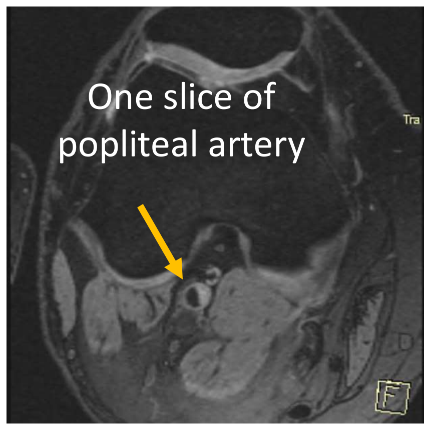
Dr. Chun Yuan

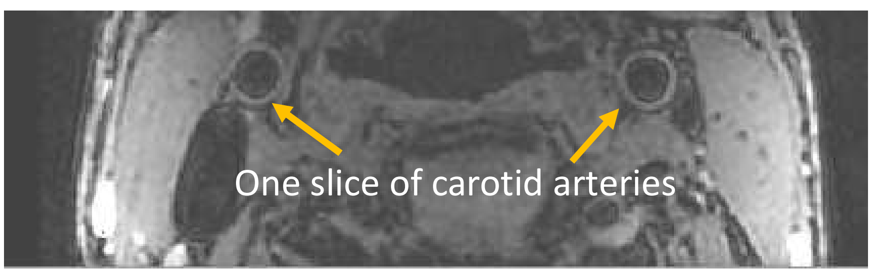
- Professor — Department of Radiology and Bioengineering
- Vice Chair for Global Affairs Research

Human vasculature

> A complicated system visualized by Magnetic Resonance Imaging (MRI)







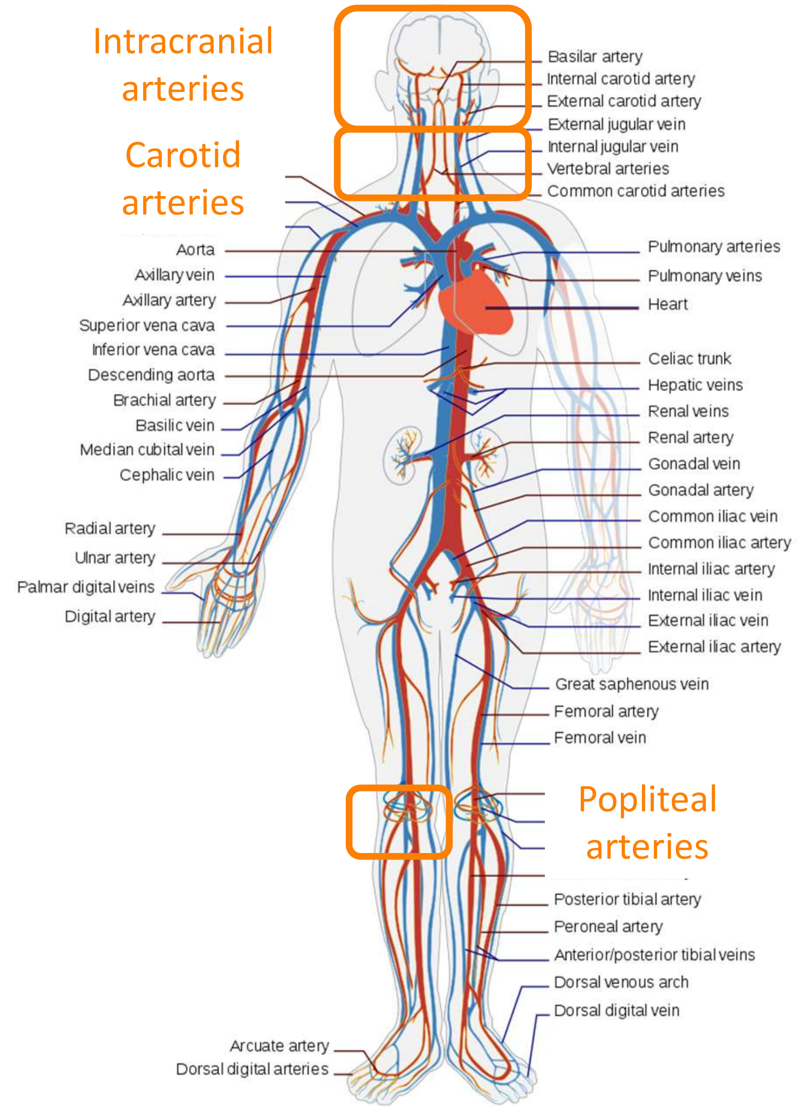


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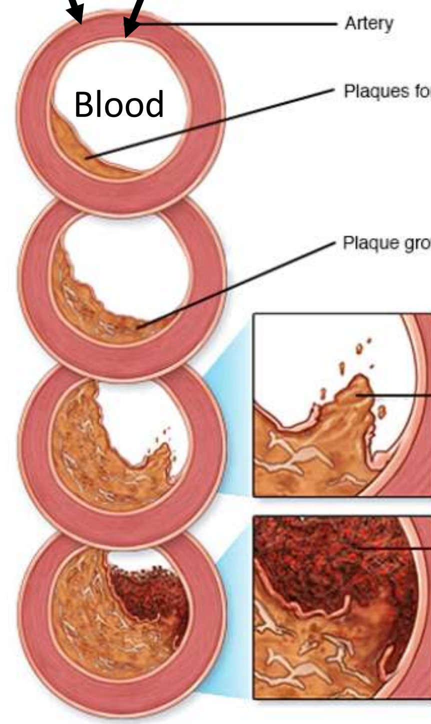
Image from Wikipedia: Circulatory_system

Background: atherosclerosis

- Vascular disease: top death causes worldwide
- Atherosclerotic plaque: cause of ischemic strokes, visualizable from MRI
- Comprehensive vasculature analysis needed
  - Identify centerlines for structure and blood flow
  - Identify vessel wall for plaque assessment
- Automation
  - Unbiased, applicable to large datasets
- Challenges
  - Tiny region, weak signal, limited samples



Cross sectional view of an artery with accumulating plaque

Image from https://www.mayoclinic.org/diseases-conditions/arteriosclerosis-atherosclerosis/symptoms-causes/syc-20350569

Solution: iCafe toolset for quantitative vascular analysis

iCafe family toolset ("coffee menu")

Medical applications (Coffee names)

- Intracranial artery
  - **AICafe: iCafe with AI for automation**
  - MOCHA: multiplanar reformation for artery visualization
  - iCafe+: quantify vessel wall features
- Popliteal artery
  - **FRAPPE: automated analysis of popliteal artery**
- Carotid artery
  - **LATTE: detect and classify carotid lesions**

Techniques/ modules (Coffee ingredients)

- **Artery tracing**
- Multi-contrast registration
- **Anatomical labeling**
- **Lumen/wall segmentation**
- **Artery localization**
- **Image quality assessment**
- **Domain adaptation**

+

iCafe: vascular centerline generation (the espresso for all coffee)

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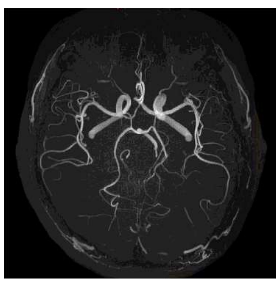
Due to the time limit, this presentation only covers drinks/modules in bold

iCafe (intraCranial artery feature extraction): the espresso

- Centerlines are the key: locate artery of interest and quantify blood flow
- iCafe: a C++ tool converting 3D MRA to quantitative vascular map [1]
  - Each artery modeled as a radius varying tube and labeled with a certain anatomical type
- AICafe: automated segmentation, tracing and labeling [2-4] with artificial intelligence



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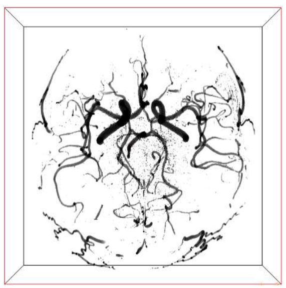

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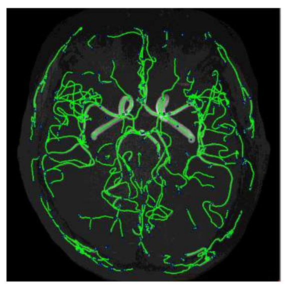

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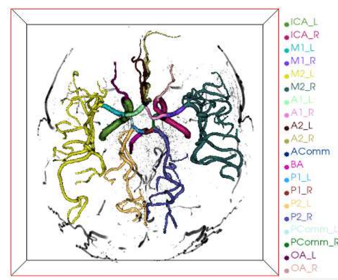
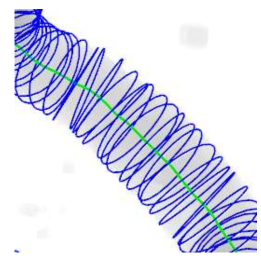


(d)



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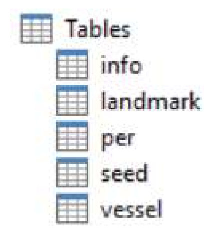

(f)

Image Preprocessing → **Lumen Segmentation** → **Vessel Tracing** → **Artery Labeling** → Feature Calculation → Output and Analysis

iCafe website: icafe.clatfd.cn

[1] Chen, et. al, Magn Reson Med, 2018.
[2] Chen, et. al, IEEE BIBM, 2017.
[3] Chen, et. al, MICCAI CVII-STENT Workshop 2019.
[4] Chen, et. al, MICCAI, 2020.

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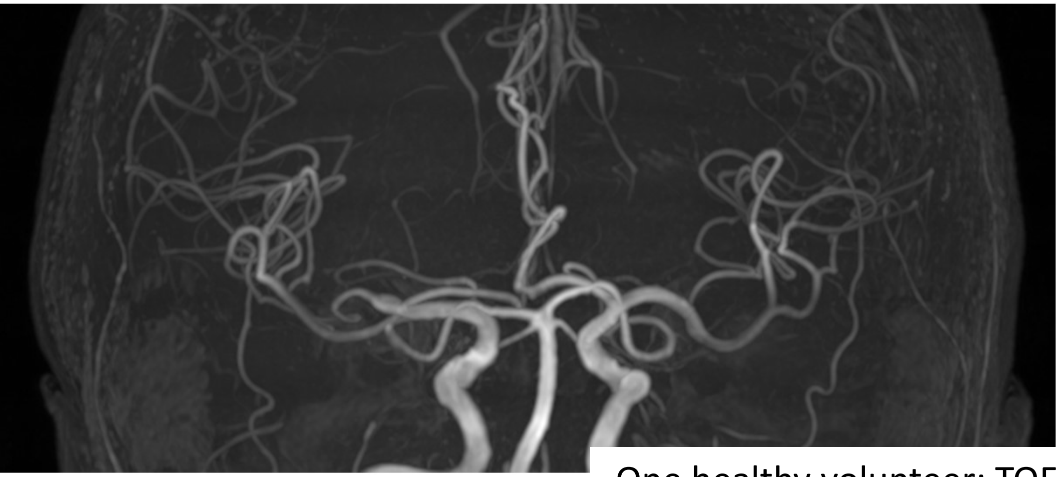
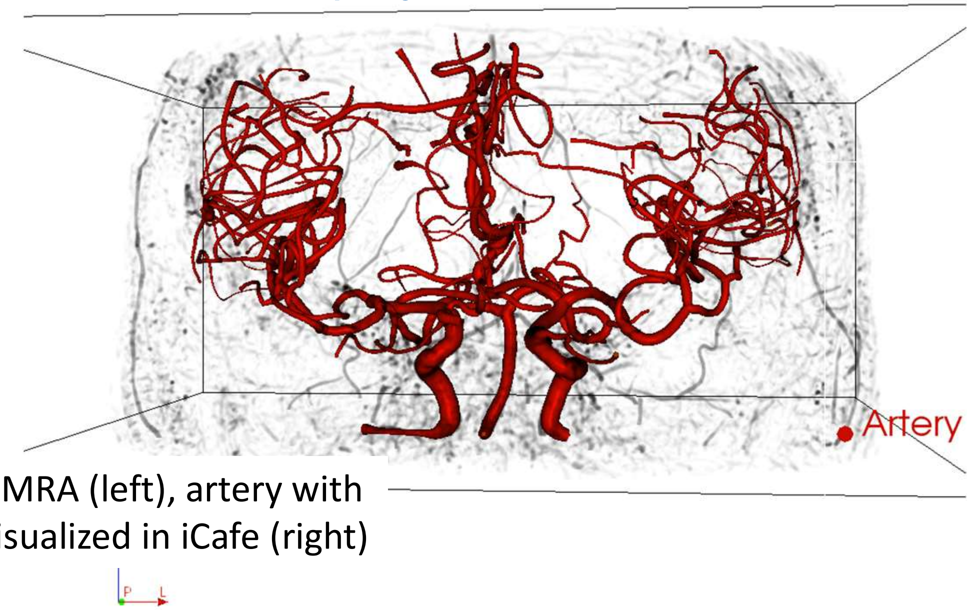
What is unique in iCafe

> Accurate [1]: Automated artery labeling with easy human corrections

> Comprehensive/Regional features useful for quantitative medical research
  - Features such as Left MCA length, Right anterior circulation artery volume, etc.
  - Easy translations: 15+ publications and used by 14+ sites globally

> Visualization: A united platform for vasculature display



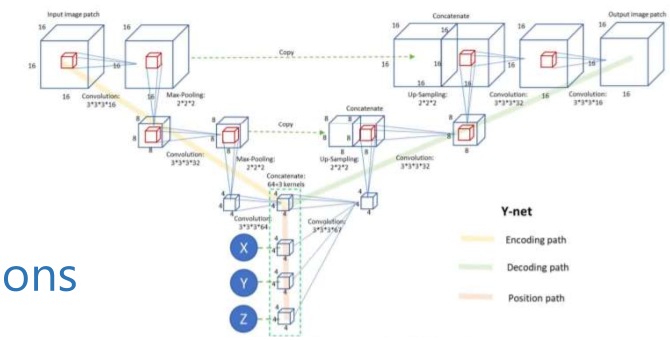


One healthy volunteer: TOF MRA (left), artery with different labeling schemes visualized in iCafe (right)

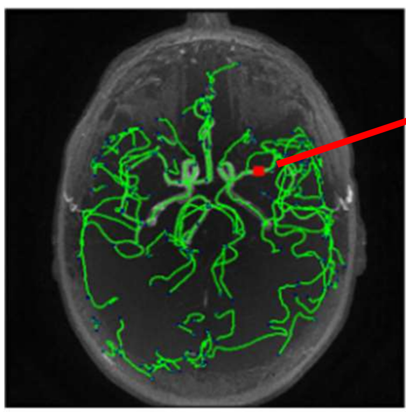
[1] Chen, et. al, Magnetic Resonance Imaging, 2019

Module 1: Y-net for lumen segmentation

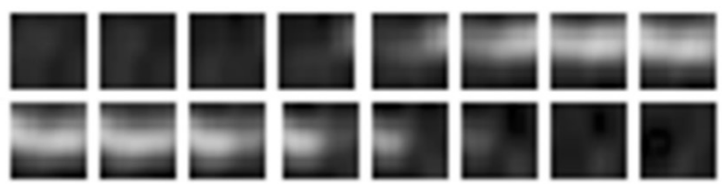
> Y-net: 3D CNN segmentation for lumen
  - Extract patches to better use limited data
  - Patch origin encoded in the CNN
  - One of the earliest CNN-based lumen segmentations



Network structure

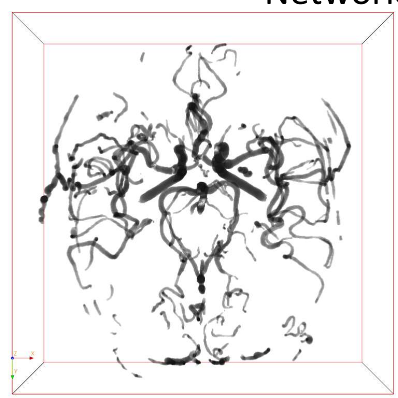


3D MRA with traces from iCafe

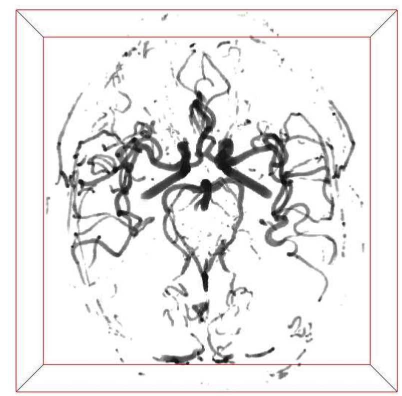


Original image patch

Label image patch



iCafe (Ground truth) segmentation

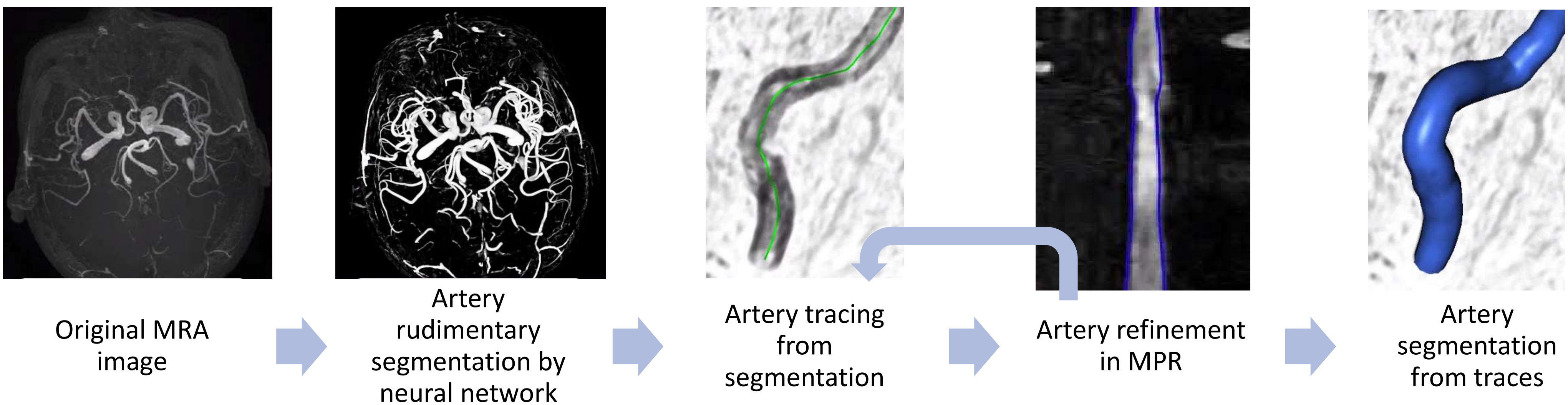


Y-net segmentation

From Chen, et. al, IEEE BIBM, 2017

Module 2: Artery tracing

> Use segmentation results to help better tracing (better contrast)
> Take advantage of cross-sectional plane relations and multiplanar reformation (MPR) to match and refine traces
> Use tracing results to help better segmentation (separate close arteries)



From Chen, et. al, MICCAI CVII-STENT Workshop 2019

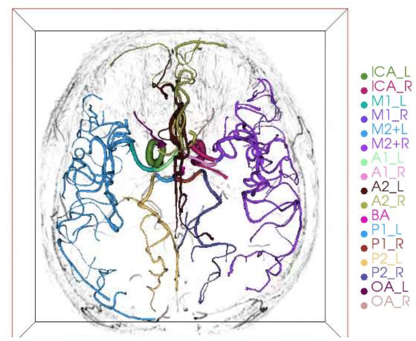
Module 3: Artery landmark labeling

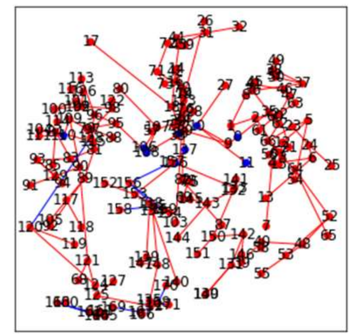
> Graph constructed from centerlines

> A message passing Graph Neural Network (GNN) for node and edge type prediction

> Combine human wisdom with machine knowledge in the design of hierarchical labeling framework

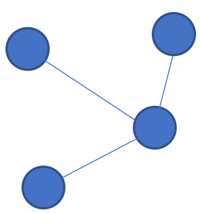
- Robust for anatomical variations

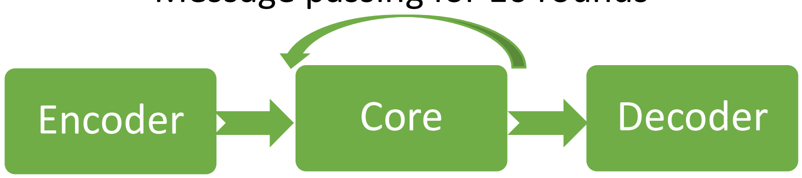


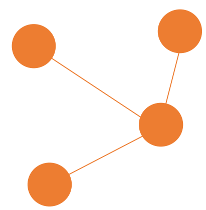


Intracranial arteries: a natural graph with 24 major types

Message passing for 10 rounds







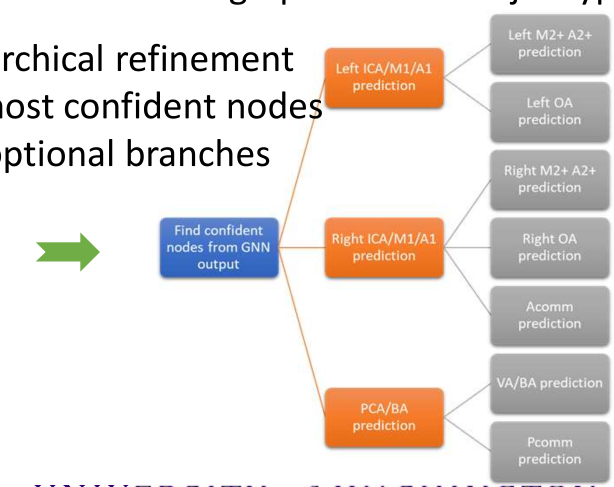
- Node (bifurcation/ending points) features
- Edge (artery) features

Encode edge and node features

Decode edge and node features

- Node features and labels
- Edge features and labels

Hierarchical refinement from most confident nodes to optional branches



From Chen, et. al, MICCAI 2020

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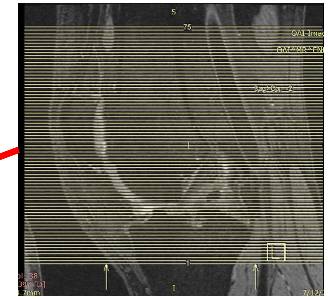
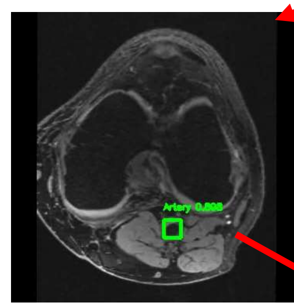
FRAPPE: Popliteal vessel wall analysis

iCafe | Lumen/wall segmentation | Artery localization

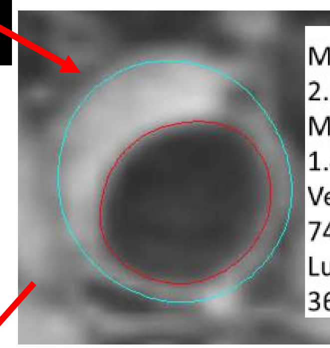
- Vessel wall in MR knee scans has valuable information for cardiovascular risk assessments [1]
- OAI dataset (4796 subjects, 8 time points, 3.5 million knee images) [2]
- FRAPPE [3]: accurately and automatedly **locate** and **quantify** vessel wall
  - Comparable with inter-rater variability
  - Process time <8 minutes/scan
- Equivalent of 67 years of manual work



Scan locations for knee



Example of an image slice with the artery region outlined in a green bounding box



Max wall thickness: 2.62 mm
Mean wall thickness: 1.46 mm
Vessel wall area: 74.49 mm^2
Lumen area: 36.30 mm^2

Enlarged region for vessel wall area with contours
Red: lumen contour
Blue: outer wall contour

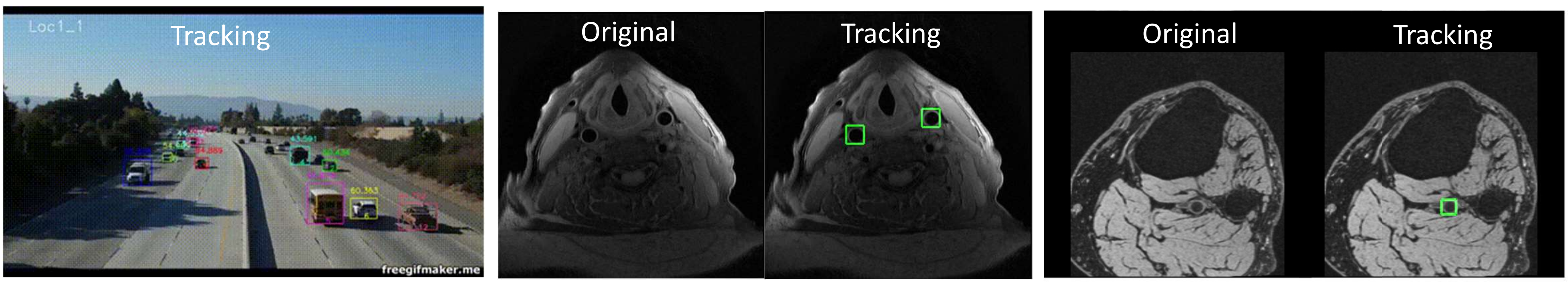
3D visualization with color map showing thickness

[1] Liu, et al, ATVB 2019 [2] https://nda.nih.gov/oai/
[3] Chen L, et. al, Magn Reson Med, 2020

FRAPPE: **F**ully automated and **R**obust **A**nalysis Technique for **P**o**p**liteal Artery Vessel Wall **E**valuation

Module 4: Artery localization

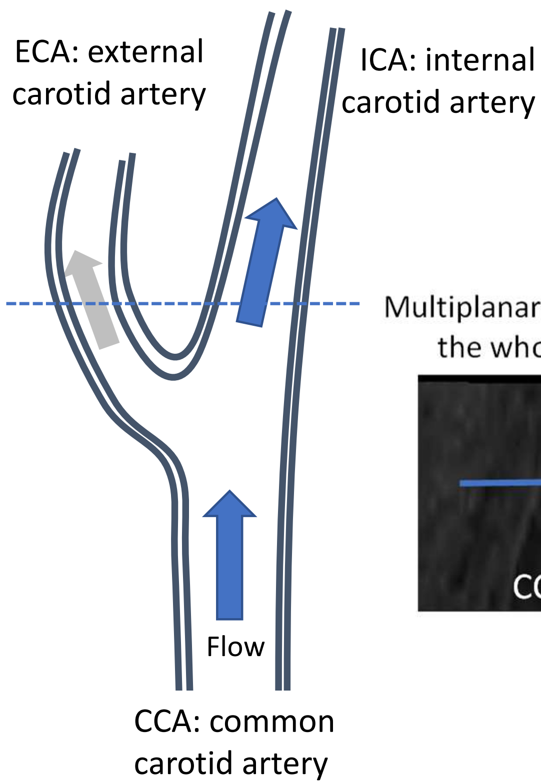
> Automatically find relatively straight arteries from 3D vessel wall images
> Time dimension in video equivalent to depth dimension in 3D medical image
> Centerline generation: tracking by detection
  - **Detection** of bounding boxes from each axial image slice
  - Combining detections using **tracklet refinement** algorithm



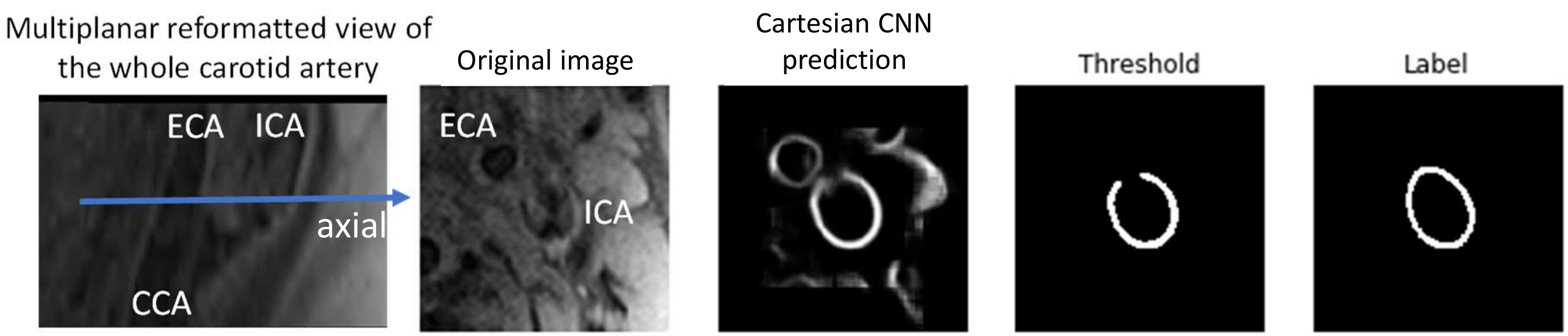
Left: Tracking results of cars in NVIDIA AI City Challenge [2]
Middle: Tracking results of a carotid artery (16 slices, 2mm thickness) [3]
Right: Tracking results of a popliteal artery (76 slices, 1.5mm thickness) [4]

[1] J. Redmon, CVPR, 2017 [2] Z. Tang, CVPR, 2018 [3] From Chen, et. al, IEEE Access, 2020. [4] Chen L, et. al, Magn Reson Med, 2020

Problem of vessel wall segmentation using Cartesian CNN



- Artery bifurcations cause many arteries coexist in the view
- Similar intensity patterns of all vessel walls highlighted
- Boundary continuity cannot be ensured where wall signal drops

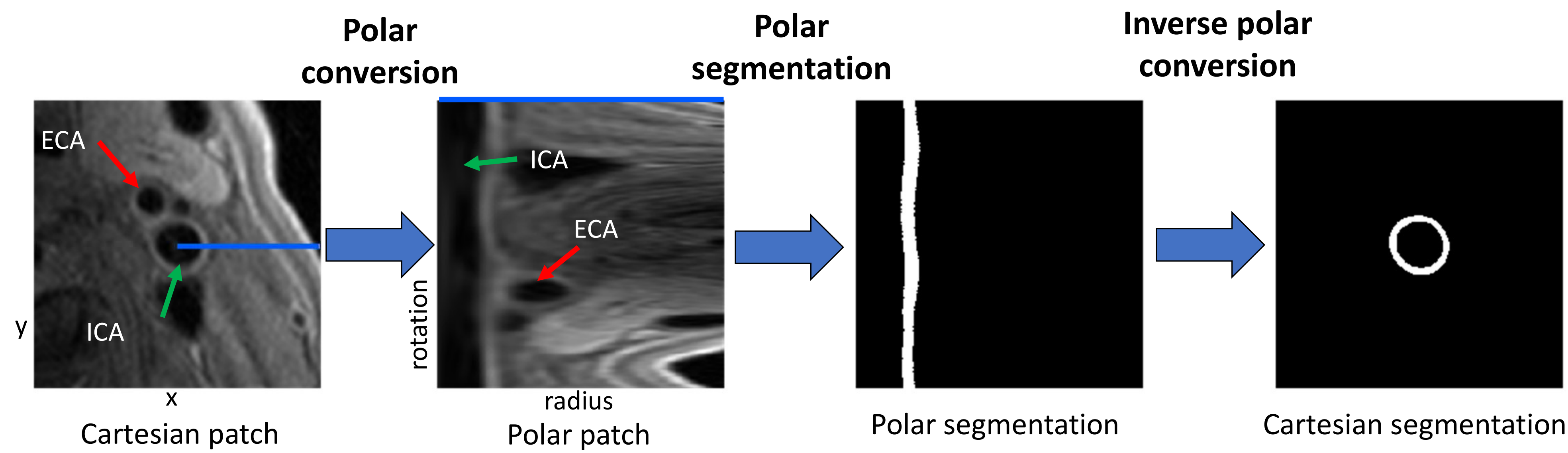


Exemplary problems encountered in Cartesian based neural network models [1]

[1] Chen, et. al, ISMRM, 2018

Module 5: Polar vessel wall segmentation

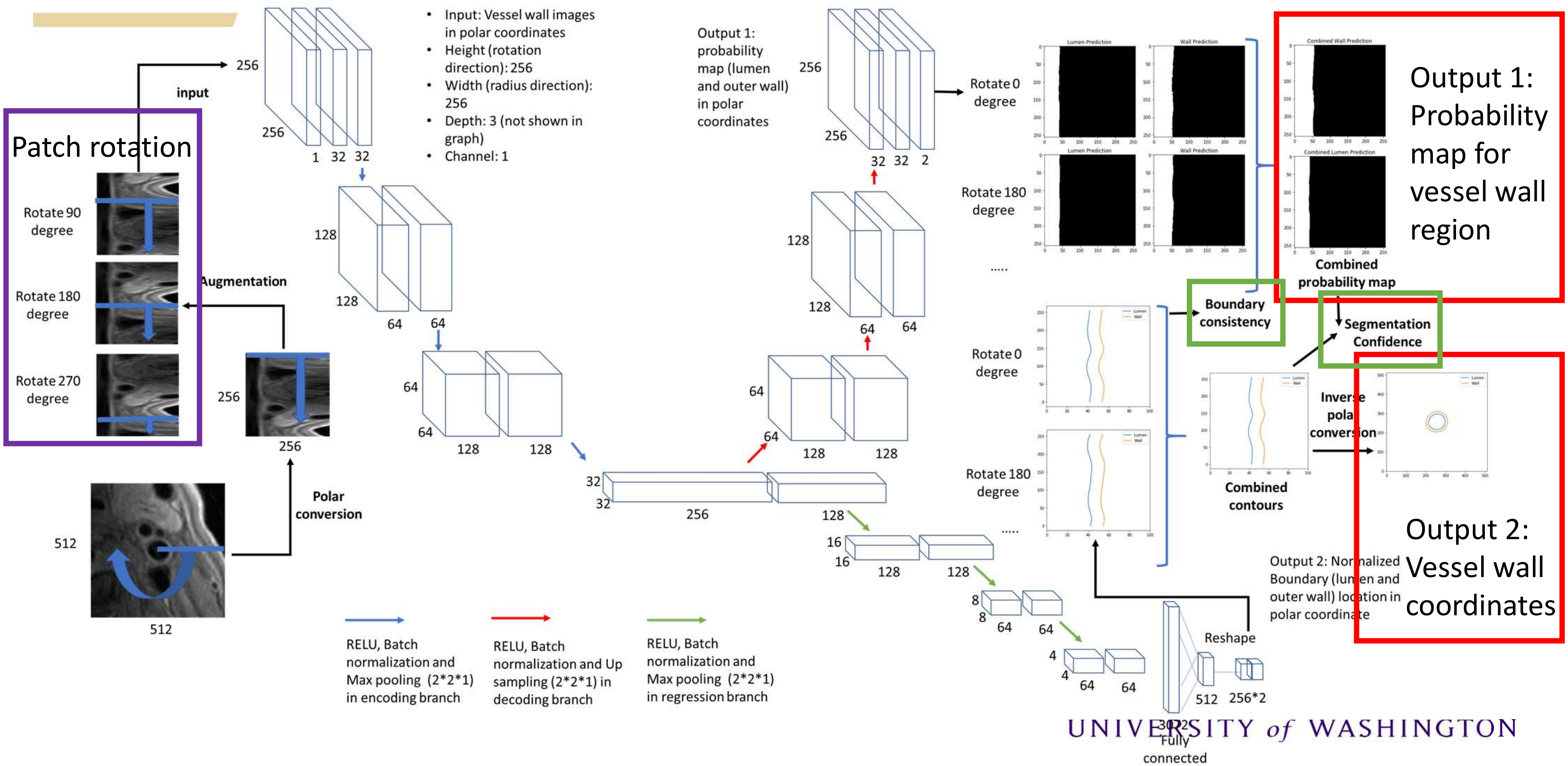
> Benefits of segmenting in polar coordinate system
  - Neighboring arteries (ECA) are quite different from the artery of interest (ICA).
  - Contours are represented as two vertical lines, easy to ensure continuity



Example of polar segmentation in a carotid artery

From Chen, et. al, IEEE Access, 2020.

Dual output network for segmentation + confidence



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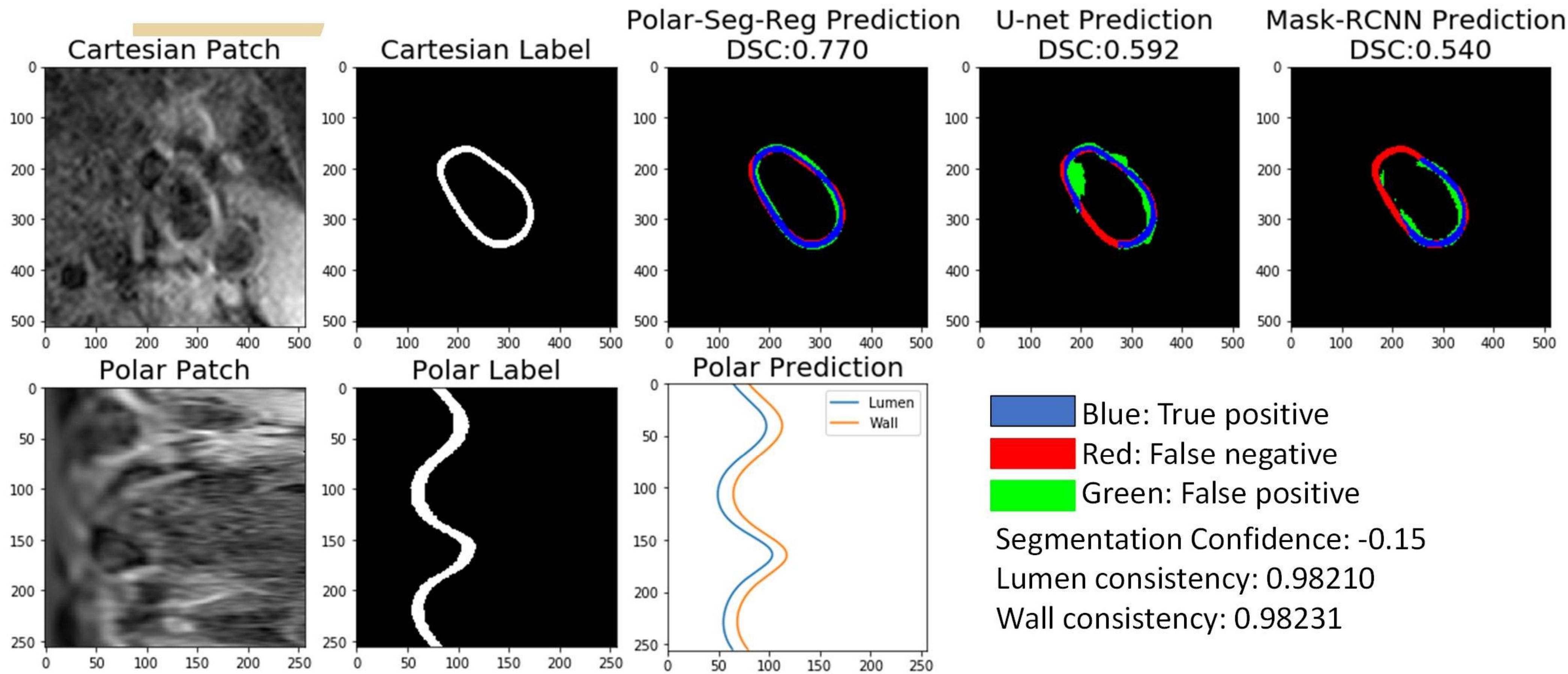
An example of polar segmentation at a challenging slice



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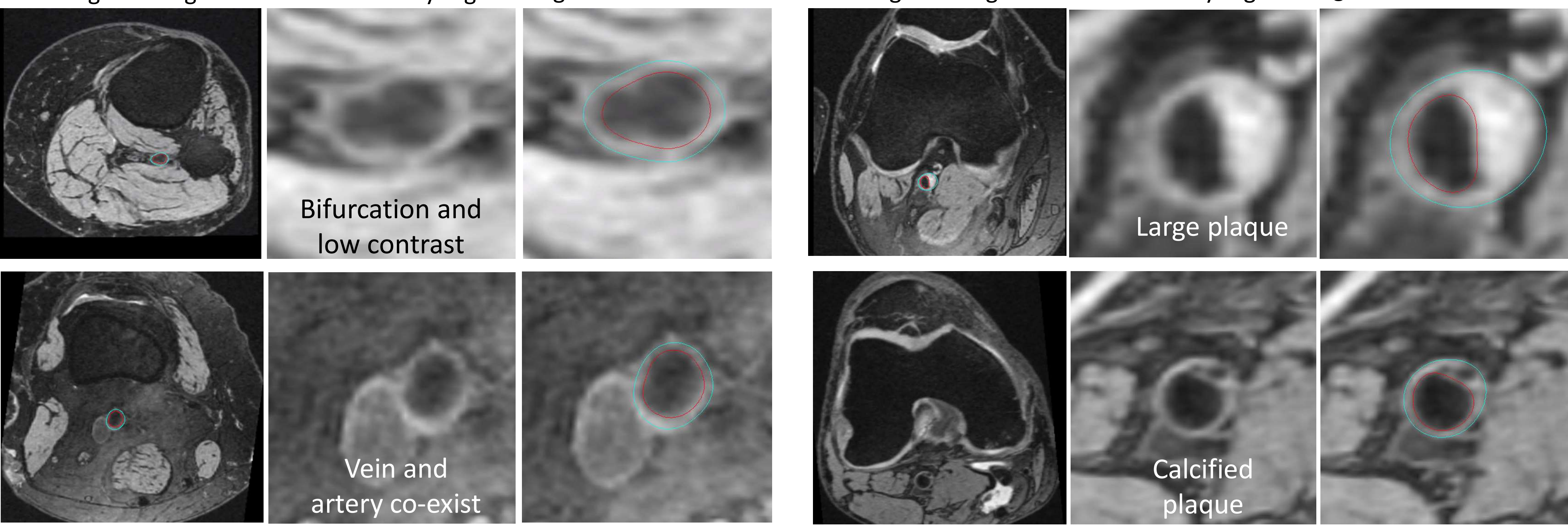
[1] U-Net: Ronneberger, et. al, arXiv, 2015. [2] Mask-RCNN: He, et. al, ICCV, 2017.

FRAPPE: Robust and accurate vessel wall segmentation

Lumen boundary in red contours
Outer wall boundary in blue contours

> With active learning/transfer learning, only 30 cases needed for labeling

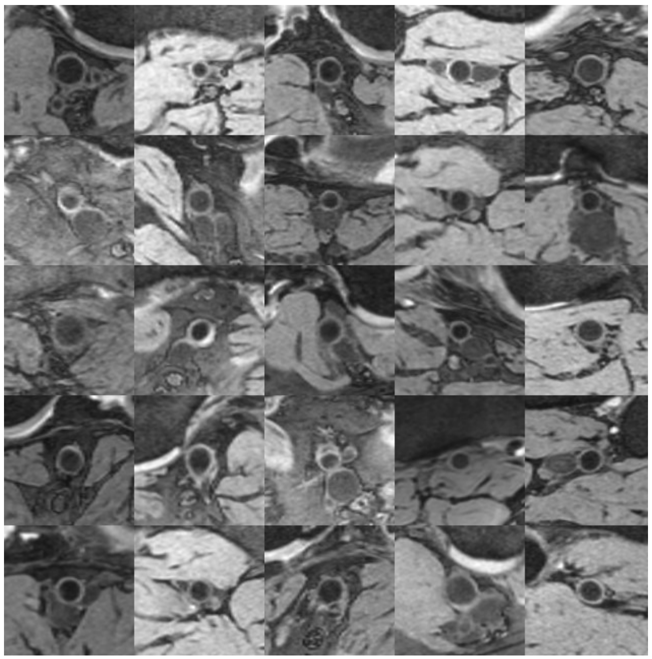
Original Image | Located artery region | Segmentation contours | Original Image | Located artery region | Segmentation contours



From Chen L, et. al, Magn Reson Med, 2020

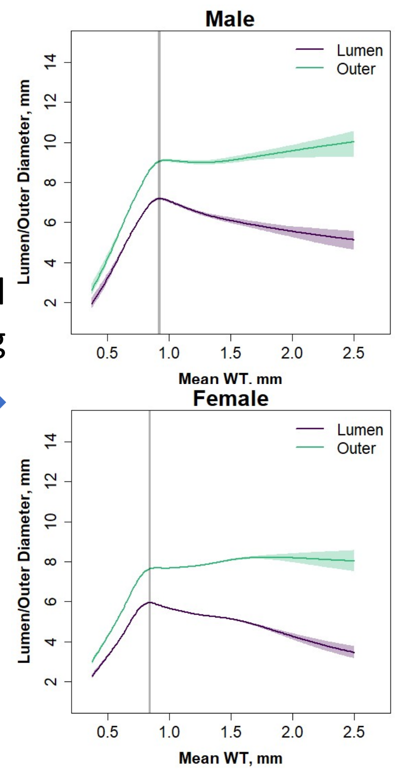
Useful FRAPPE results of 3.5 million images

With only 512 slices labeled using active learning and metric learning

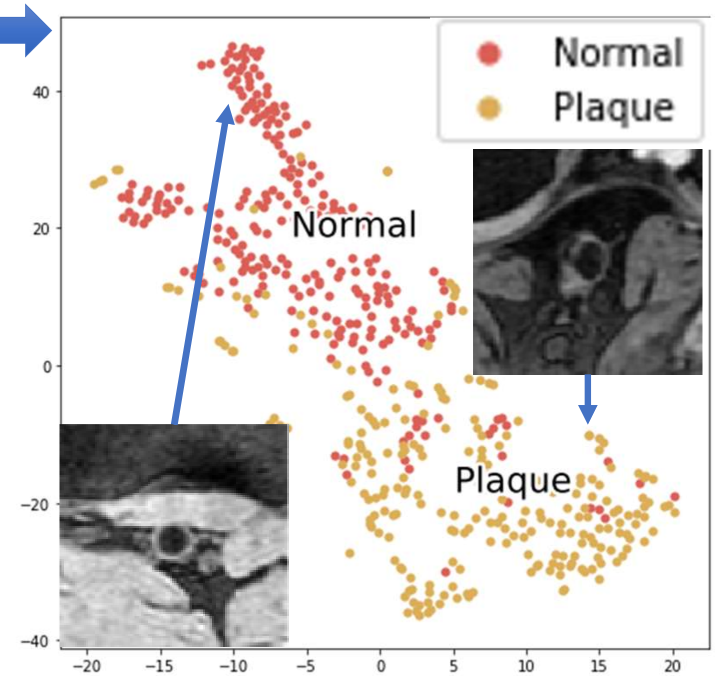


Examples of popliteal artery patches extracted from the center of arteries

Statistical averaging



Vessel wall remodeling patterns [1]: Turning point of 0.92 mm for males and 0.84 for females



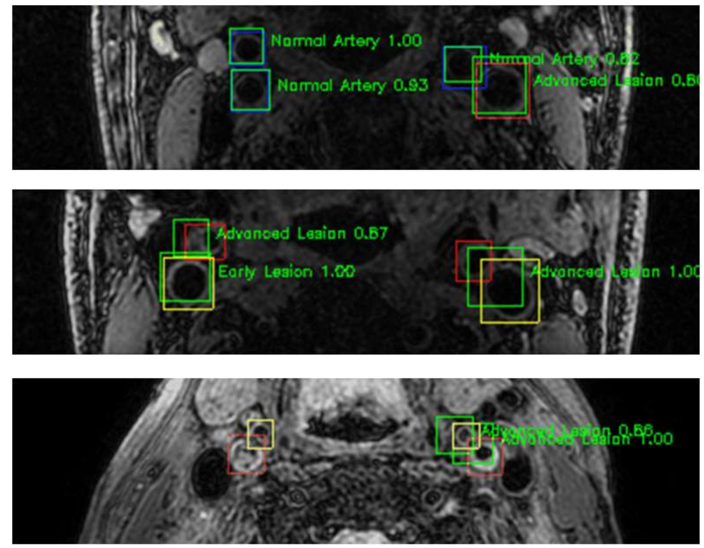
Construct feature map for visualizing normal and plaques distributions [2]

[1] Canton et al, JAHA, 2021
[2] Chen L, et. al, ISMRM, 2020

LATTE: Fast MR screening for plaques

iCafe | Lumen/wall segmentation | Artery localization | Image quality assessment | Domain adaptation

- 5-minute MR solution for carotid lesion screening/assessment
- Fast 3D MERGE fast MR imaging [1]
- Automated image quality assessments [2]
  - Rescan? Qualified range of slices for review?
- Locate artery wall and classify degree of plaques [3]
  - Categorize vessel walls into normal, early-disease, and advanced-disease
  - Domain adaptive for multiple sites



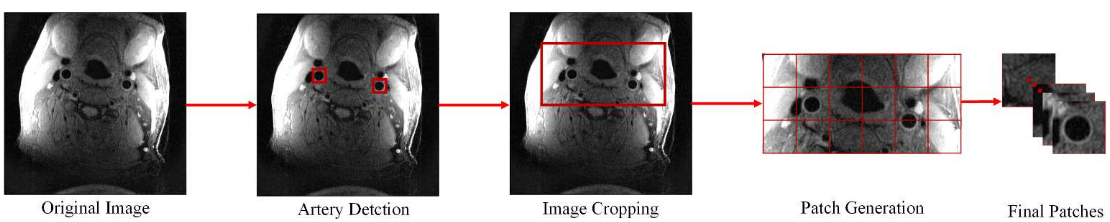
Examples of predictions of test sets
Green boxes: predictions with class and confidence
Blue/Yellow/Red boxes: ground truth for normal artery, early lesion, and advanced lesion

[1] Balu N, et. al, Magn Reson Med, 2011
[2] Chen L, et. al, SMRA, 2018 and ISMRM, 2019
From Chen L, et. al, Magn Reson Med, 2021
LATTE: **L**esion **A**ssessment **T**hrough **T**racklet **E**valuation

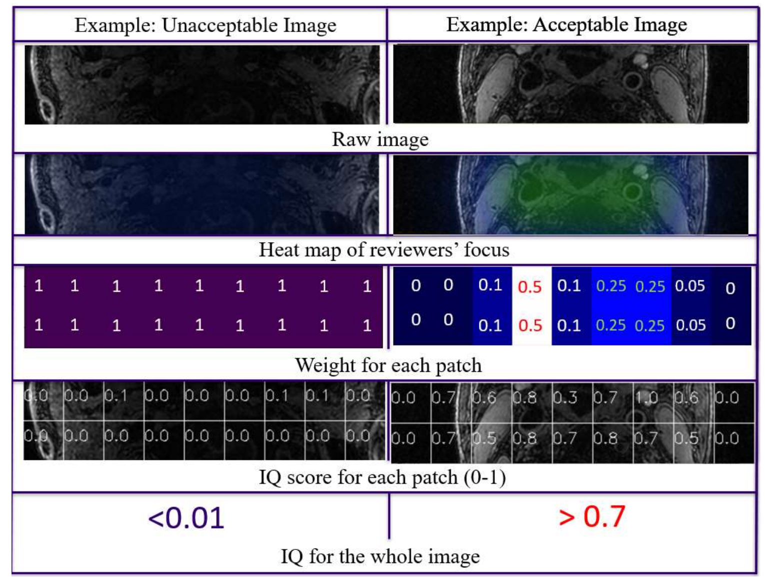
Module 6: Automated image quality assessments

Patch based image quality assessment

- Identify a range of slices from 3D image stack with qualified images for review
- Patch based prediction with weights higher near artery region (detected from localization model)



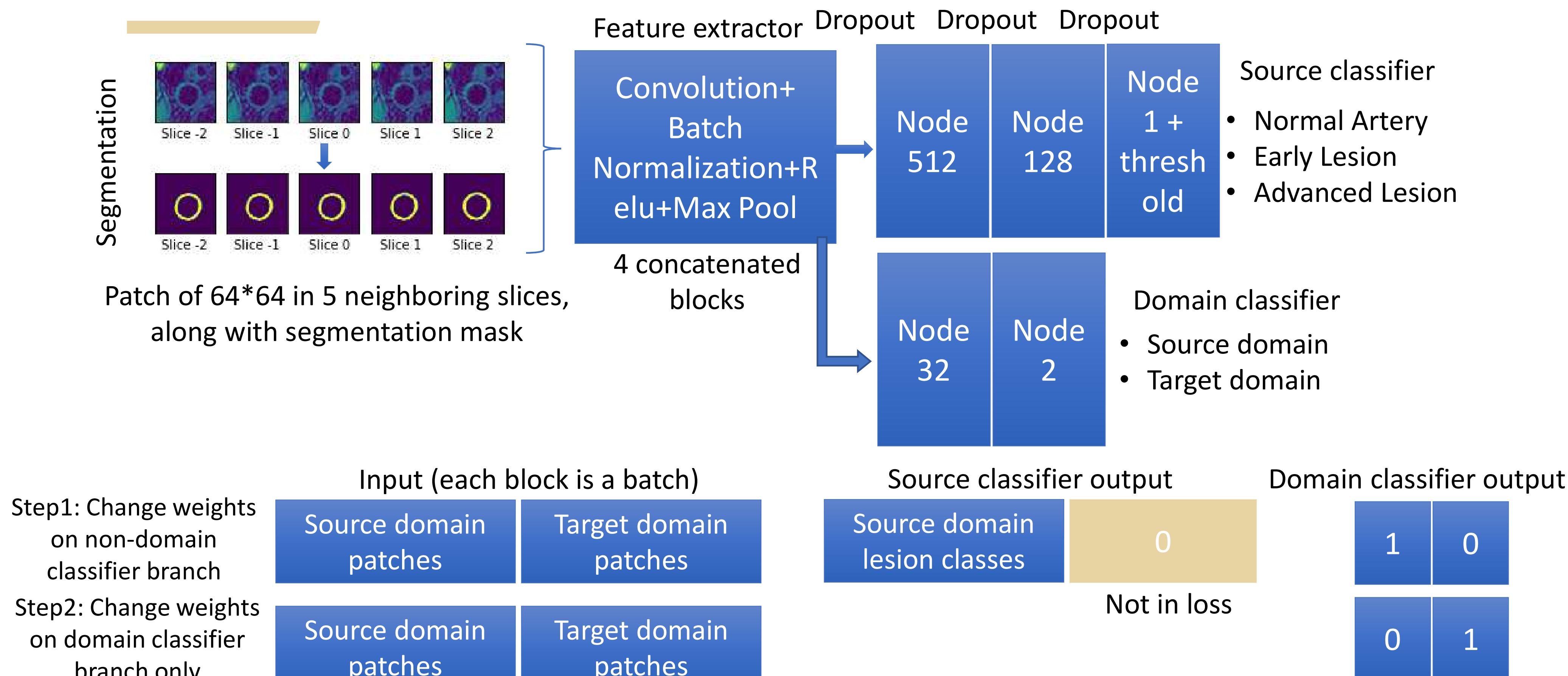
Workflow for patch-based artery focused image quality assessment



Example of a bad (left) and good (right) quality image slice

From Jiang, Chen, et. al, SPIE Medical Imaging, 2020

Module 7: domain adaptive CNN with its training strategy



From Chen L, et. al, Magn Reson Med, 2021

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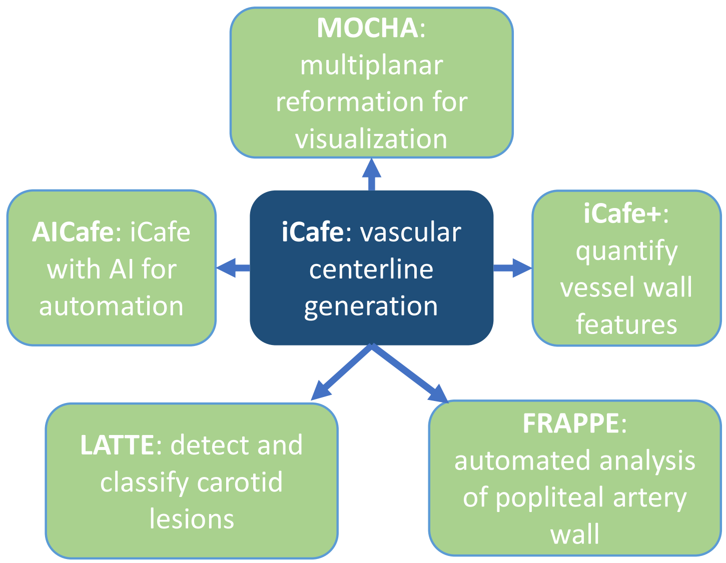
Conclusions

> Novel image analysis techniques (iCafe family) on vascular imaging:
  - Provide quantitative features for medical research
  - Explore novel biomarkers having potential values
  - Make large population studies/screening feasible

> Artificial intelligence on vascular image analysis
  - Extract subtle patterns not easily describable
  - Modular design in the workflow for explainability
  - Human and machine know/work with each other to reduce workload and improve accuracy



iCafe family toolset

Acknowledgement

> We acknowledge the contributions from our collaborators.
  - CBIR/CARE II/OAI/CROP investigators

> Thanks for the funding supports from Philips healthcare, National Institute of Health, and American Heart Association.

> We gratefully acknowledge the support of NVIDIA Corporation for donating the Titan GPUs.

Questions and answers

Thanks for your attention