Feature extraction and quantification to explore human vasculature

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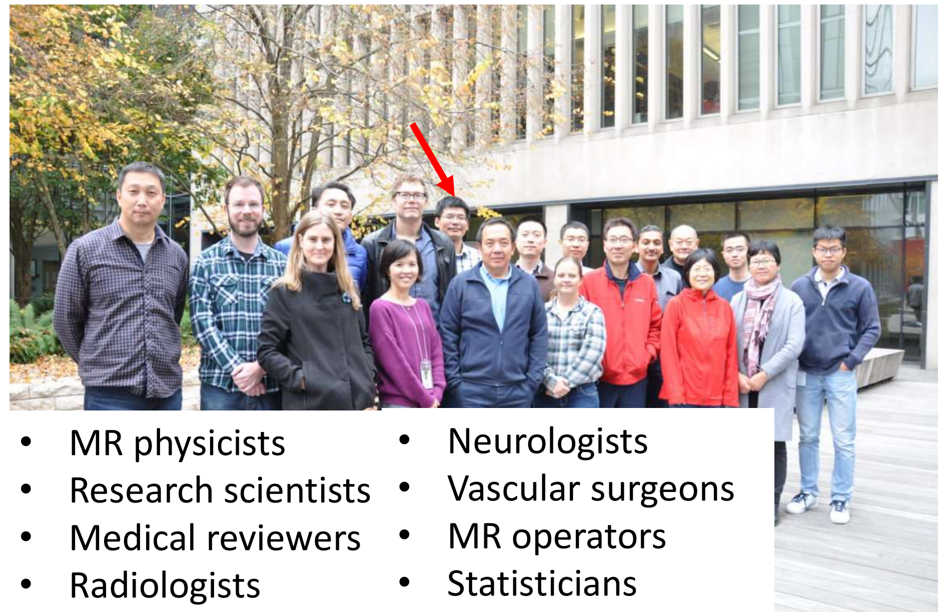
Introduction of myself

A 5th year Electrical Engineering PhD student receiving funding from a Radiology lab

Engineering students with specialty in each technical area

Information Processing Lab
Department of Electrical and Computer Engineering
University of Washington



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

Vascular Imaging Lab
Department of Radiology
University of Washington

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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

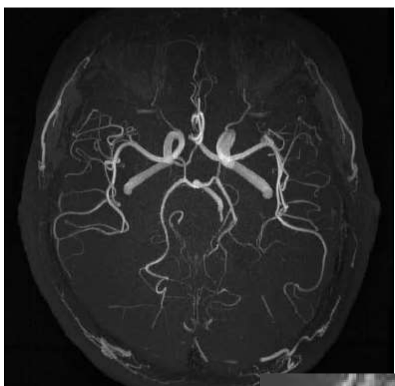
Dr. Chun Yuan

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

Background: Human vasculature

> A complicated and important system

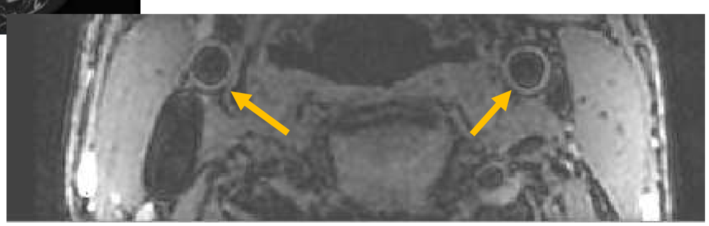
> Arteries visible from Magnetic Resonance Imaging (MRI) techniques
  - MR angiography (MRA), MR vessel wall imaging

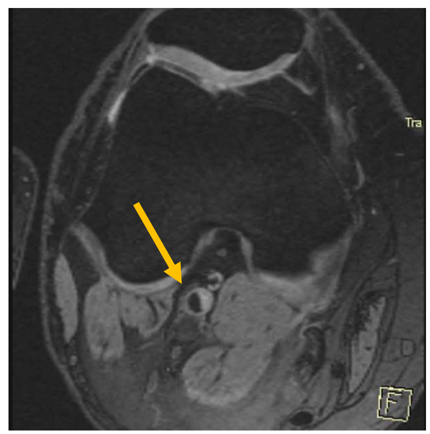


Left: Maximum intensity projection of intracranial arteries

Bottom: One slice of carotid arteries pointed by the arrow

Right: One slice of popliteal artery pointed by the arrow





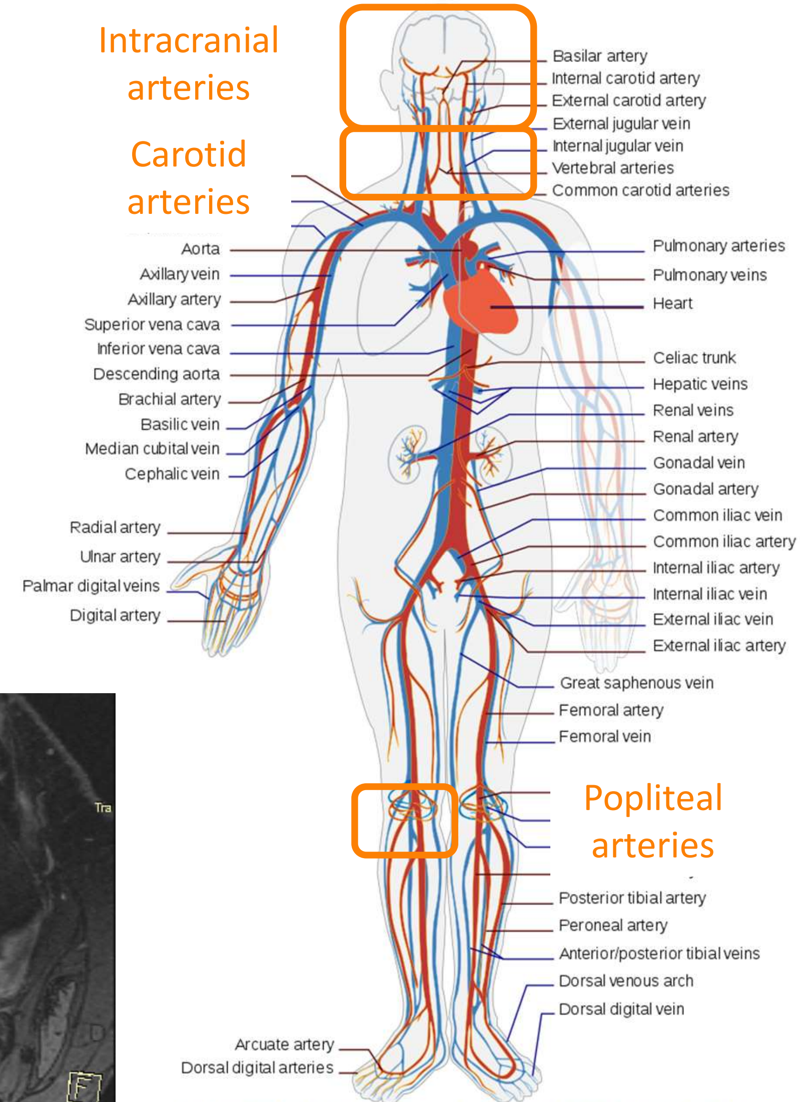


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Image from Wikipedia: Circulatory_system

Background: atherosclerosis

> Cholesterol accumulates on vessel wall, forming atherosclerotic plaque
> Plaque may narrow/block arteries, may also burst, causing ischemic stroke
> A systemic disease affecting multiple vascular beds
> Quantitative analysis of all human vasculature
  - Monitor vascular health
  - Help vascular research

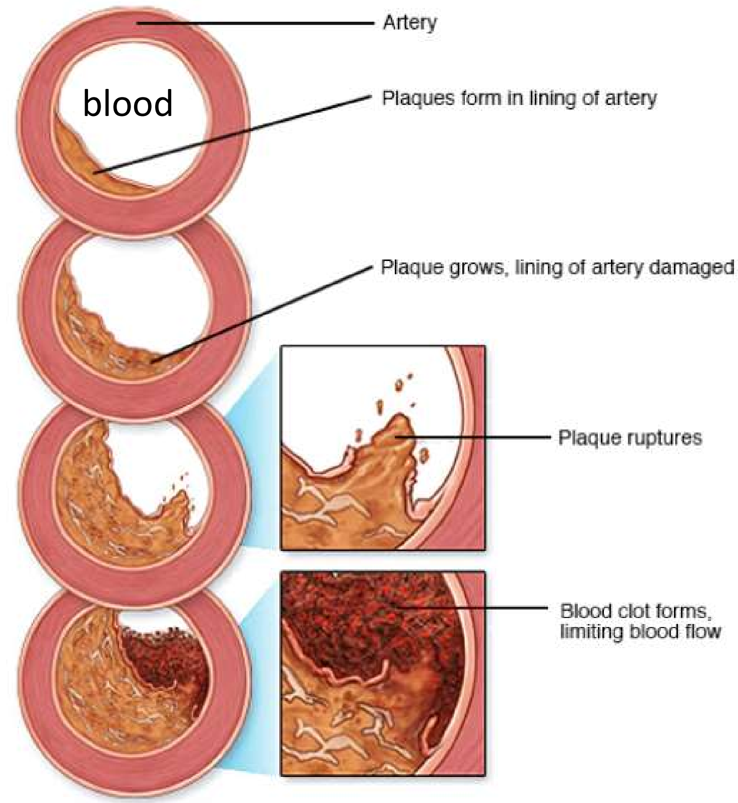


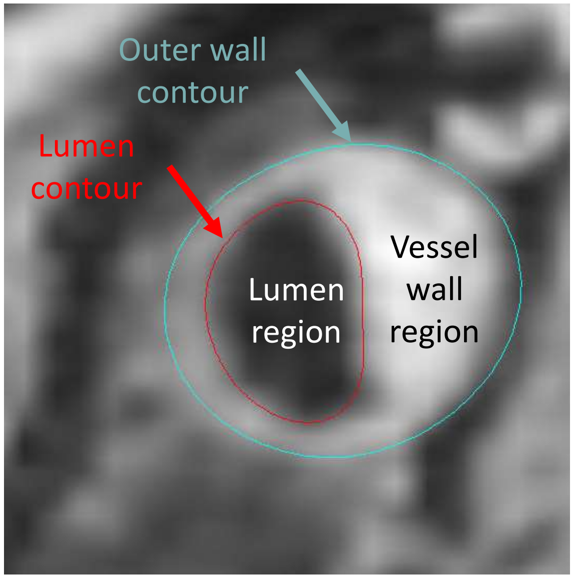
Image from https://www.mayoclinic.org/diseases-conditions/arteriosclerosis-atherosclerosis/symptoms-causes/syc-20350569

Aim: comprehensive and automated vasculature analysis

> Comprehensive vasculature analysis needed
  - Lumen: identify artery centerlines to extract artery structures and blood flow features
  - Vessel wall: identify contours to extract plaque features

> Automated solutions
  - Objective and repeatable measurements
  - Analysis on large datasets

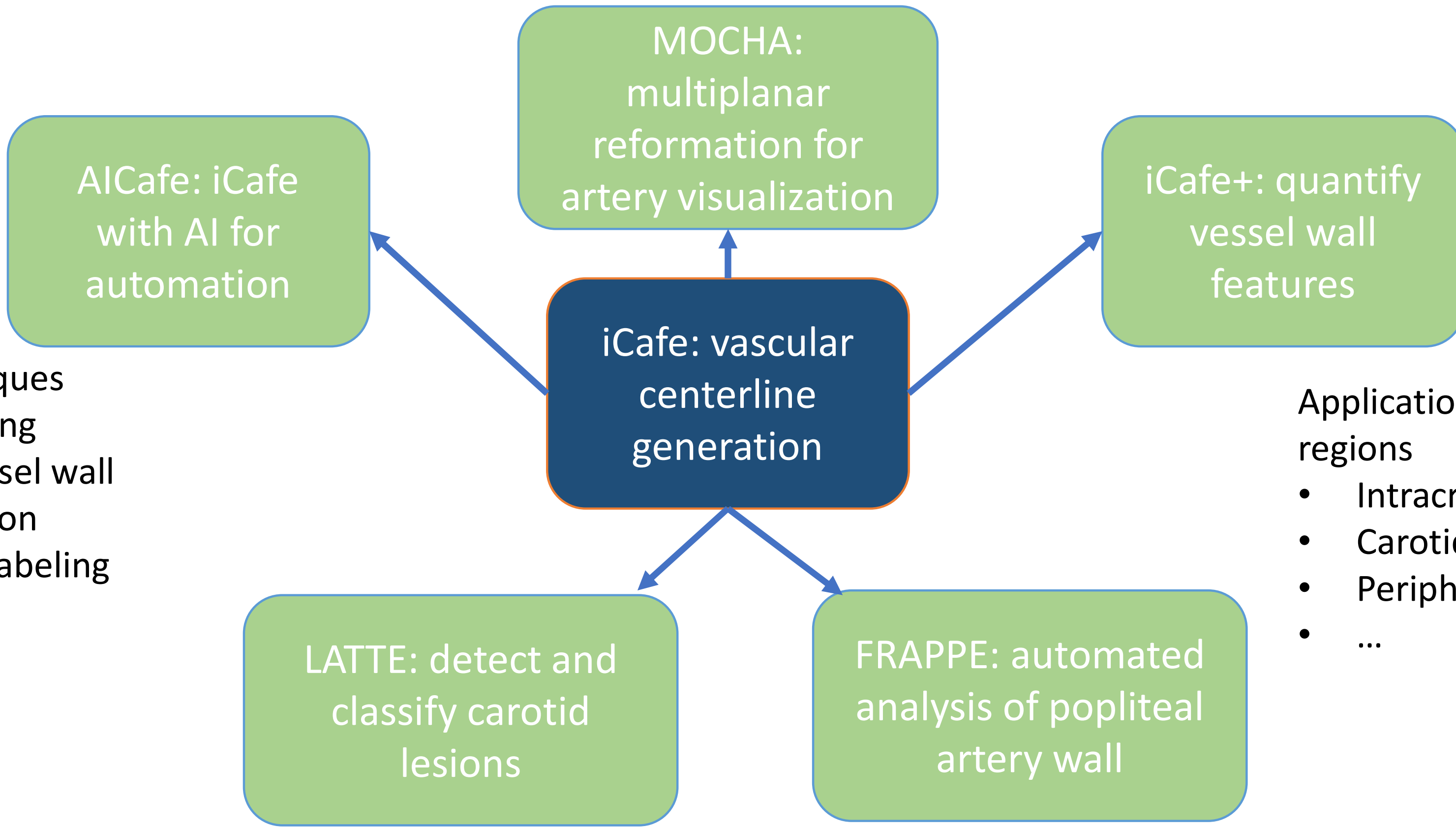
> Challenges
  - Tiny structure of artery and vessel wall (~1mm, <0.1% in image area)
  - Signal low, contrast weak, flow artifacts in vascular images
  - Limited samples, expensive manual labeling



Lumen (red) and outer wall (blue) contours on a slice of popliteal vessel wall

Solution: iCafe family for vascular analysis

Related techniques
- Artery tracing
- Lumen/Vessel wall segmentation
- Landmark labeling
- Clustering
- …



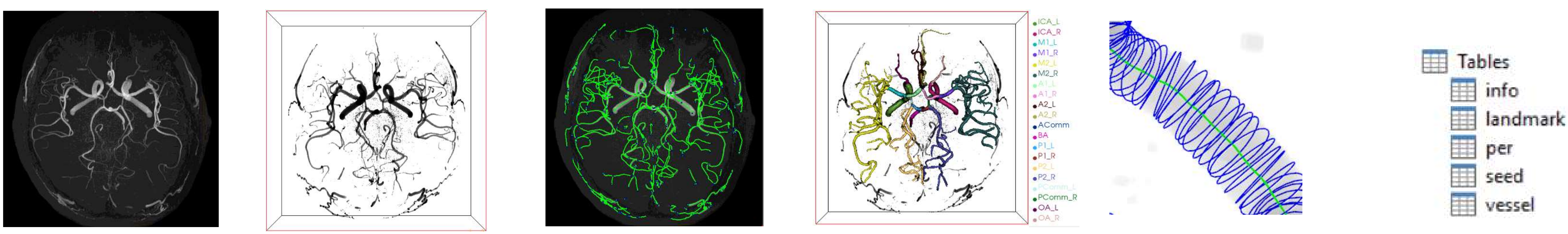
Application on various vascular regions
- Intracranial
- Carotid
- Peripheral
- …

iCafe (intraCranial artery feature extraction)

A tool to trace and quantify intracranial arteries

> From 3D MRA images to quantitative vascular map

- Each artery reconstructed as a radius varying tube
- Each artery labeled with a certain anatomical type



(a) (b) (c) (d) (e) (f)

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

iCafe workflow

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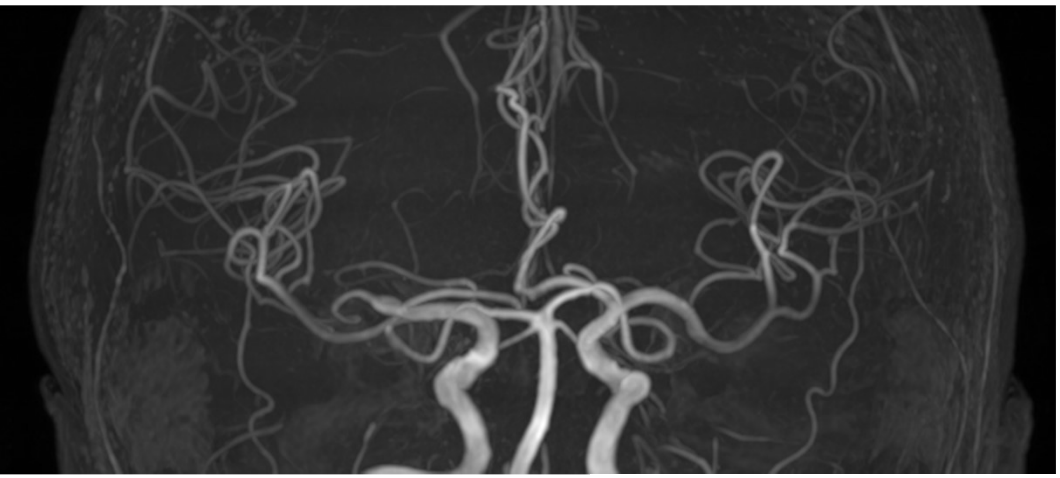
From Chen L, et. al, Magn Reson Med, 2018

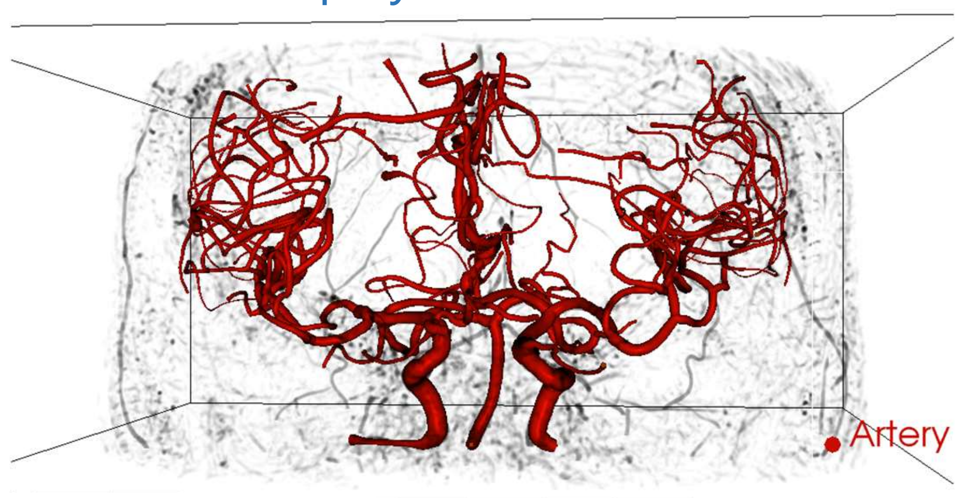
What is unique in iCafe

> Accurate [1]: Semi-automated artery labeling with easy human corrections

> Comprehensive: Up to 1456 regional features per case available
  - Left MCA length, Right anterior circulation artery volume, etc.

> Visualization: A united platform for vasculature display



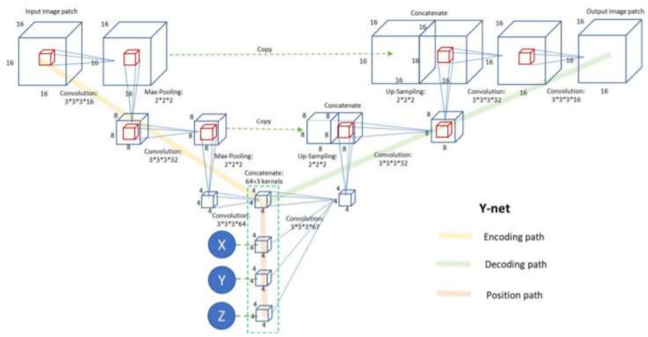


One healthy volunteer: TOF MRA (left), artery with different labeling schemes visualized in iCafe (right)

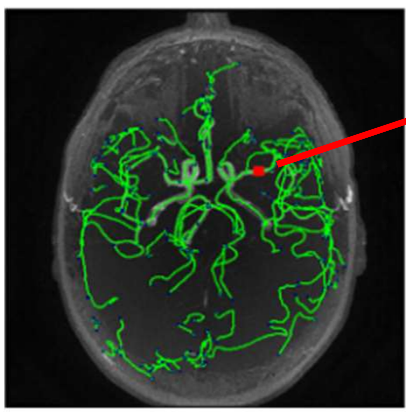
[1] Chen, et. al, Magnetic Resonance Imaging, 2019

Segment luminal areas using artery traces

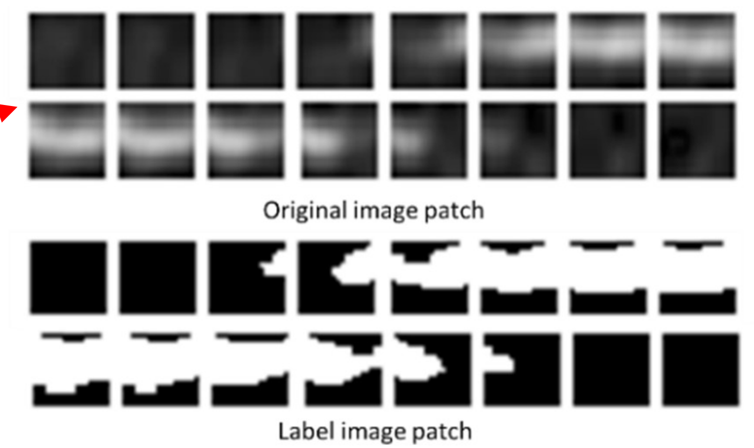
- From iCafe traces to train lumen segmentation
- Y-net: 3D Patch based CNN segmentation
  - use similarity between arteries
- Patch origin added as additional information

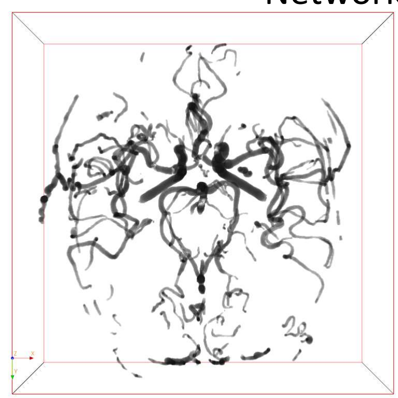


Network structure

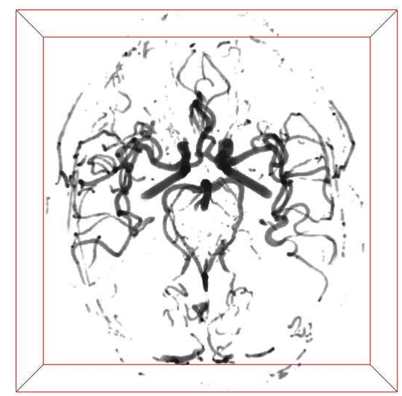


3D MRA with traces from iCafe





iCafe (Ground truth) segmentation

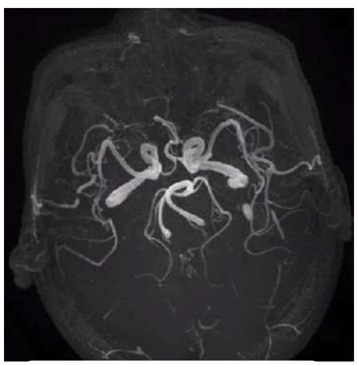


Y-net segmentation

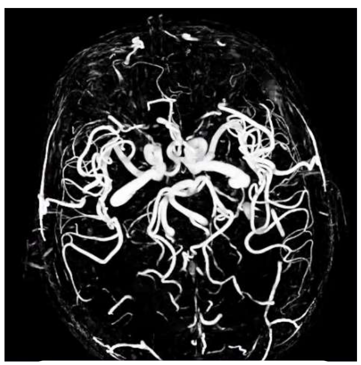
From Chen, et. al, IEEE BIBM, 2017

Simultaneous intracranial artery tracing/segmentation

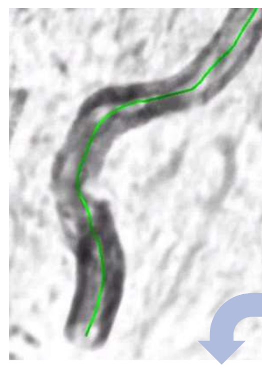
- Use segmentation results to help better tracing (better contrast)
- Use tracing results to help better segmentation (separate close arteries)
- Take advantage of cross-sectional plane relations and Multiplanar reformation (MPR) to match and refine traces



Original MRA image

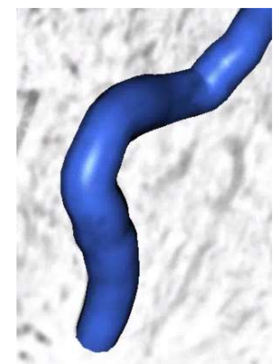


Artery rudimentary segmentation by neural network



Artery tracing from segmentation

Artery refinement in MPR



Artery segmentation from traces

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

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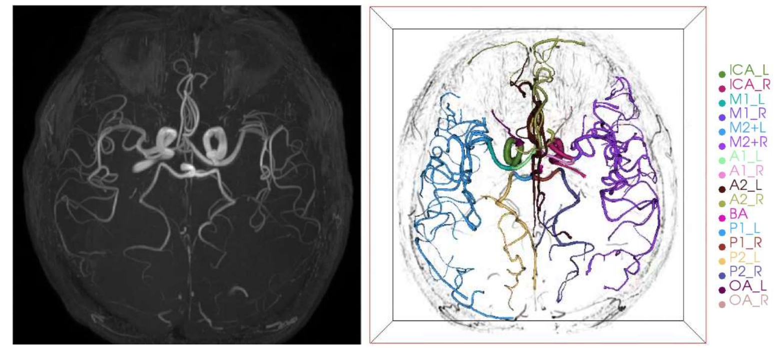
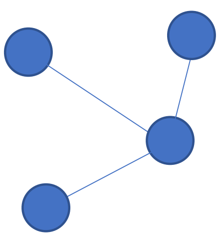
Graph neural network for artery landmark labeling

- A message passing graph neural network for node and edge type prediction
- Combine prior knowledge of hierarchical structures of arteries
  - Robust for anatomical variations

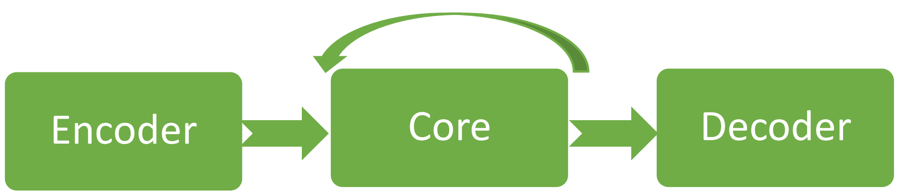


Intracranial arteries: a natural graph with 24 major types

Message passing for 10 rounds

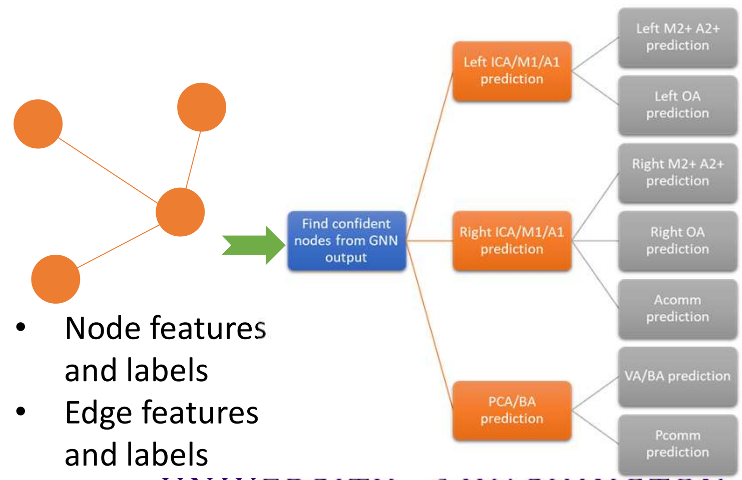


- Node (bifurcation/ending points) features
- Edge (artery) features



Encode edge and node features

Decode edge and node features



- Node features and labels
- Edge features and labels

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From Chen, et. al, MICCAI 2020

iCafe applications

- Vascular reduction on healthy aging [1]
- Monitor vascular change before and after carotid revascularization [2]
- Vascular analysis on dementia subjects with controls [3]
- iCafe to compare novel MR sequence on vasculature [4]
- Quantitative measurement of peripheral arteries [5]
- Arterial collateralization comparison on peripheral artery disease [6]
- iCafe on CTA images and for stenosis detection [7]
- Distributed for 15 sites for academic uses [8]

[1] Chen, et. al, Neurobiology of Aging 2019. [2] Shirakawa, et. al, ISMRM 2019.
[3] Chen, et. al, ISMRM 2019. [4] Zhang, et. al, Magnetic Resonance Imaging 2019.
[5] Chen, et. al, ISMRM 2019. [6] Balu, et. al, ISMRM 2019.
[7] Han, et. al, ASNR 2020.
[8] iCafe website: icafe.clatfd.cn

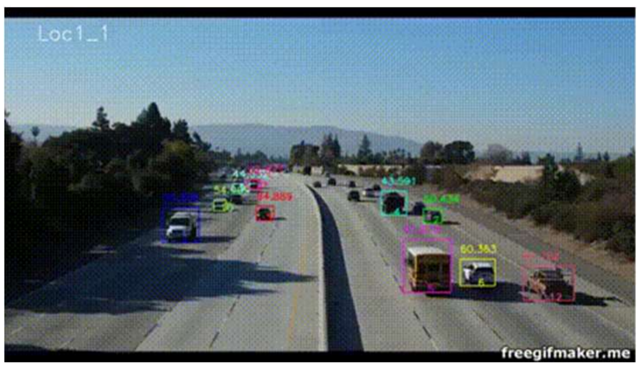
Automated artery localization

> Automatically find relatively straight arteries from 3D vascular images

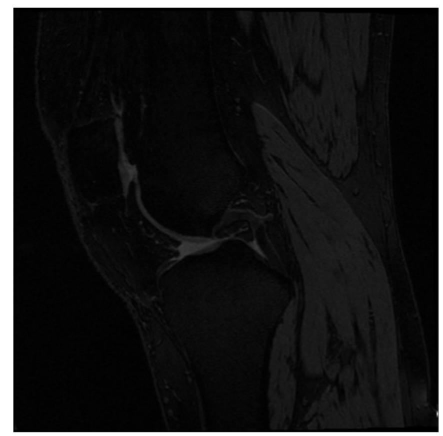
> Time dimension in video is equivalent to depth dimension in 3D medical image

> Centerline generation: tracking by detection

- **Detection** of bounding boxes from each axial image slice
- Combining detections using **tracklet refinement** algorithm



Tracking results of cars (in bounding boxes) using Yolo V2 provided from our group in NVIDIA AI City Challenge [2]



Bounding box detection result for a popliteal artery

[1] J. Redmon, CVPR, 2017 [2] Z. Tang, CVPR, 2018

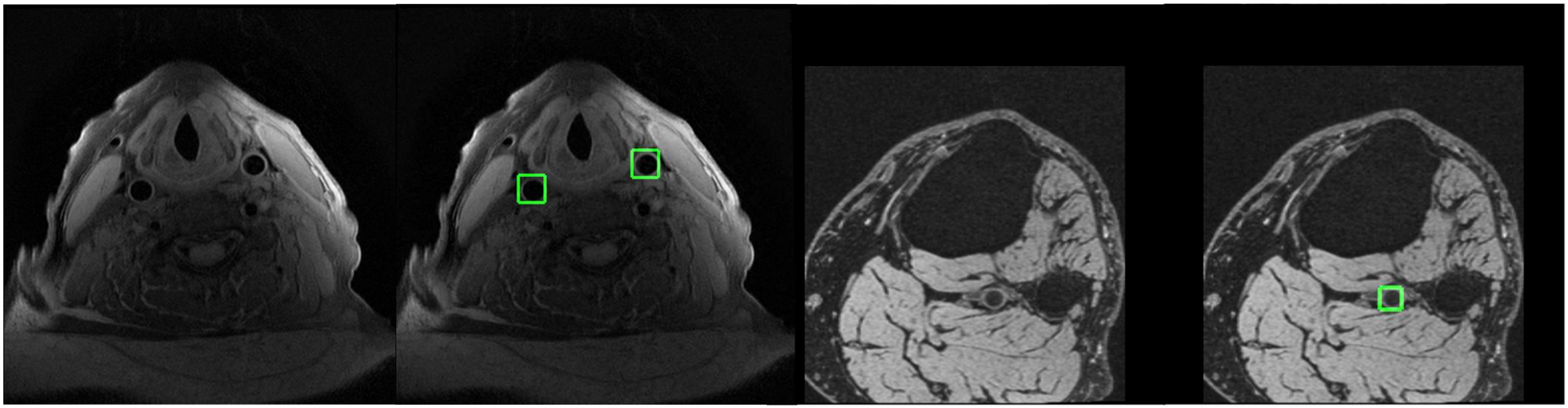
Artery localization: detection + tracklet refinement

- Detection of arteries in each slice using Yolo V2 [1] detector
  - Predict objects in bounding boxes with a confidence score
  - Noise detections
  - Missing detections
- Tracking by detection
  - Form tracklets with closely matching neighboring detections
  - Tracklet merge
  - Tracklet remove
  - Find target centerlines

Example bounding boxes (with confidence score) on a slice of carotid artery image
Bounding boxes: minimum encompassing rectangle around the artery

From Chen L, et. al, arXiv, 1909.02087
[1] Redmon, et.al, CVPR, 2017.

Automated artery tracking results

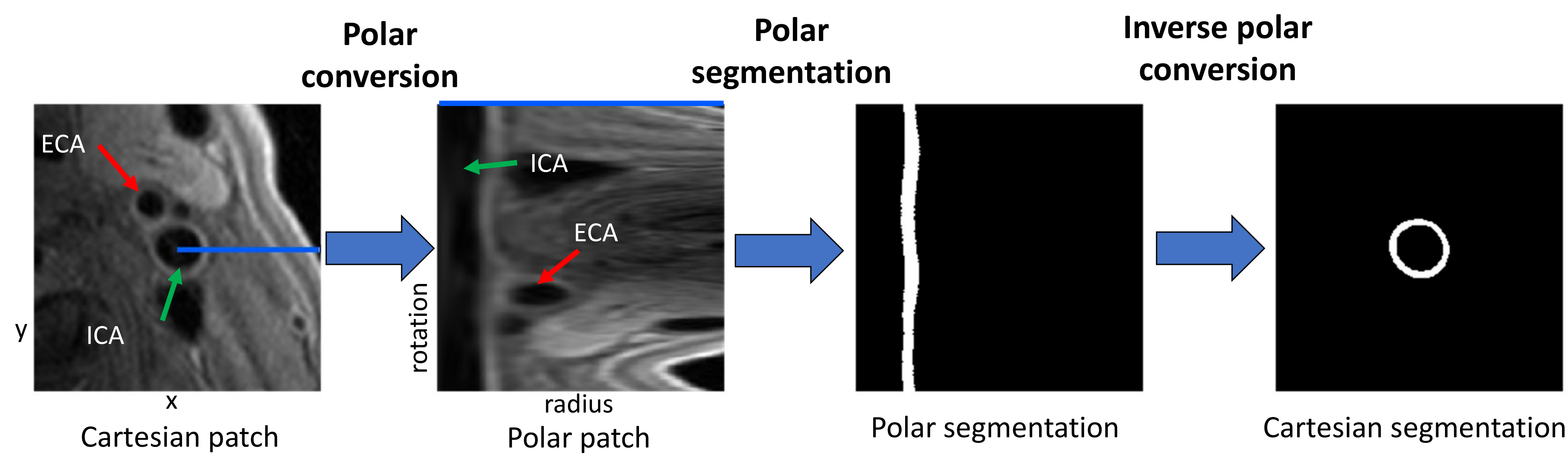


Bounding boxes along carotid artery
(16 slices, 2mm thickness)

Bounding boxes along popliteal artery
(76 slices, 1.5mm thickness)

Vessel wall segmentation in polar coordinate system

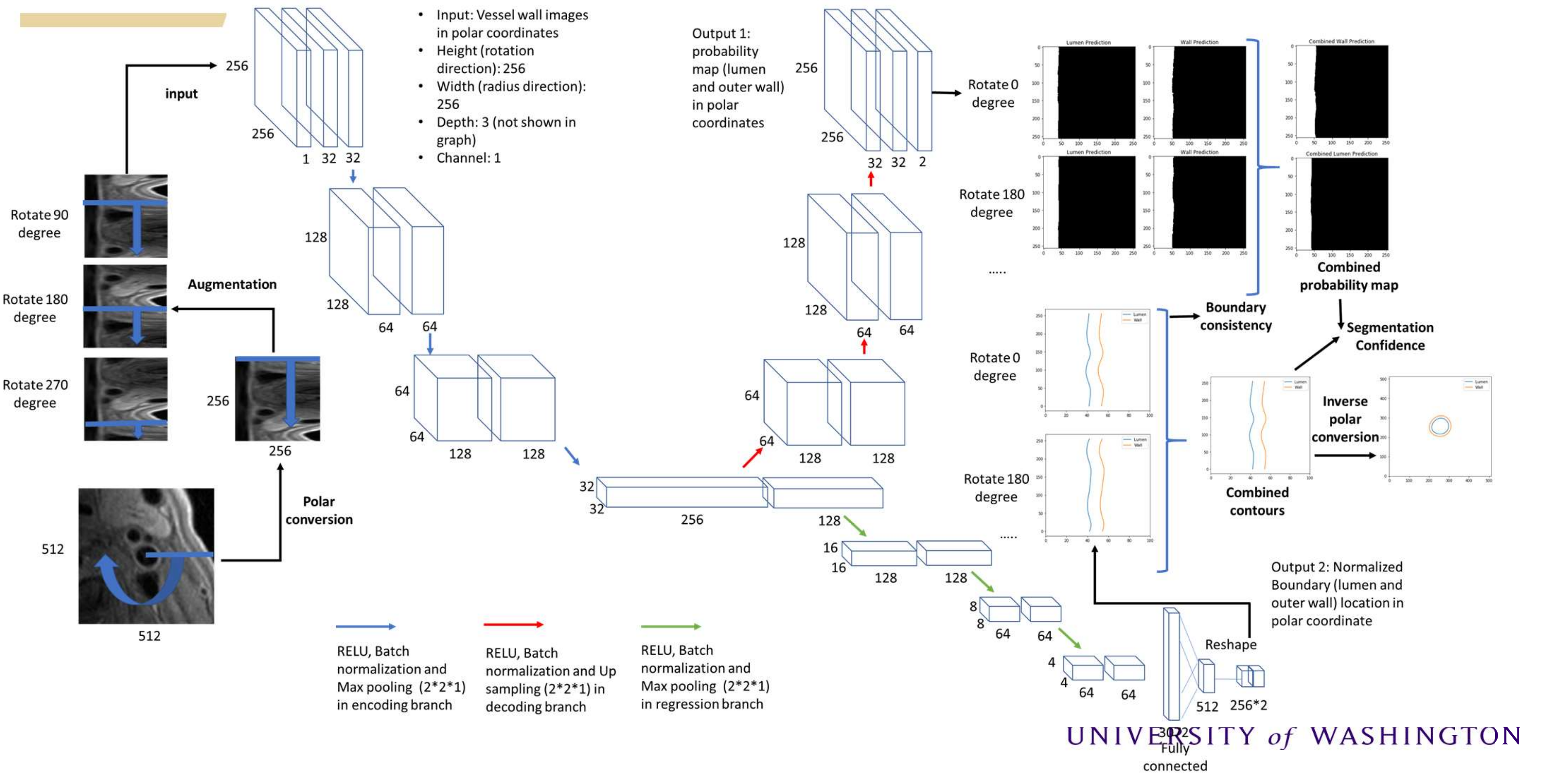
> Benefits in polar coordinate system
  - Neighboring arteries (ECA) are quite different from the artery of interest (ICA).
  - Contours are represented as two vertical lines, easy to ensure continuity



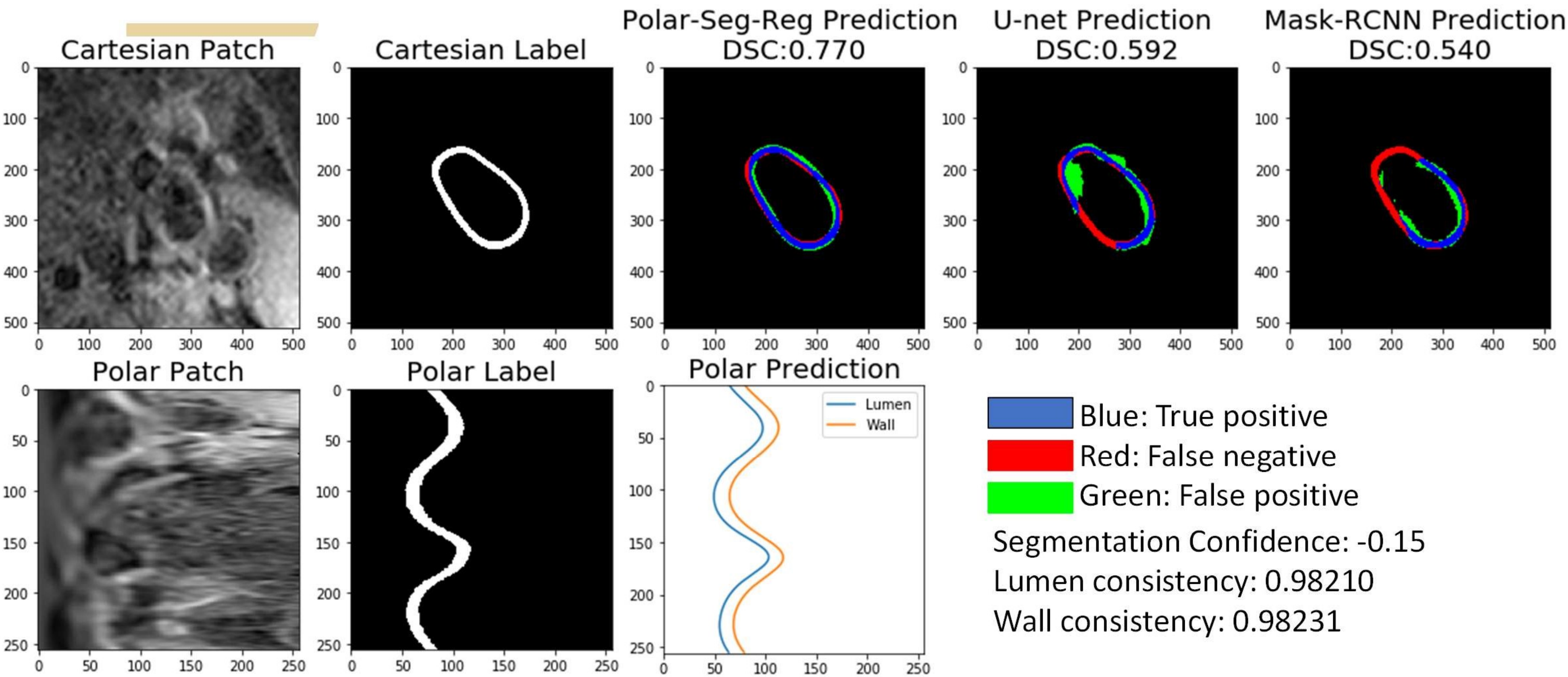
From Chen L, et. al, arXiv, 1909.02087

Example of polar segmentation in a carotid artery

Network structure with rotated polar patches



Example of polar segmentation result



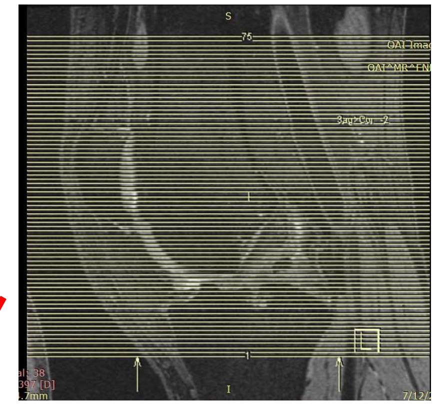
Blue: True positive
Red: False negative
Green: False positive

Segmentation Confidence: -0.15
Lumen consistency: 0.98210
Wall consistency: 0.98231

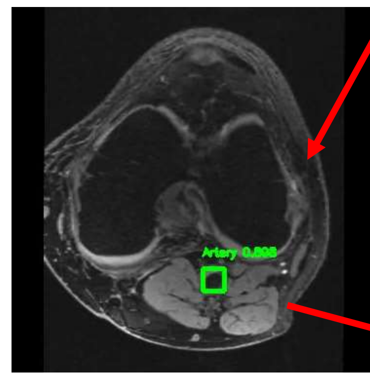
[1] U-Net: Ronneberger, et. al, arXiv, 2015. [2] Mask-RCNN: He, et. al, ICCV, 2017.

Application: Popliteal vessel wall analysis

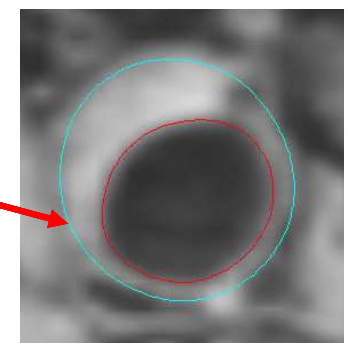
- Vessel wall in MR knee scans has valuable information for cardiovascular risk assessments [1]
- OAI dataset (3.5 million knee images) [2]
- Aim: Accurately locate popliteal artery from MRI and quantify vessel wall features in a **fully** automated way



Scan locations for knee



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



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

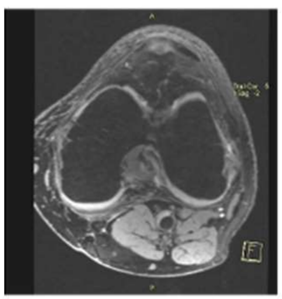
[1] Liu, et al, ATVB 2019
[2] https://nda.nih.gov/oai/

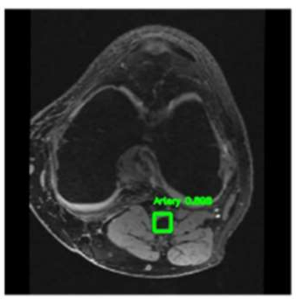
FRAPPE Workflow

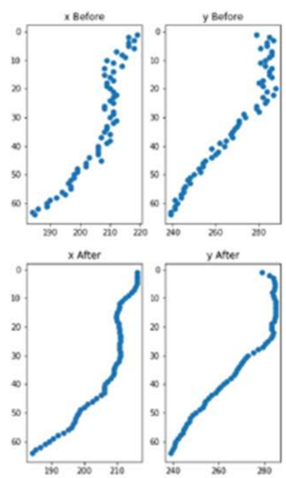
- The processing time for each artery is <8 minutes *
- Multiple GPUs accelerate the process
- All the OAI dataset processed within 2 months

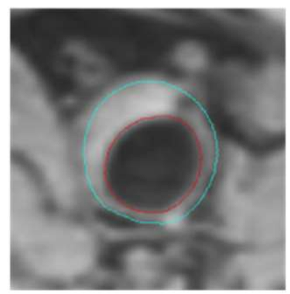
Fully automated and **R**obust **A**nalysis Technique for **Po**pliteal Artery Vessel Wall **E**valuation

Original image → Artery detection → Tracklet refinement → Vessel wall segmentation → Feature calculation → Export and display

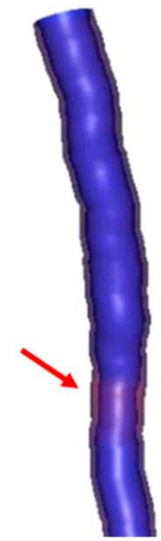








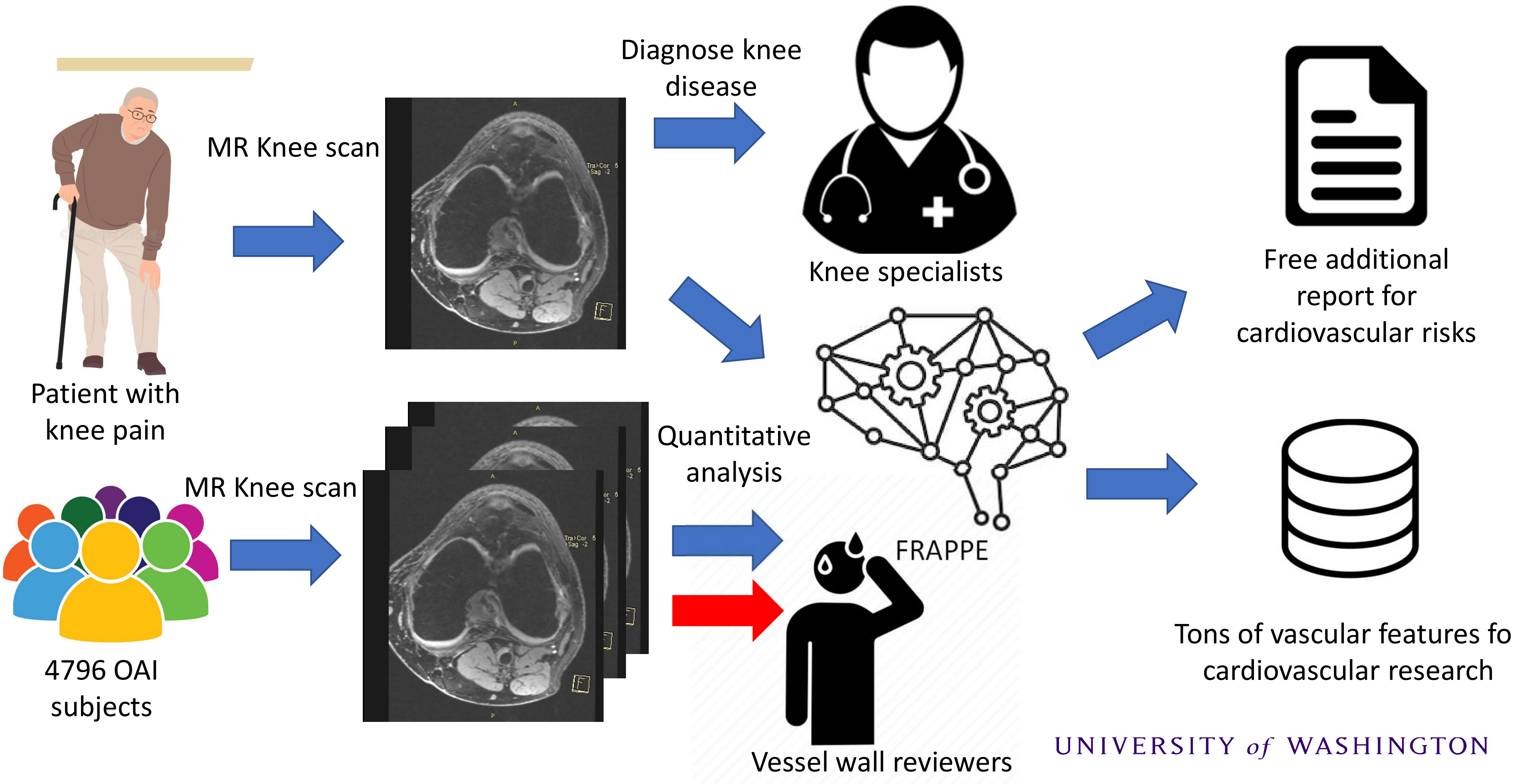
Max wall thickness:
2.62 mm
Mean wall thickness:
1.46 mm
Vessel wall area:
74.49 mm^2
Lumen area:
36.30 mm^2
……



* Based on our workstation with Intel Xeon CPU E5-1650 v4 @3.6GHz 6 cores, 64 GB Memory, single NVIDIA GeForce GTX TITAN V on Window 10

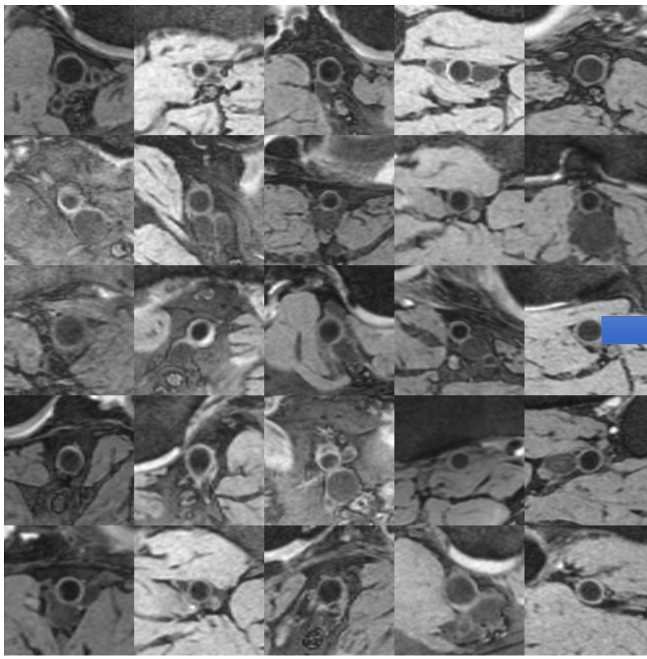
From Chen L, et. al, Magn Reson Med, 2020

Clinical and research potentials for FRAPPE

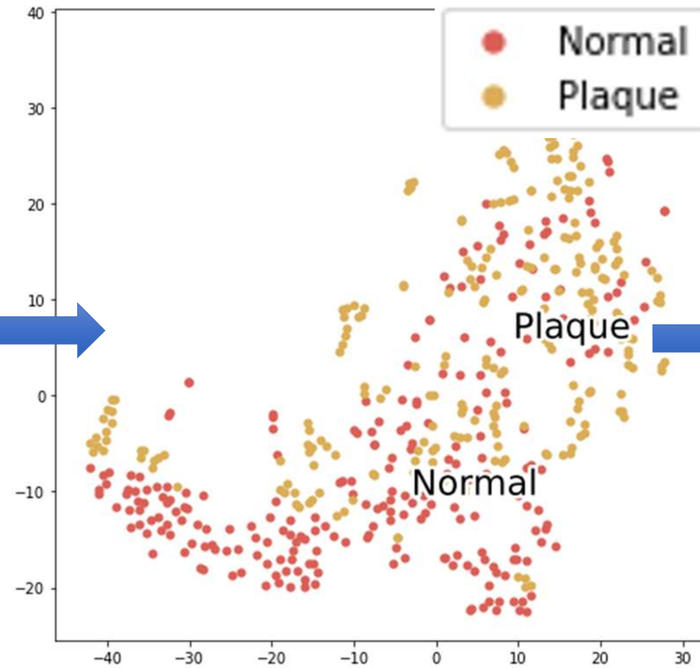


Visualizing features of vessel wall images

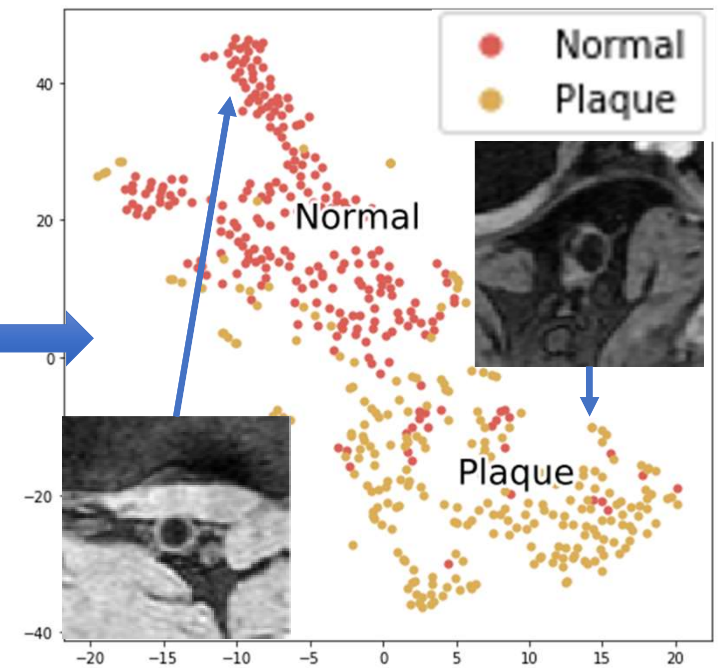
With only 512 slices labeled using active learning and metric learning



Examples of popliteal artery patches extracted from the center of arteries



Visualizing the feature map of popliteal artery patches using t-SNE method (painted with ground truth labels)



Feature map after transformation using our method

From Chen L, et. al, ISMRM, 2020

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Conclusions

> Novel image analysis techniques (iCafe family) on vascular imaging:
- Quantitative features for medical research
- Objective review workflow for vascular images
- Make large population studies/screening feasible

> Artificial intelligence on vascular image analysis
- Extract subtle patterns not easily describable
- Data drives models, which are improved with more data
- Human knowledge and machine knowledge for better models

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.