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Automated Segmentation of Temporal Bone CT Imaging for Robot-Assisted Microsurgery

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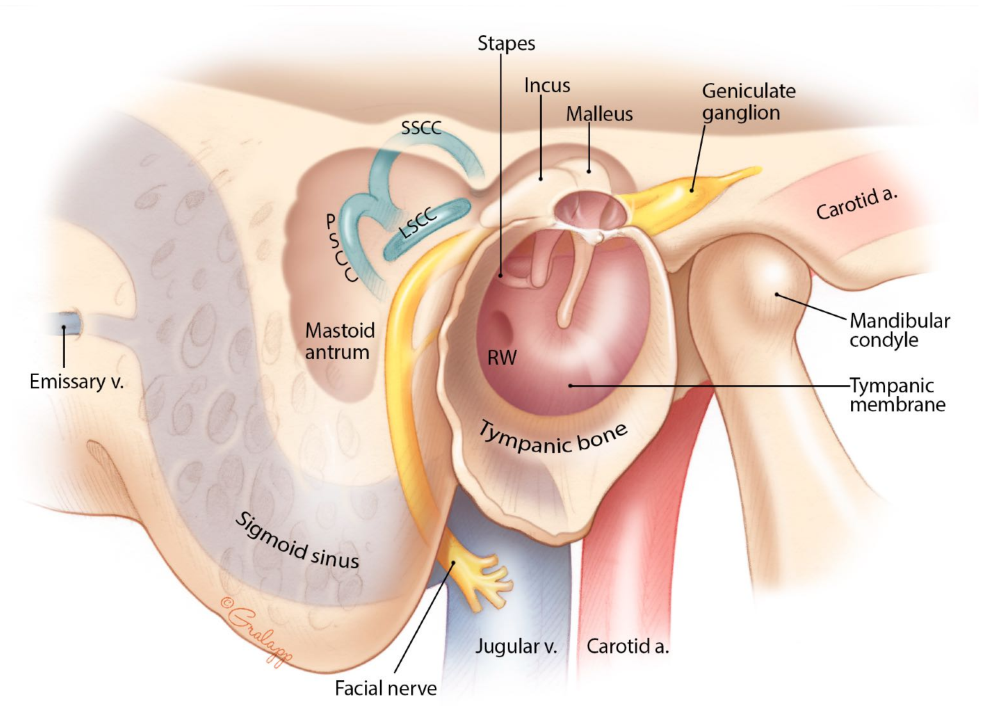
Project Overview

- Problem
  - Temporal bone anatomy is geometrically complex with critical structures often within millimeters of each other.
  - Surgery in this area poses a high risk of damage to anatomy.
- Goal
  - Develop an automated system for segmenting the temporal bone to help prevent intraoperative damage to critical anatomy.



Credit: Christine Gallup
https://otosurgeryatlas.stanford.edu/

Paper

Toward an automatic preoperative pipeline for image-guided temporal bone surgery

Johannes Fauser ✉, Igor Stenin, Markus Bauer, Wei-Hung Hsu, Julia Kristin, Thomas Klenzner, Jörg Schipper & Anirban Mukhopadhyay

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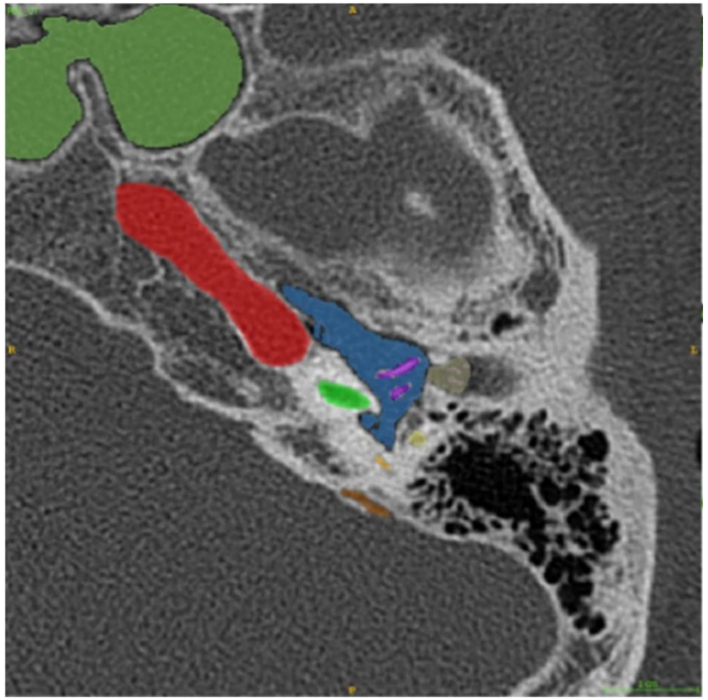
- First major deep learning-based approach to automated temporal bone segmentation [1]
- Discusses strategies to handle scarcity of available labeled data
- Baseline network architecture is similar to our proposed method with nnUNet
- Demonstrates potential issues with purely using a UNet model

[1] Fauser *et al*, 2019

Paper: Summary & Key Takeaways

- Summary
  - Automatic temporal bone segmentation with UNet and probabilistic active shape modeling (PASM) for pre-operating path planning (e.g., cochlear access, superior semicircular canal approach, retrolabyrinthine approach)

- Key Results
  - Segmentation accuracy evaluation of UNet + PASM hybrid against UNet or PASM alone
  - Pre-operative planning success with UNet + PASM hybrid vs. UNet or PASM alone

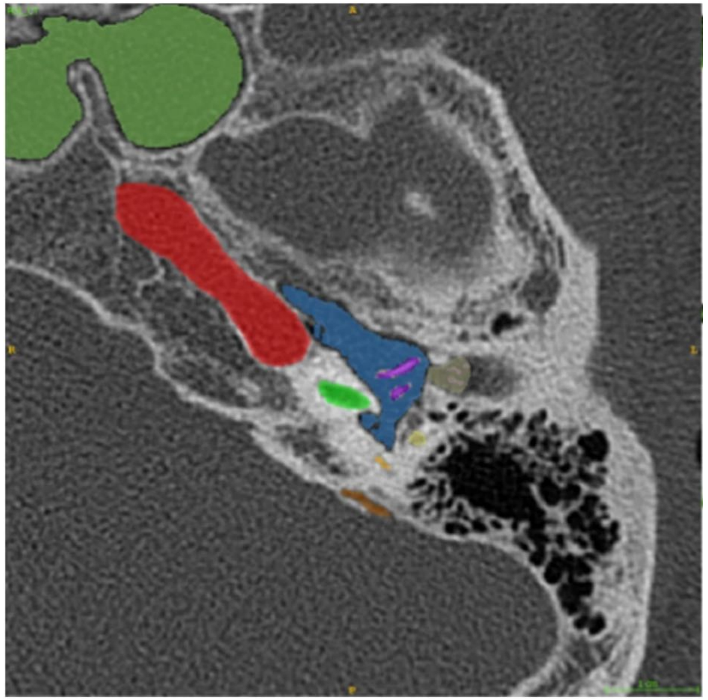


Fauser *et al*, 2019 (Figure 1)

Paper: Background

- Minimally invasive surgery (MIS) in the temporal bone procedures is increasing in popularity
  - Cochlear implants
  - Middle ear access
  - Multi-port setups analogous to laparoscopic procedures in the abdomen

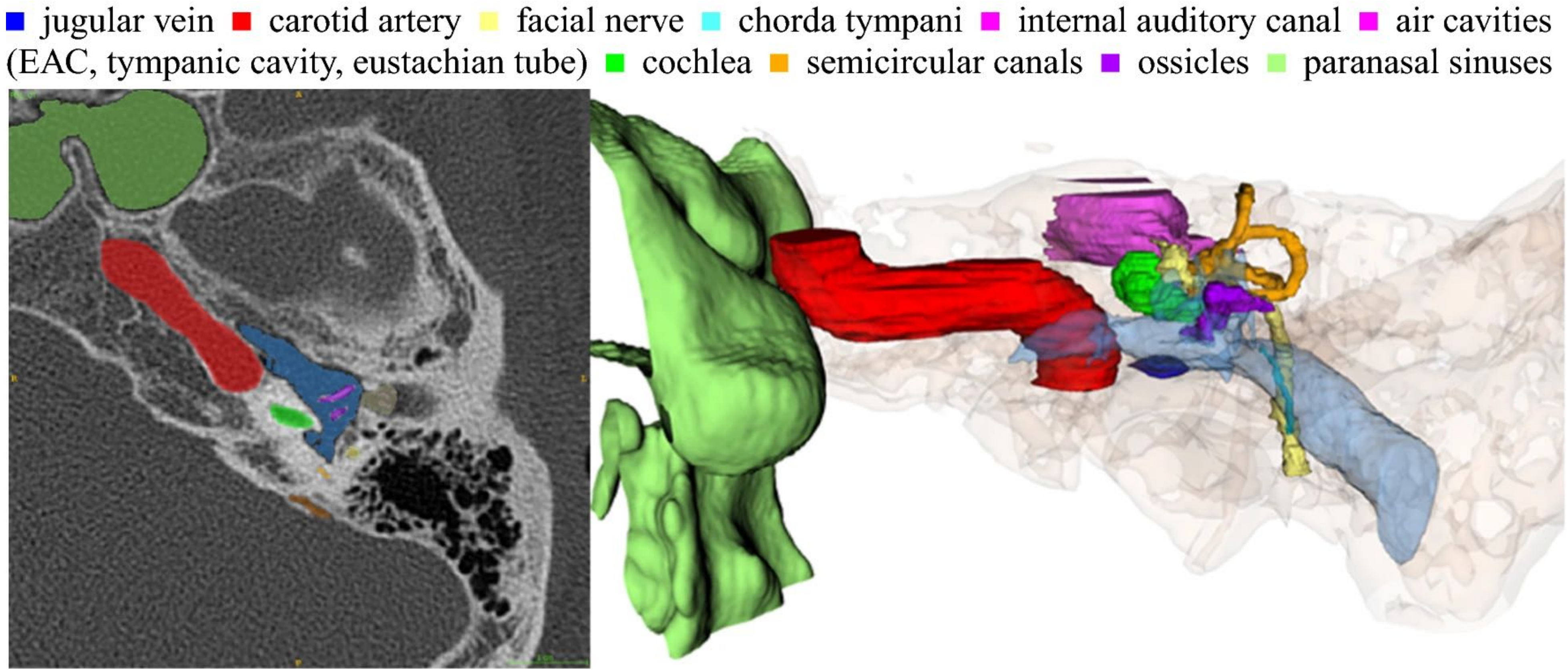
- MIS requires pre-operative planning, ideally with segmented CTs



Fauser *et al*, 2019 (Figure 1)

Paper: Manual Segmentation

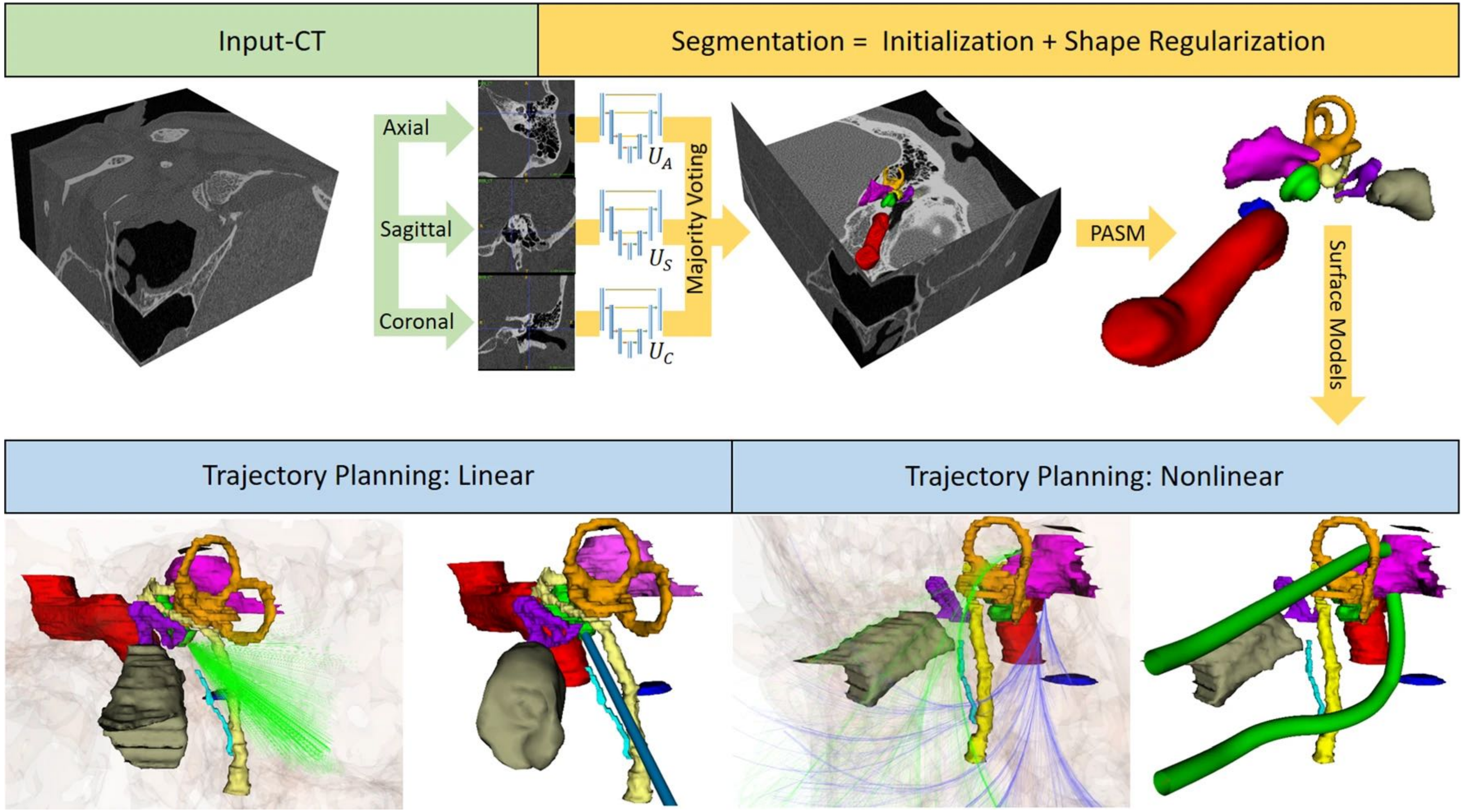
- 24 manually segmented CTs (resolution $0.2x0.2x0.4mm^3$)



Fauser *et al*, 2019 (Figure 1)

Paper: Automated Segmentation Workflow

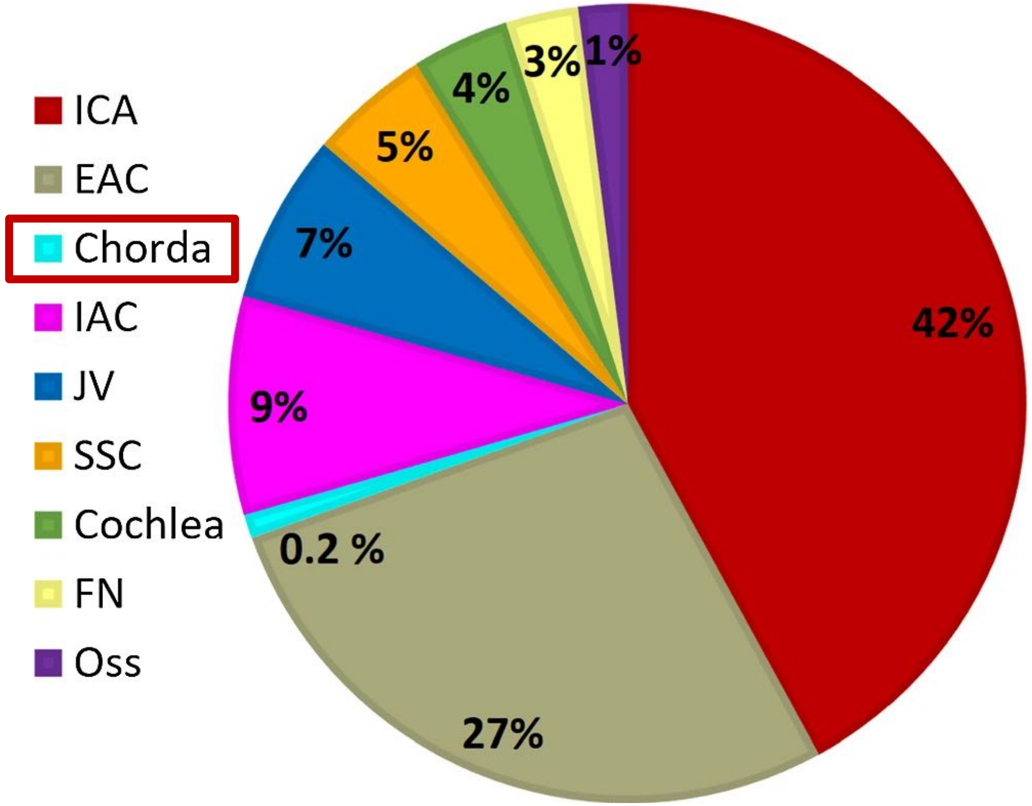
- Ensemble 2D Unet
- Shape Regularization
- Trajectory planning



Fauser *et al*, 2019 (Figure 3)

Paper: UNet Segmentation

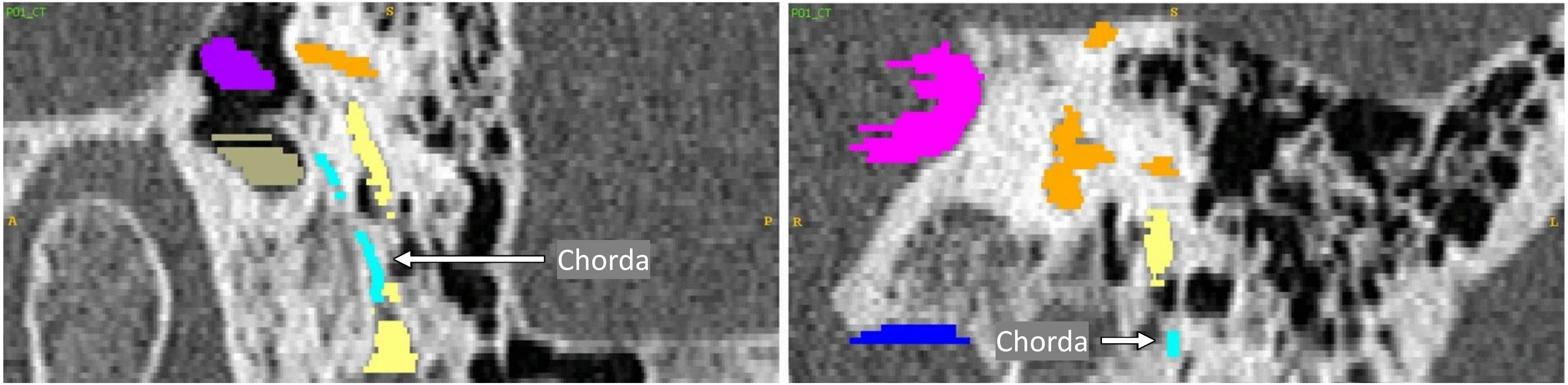
- Implemented slice-by-slice predictions with 2D UNets (coronal, axial, saggital) instead of 3D UNet
  - Due to scarcity of available labeled data
- Majority voting from the 3 independent predictions for each voxel to finalize labels
- **Extreme** heterogeneity of volumes among labeled anatomy



Fauser *et al*, 2019 (Figure 4)

Paper: The Chorda Tympani Problem

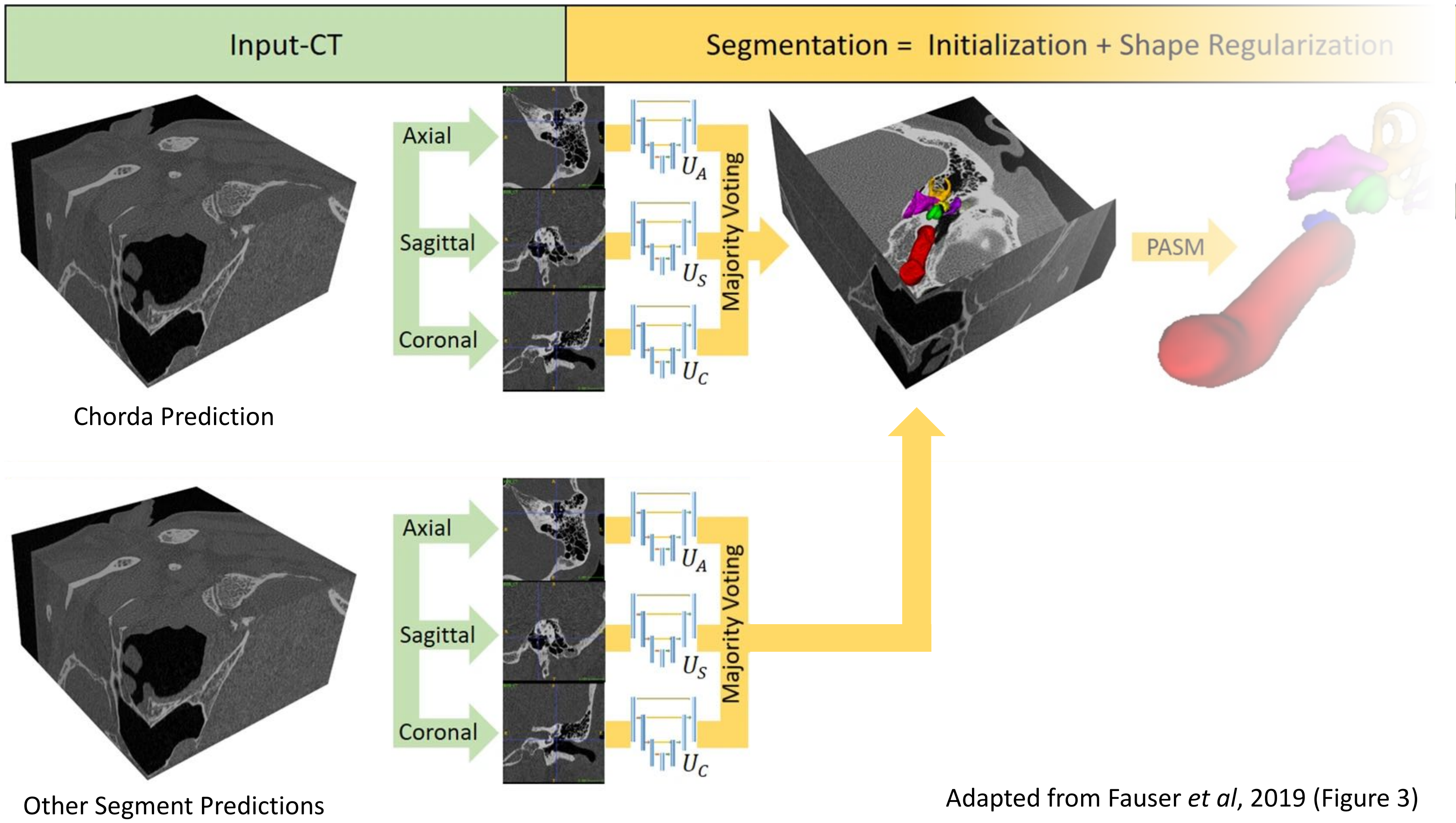
- Problem: Chorda is incredibly thin
  - 2-5 voxels in diameter
  - “Disappears” when entering the middle ear



Fauser *et al*, 2019 (Figure 2)

Paper: The Chorda Tympani Solution

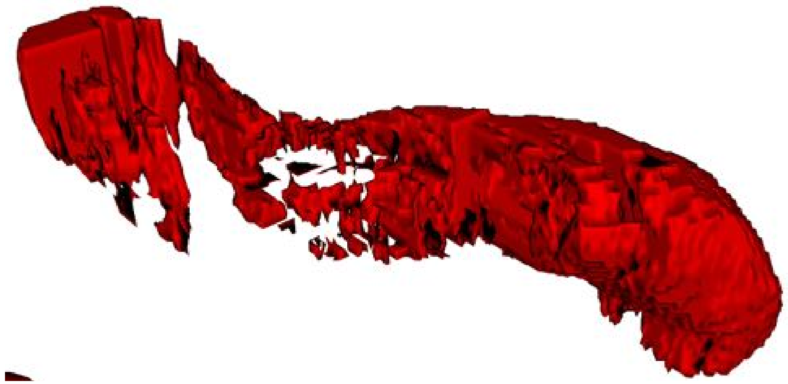
- Solution: Two UNet predictions!
  - One for chorda tympani
  - One for all other segments



Adapted from Fauser *et al*, 2019 (Figure 3)

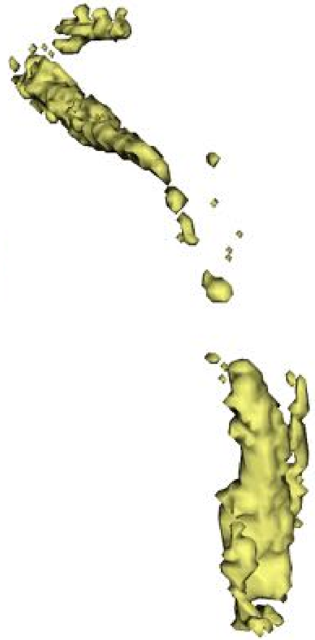
Paper: The UNet Shape Problem

- Problem: UNet has no prior knowledge of geometry
  - Predicted labels resulted in fragments, holes, and islands



Internal Carotid Artery

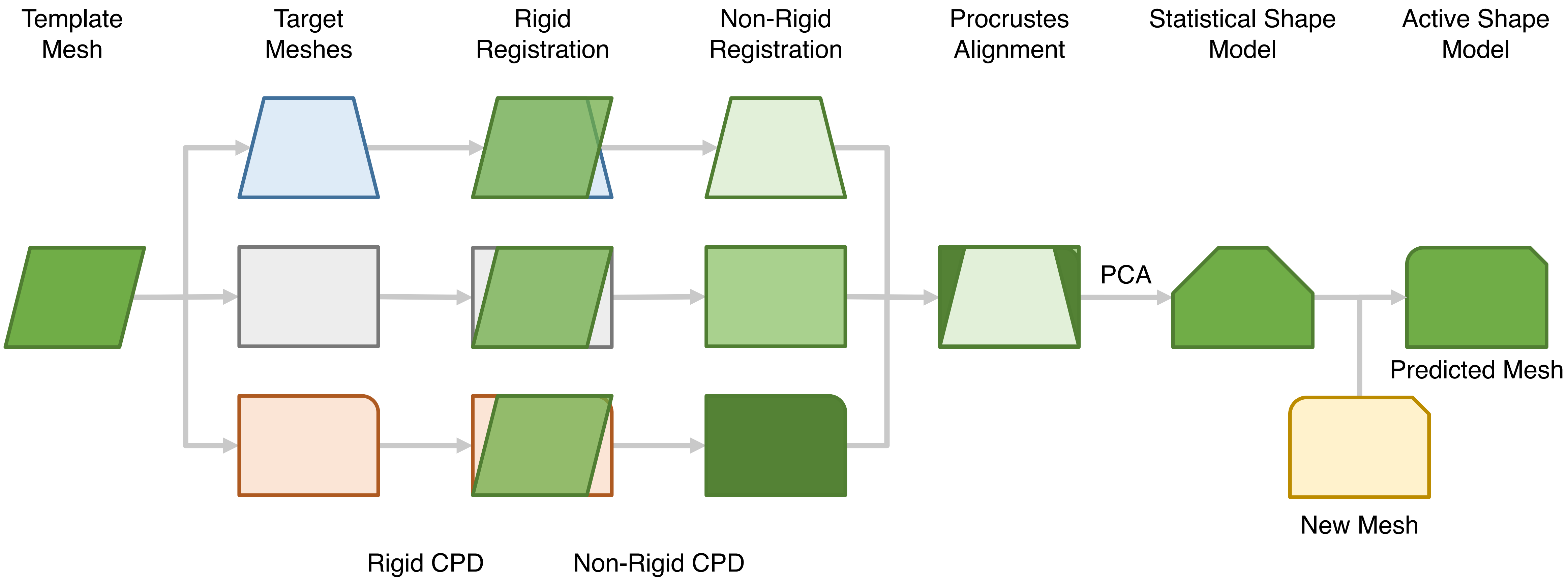
Middle Ear Ossicles



Facial Nerve

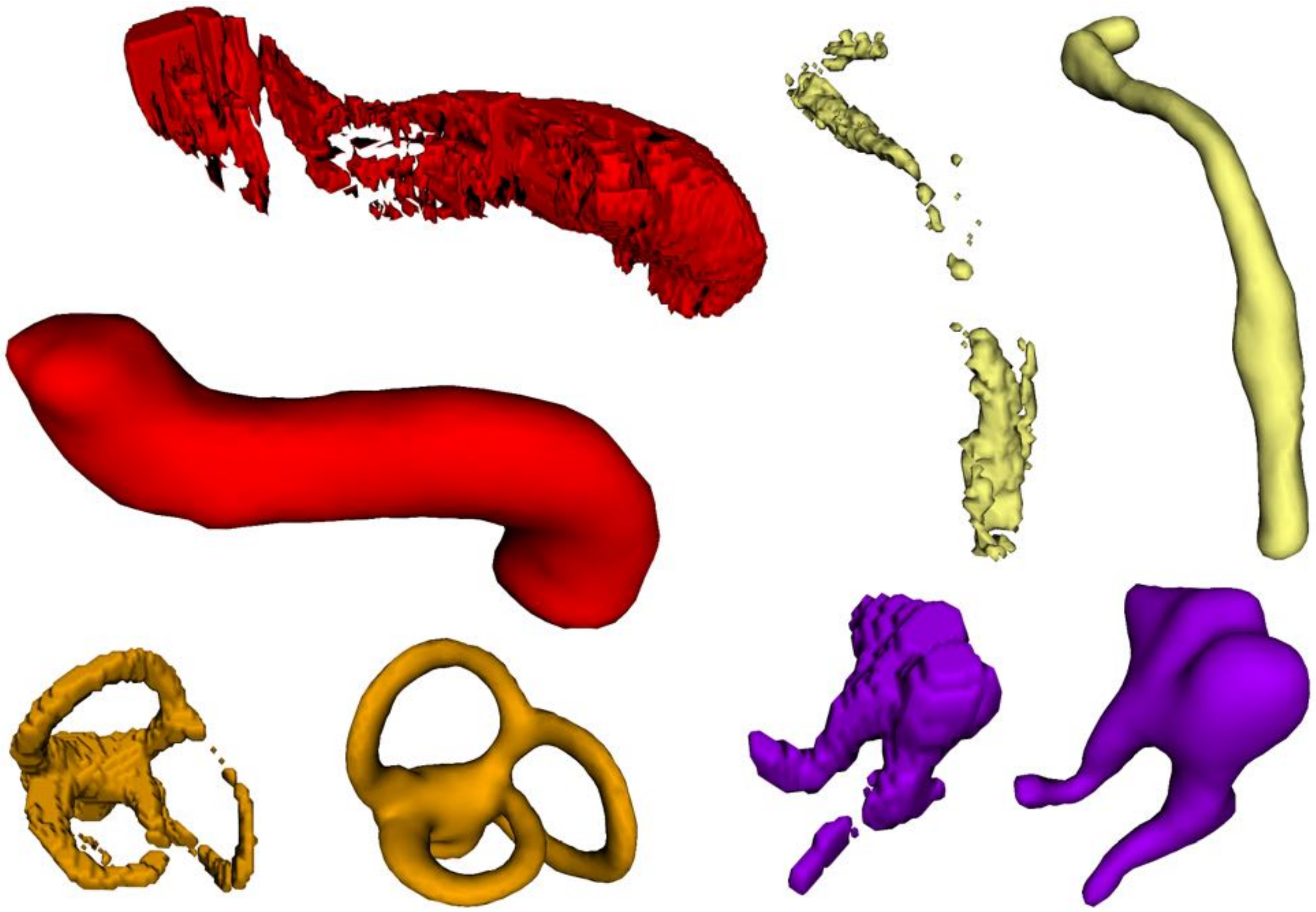
Adapted from Fauser *et al*, 2019 (Figure 5)

Paper: Active Shape Models



Paper: The UNet Shape Solution

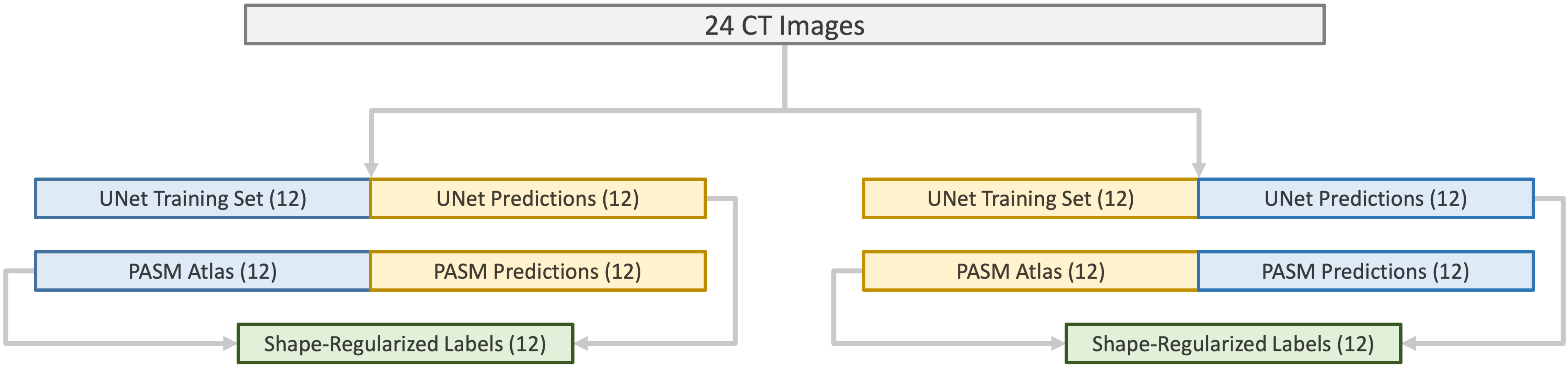
- Solution: Use probabilistic active shape models (PASM) [2] to form anatomically realistic segmentations
  - UNet predictions serve as an initialization to PASM
  - Mean shapes from statistical shape model are rigidly aligned
  - PASM deforms mean shapes to approximate target anatomy



Fauser *et al*, 2019 (Figure 5)

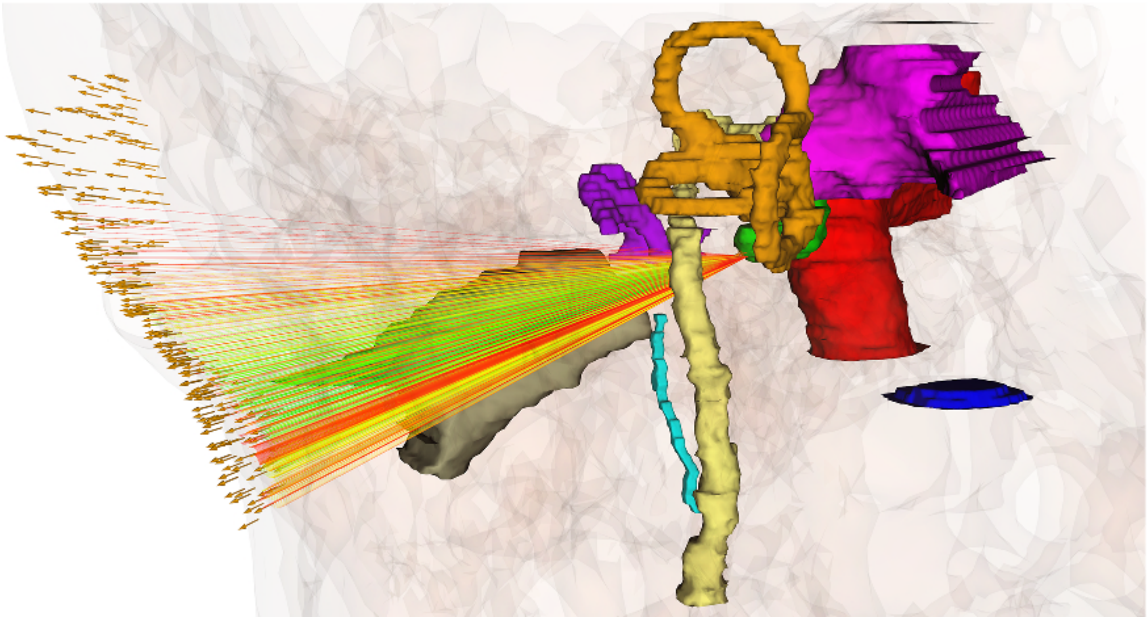
[2] Becker *et al*, 2014

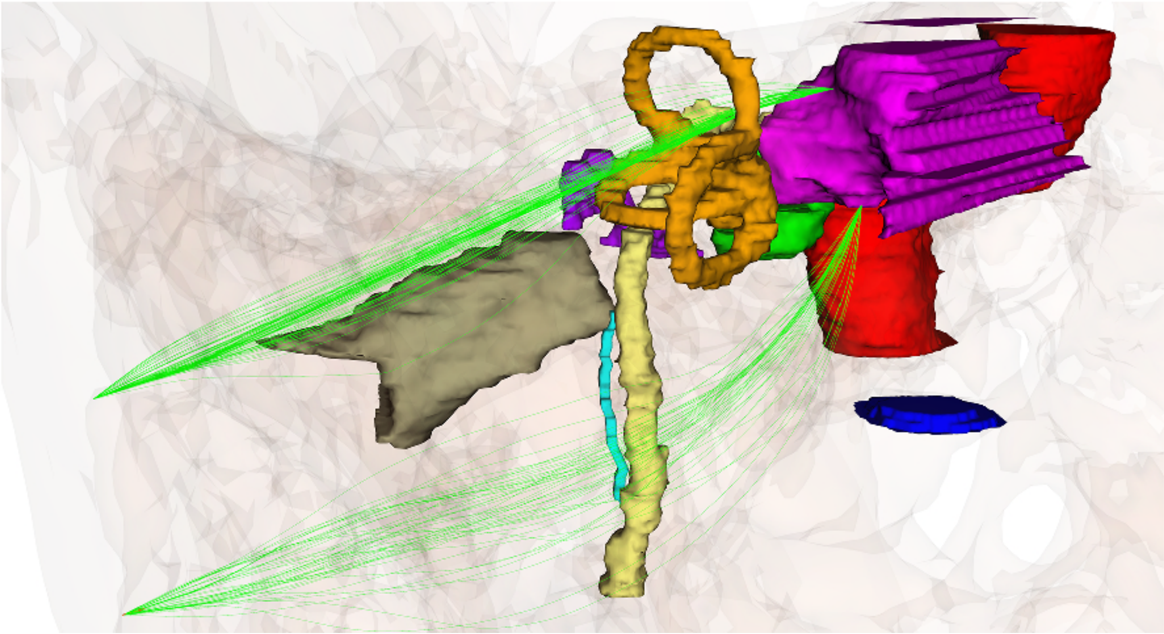
Paper: UNet + PASM Hybrid Dataset Breakdown



Paper: Minimally Invasive Operating Path Planning

- Linear trajectories were calculated using segmentations for cochlear access (cochlear implantation)
- Non-linear trajectories were calculated for internal auditory canal access (vestibular schwannoma removal)



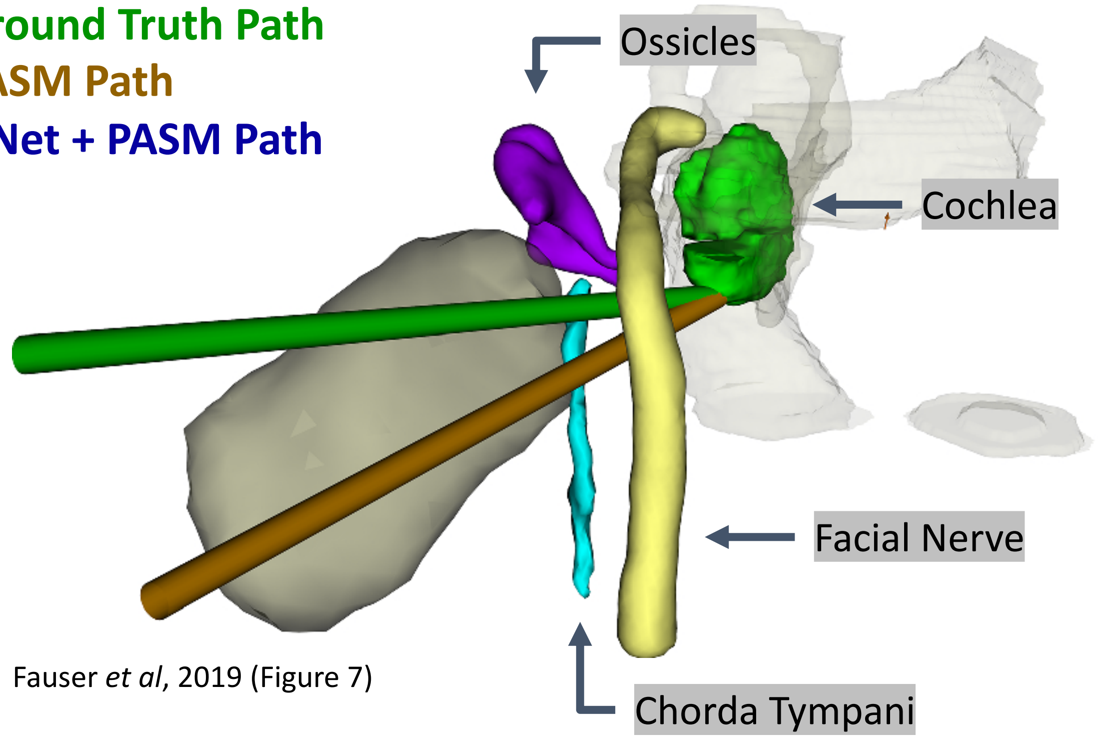


Fauser *et al*, 2019 (Figure 6)

Paper: UNet + PASM Hybrid vs. PASM – Cochlear Access

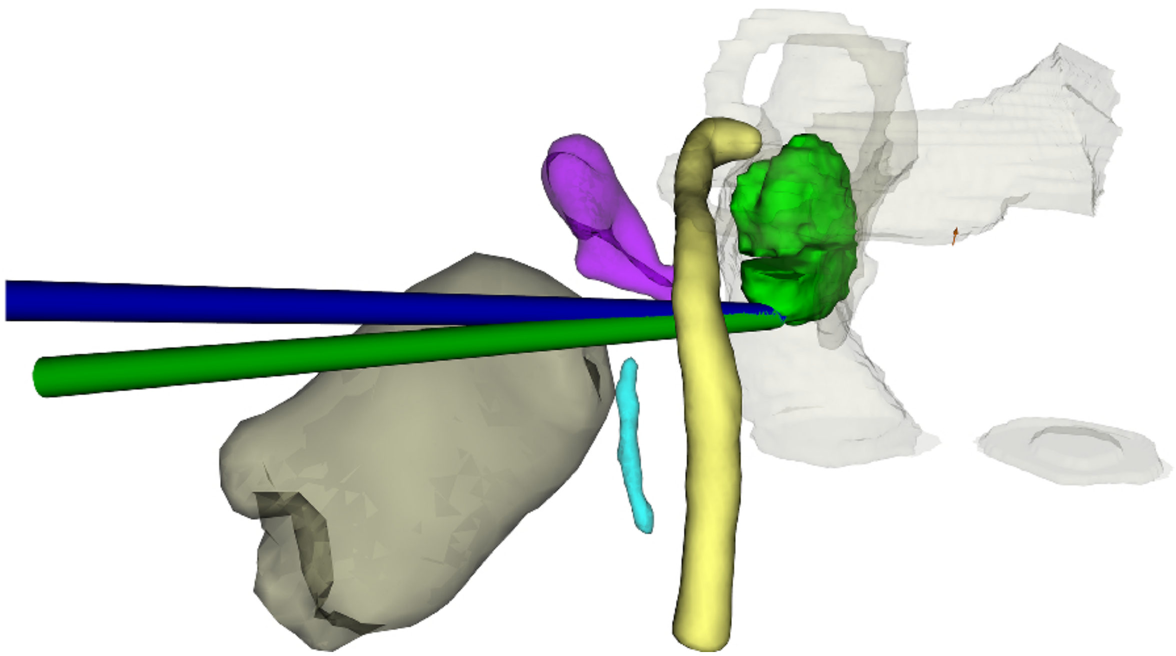
PASM Segmentation

Ground Truth Path
PASM Path
UNet + PASM Path



Fauser *et al*, 2019 (Figure 7)

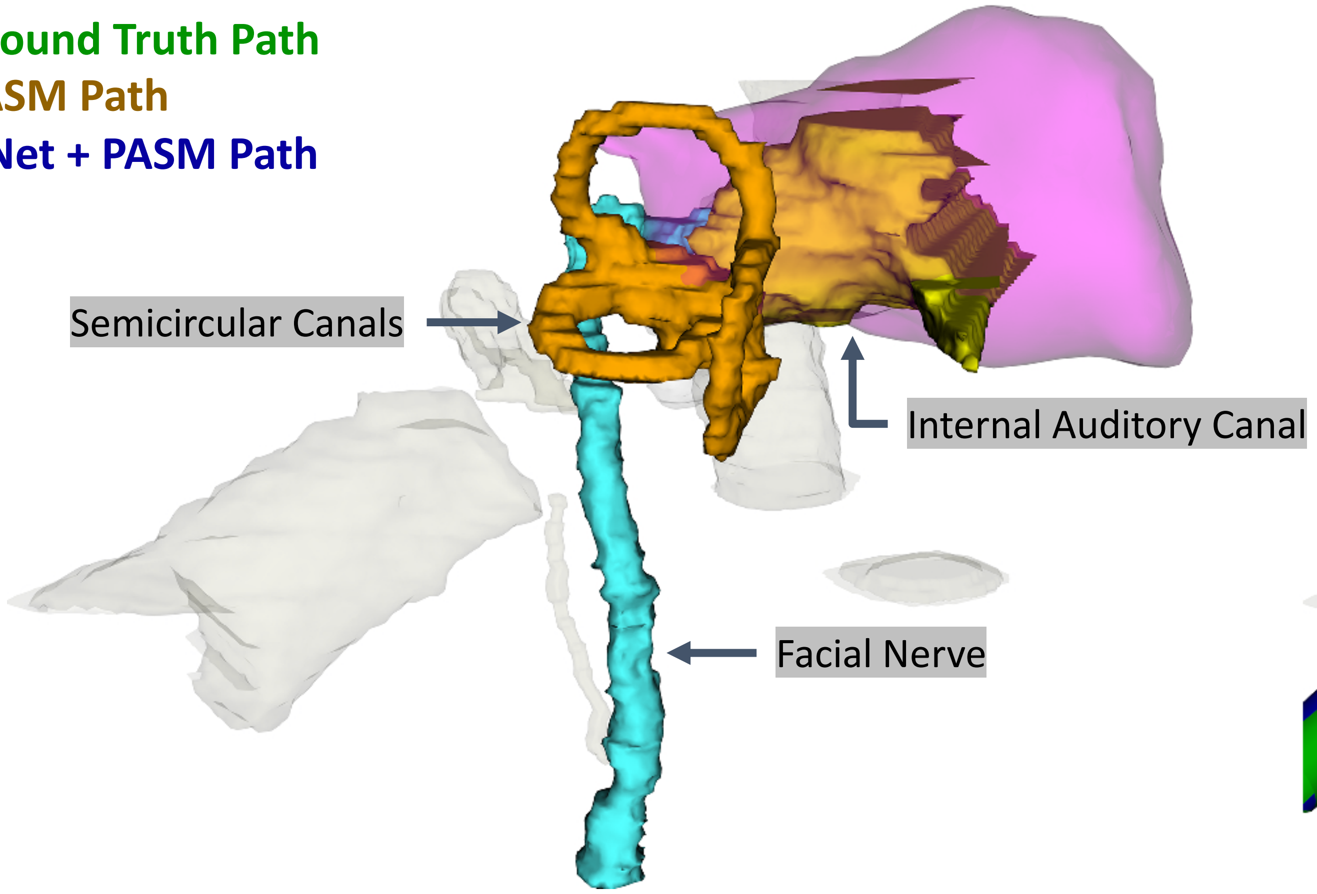
UNet + PASM Segmentation



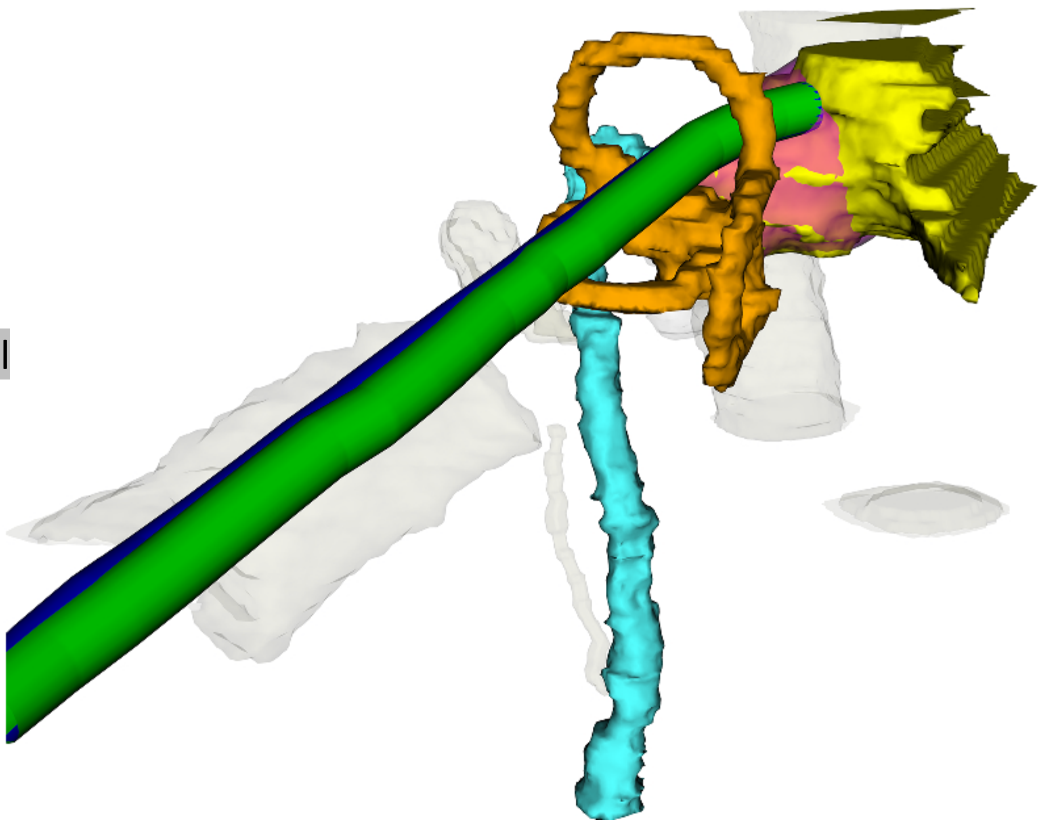
Paper: UNet + PASM Hybrid vs. PASM – Semicircular Canal Approach

Ground Truth Path
PASM Path
UNet + PASM Path

PASM Segmentation

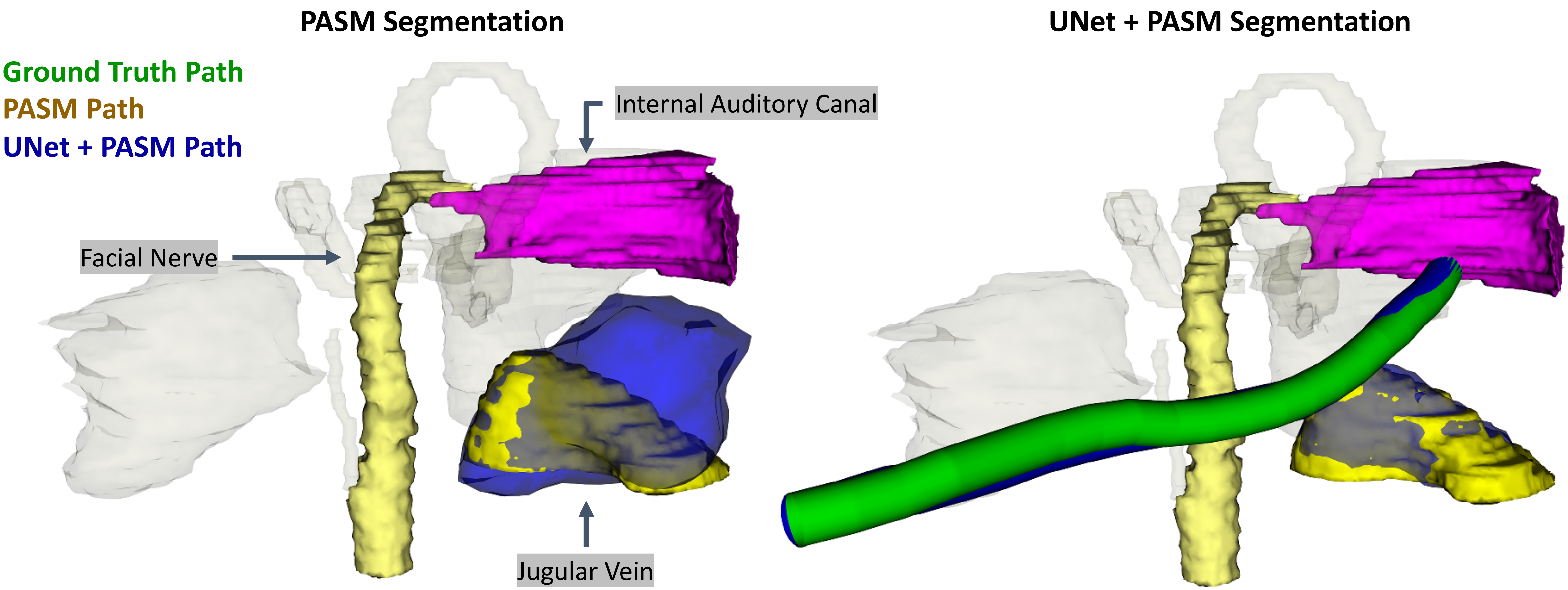


UNet + PASM Segmentation



Fauser *et al*, 2019 (Figure 8)

Paper: UNet + PASM Hybrid vs. PASM – Retrolabyrinthine Approach



Fauser *et al*, 2019 (Figure 9)

Paper: UNet + PASM Hybrid vs. PASM – Path Planning Success Rate

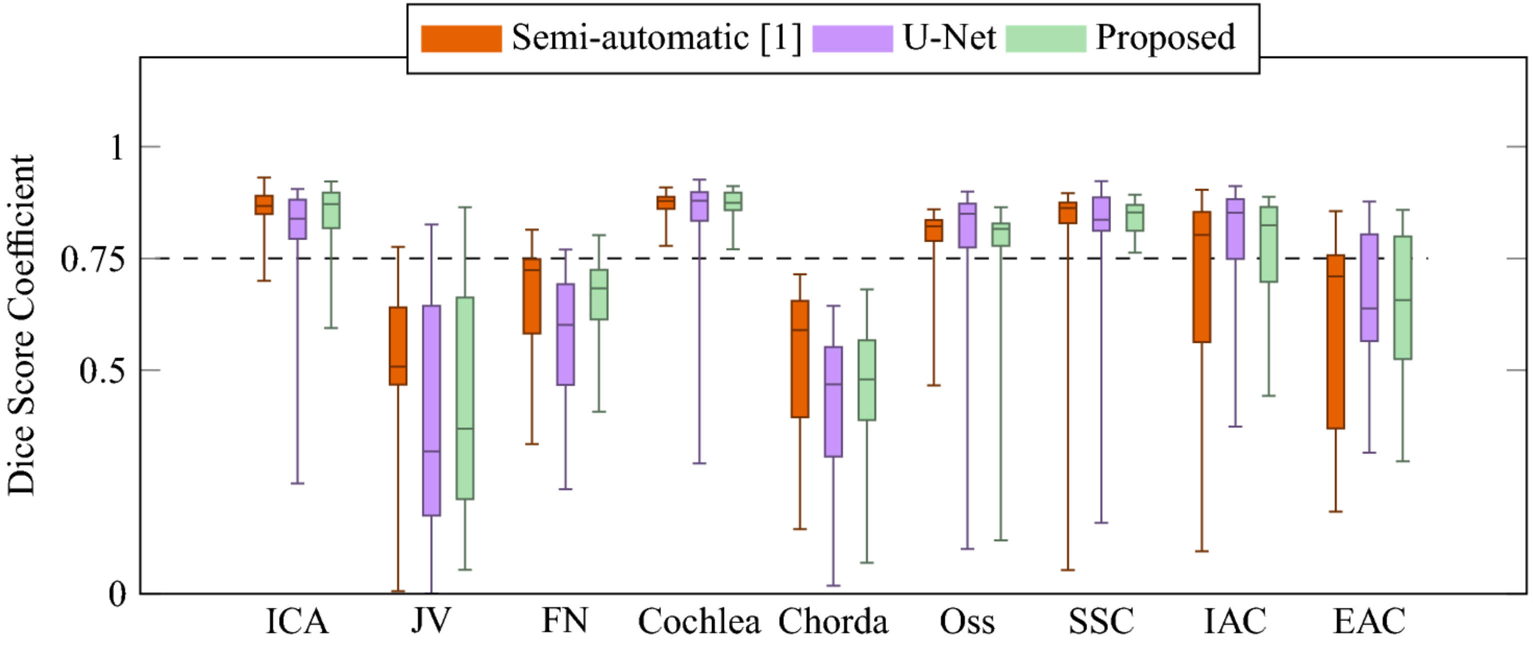
- Paths generated with UNet + PASM hybrid segmentations were more similar to ground truth paths than those generated with PASM alone

	Success rate			Mean safety distance			Violation rate ($d < d_{min}$)		
	Co	SSC	RL	Co (0.8)	SSC (1.5)	RL (1.5)	Co	SSC	RL
Ground truth	0.9	1.0	1.0	1.39	2.19	2.35	–	–	–
Semiautomatic	0.65	0.66	0.66	1.15	2.17	2.60	0.0	0.0	0.0
Ours	0.9	1.0	1.0	1.04	2.16	2.42	0.18	0.0	0.1

Fauser *et al*, 2019 (Table 2)

Paper: UNet + PASM Hybrid vs. PASM/UNet – Dice Score + Sensitivity

- Dice scores are similar among the three methods
- Hybrid model seems to have lower sensitivity compared to PASM (refer to table)



	IAC	JV	FN	Cochlea	Chorda	Oss	SSC	IAC	EAC
semi-automatic	89.9 ± 04.0	73.8 ± 18.9	69.2 ± 17.0	87.1 ± 05.6	54.5 ± 17.0	83.2 ± 08.2	81.9 ± 07.4	86.3 ± 08.0	76.6 ± 16.0
U-Net	72.5 ± 21.3	30.3 ± 26.5	43.4 ± 16.8	80.9 ± 17.1	36.6 ± 20.4	74.8 ± 21.1	74.5 ± 16.7	72.7 ± 20.5	61.5 ± 22.9
proposed	83.8 ± 11.3	37.7 ± 29.2	62.7 ± 13.4	85.3 ± 06.6	39.3 ± 18.0	78.8 ± 17.0	79.8 ± 07.0	68.4 ± 17.2	60.9 ± 24.3

Paper: Conclusions

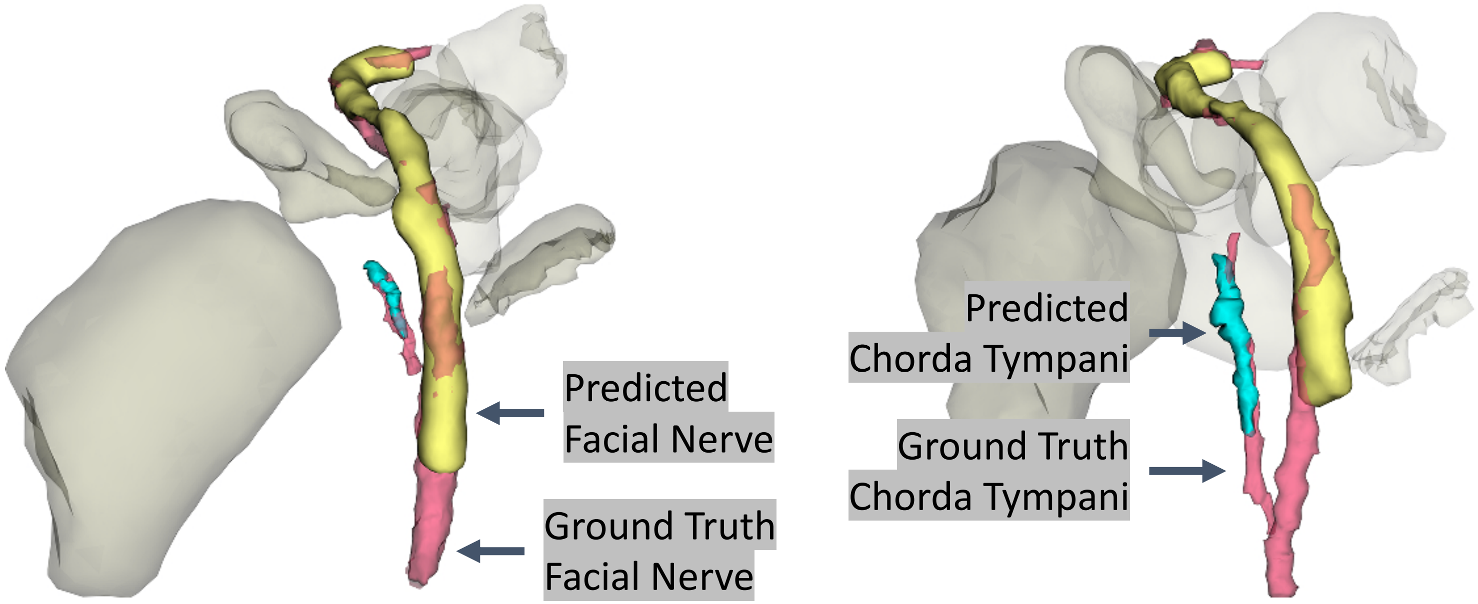
- Semantic segmentation with UNet alone was not sufficient to create robust segmentations in this dataset
- Shape regularization with PASM results in anatomically accurate segmentations in the temporal bone
- UNet + PASM hybrid model performs similar to UNet or PASM alone with respect to Dice similarity scores
- Path planning using segments from the UNet + PASM hybrid model results in more realistic and reliable trajectories than PASM alone

Paper: Critiques - Pros

- Clearly stated methods for implementing UNet and PASM together
- Elegant solution for creating intact segments of temporal bone anatomy
- Code is publicly available for testing

Paper: Critiques - Cons

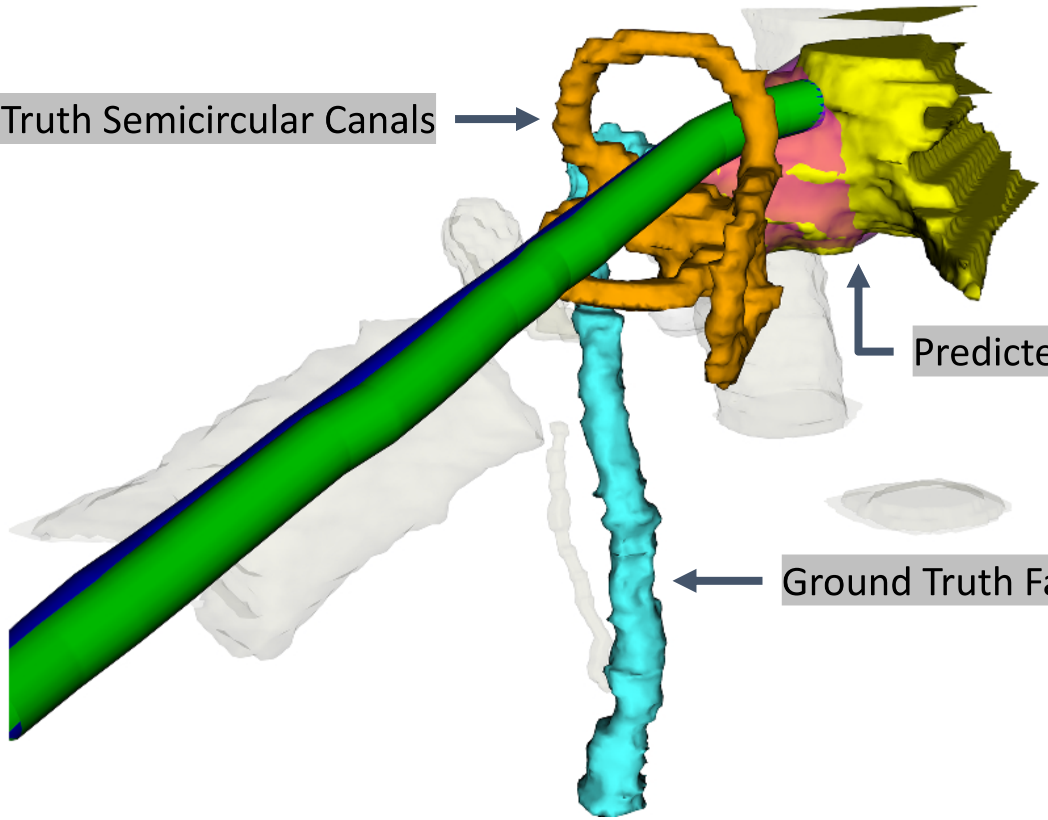
- No true test set or external validation; how generalizable is this model?
- Sensitivity of some segments is quite low
  - Is the hybrid model systematically undersegmenting?



Fauser *et al*, 2019 (Figure 12)

Paper: Critiques - Cons

- Path planning figures show ground truth and predicted segments together
  - Path planning should be tested using all predicted segments from one method



Fauser *et al*, 2019 (Figure 8)

Paper: Potential Next Steps

- Integration into a GUI application for surgeon usage
- External validation to evaluate generalizability
- Hausdorff distances to further investigate segmentation accuracy

Paper: Relevance

- Contingency plan for malformed segmentations
  - Shape regularization using a statistical atlas
  - Statistical shape model of our dataset has already been created in prior work
- The Chorda Tympani Problem
  - Major reason to explore deep learning approaches for segmentation
  - Segmentation propagation did not perform well at segmenting chorda

References

1. Fauser, J., et al. (2019). "Toward an automatic preoperative pipeline for image-guided temporal bone surgery." International Journal of Computer Assisted Radiology and Surgery **14**(6): 967-976.
2. Meike, B., et al. (2014). Segmentation of risk structures for otologic surgery using the Probabilistic Active Shape Model (PASM). Proc.SPIE.

Image References

- Temporal Bone Anatomy. https://otosurgeryatlas.stanford.edu/wp-content/uploads/2020/06/7a-1.jpg. Accessed March 8, 2021

Thank you!

Questions?