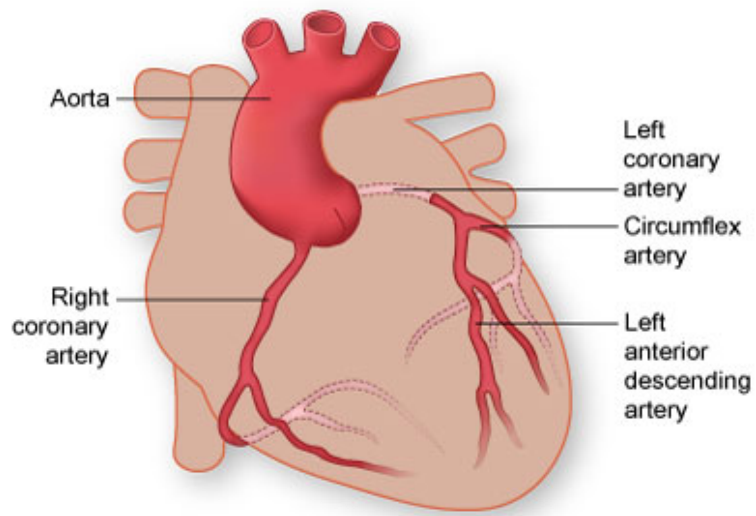
DeepCA:

Deep Learning-based 3D Coronary Artery Tree Reconstruction from Two 2D Non-simultaneous X-ray Angiography Projections



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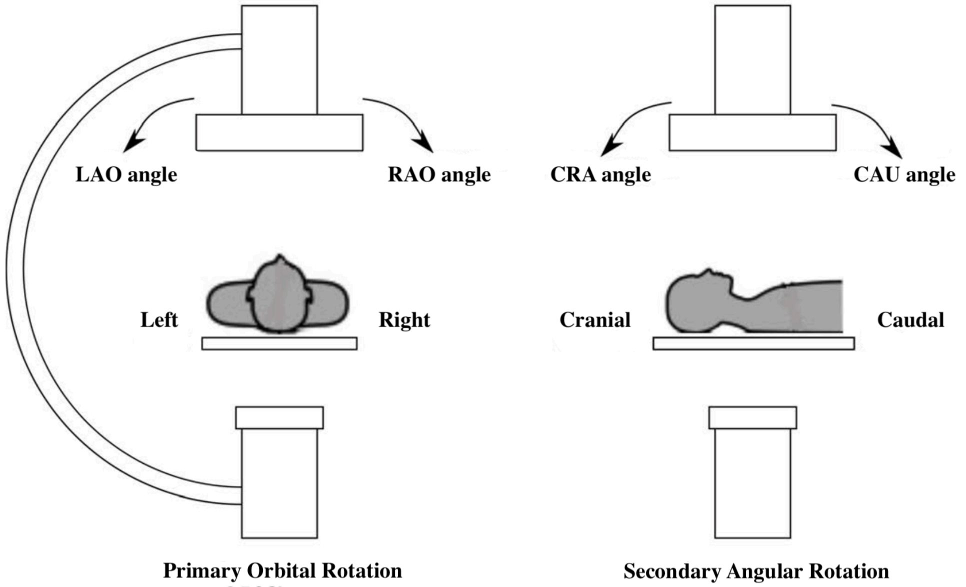
The John Radcliffe Hospital

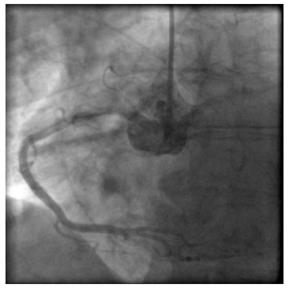
BACKGROUND

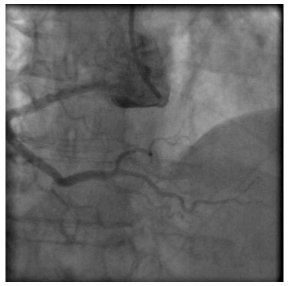
X-RAY INVASIVE CORONARY ANGIOGRAPHY (ICA)

Siemens single-plane C-arm[1]



C-arm imaging geometry[2]





ICA images

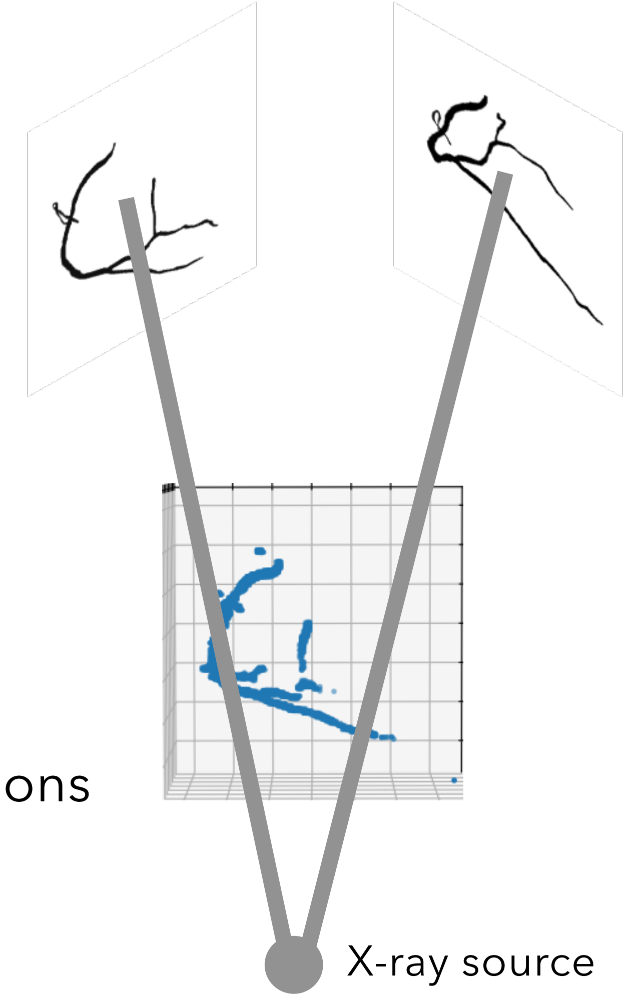
- Cardiovascular diseases are the most common cause of death worldwide, representing **32%** of all global death[3]
- ICA acquires **2D** projections of the coronary artery tree (based on C-arm) and is the gold standard during **cardiac interventions**
- Around **250,000** coronary angiograms are performed across the UK every year[4]

[1] Siemens Healthineers Official Website, Accessed: 22/01/2025
[2] Kausch et al., 2020
[3] World Health Organisation, Accessed: 22/01/2025
[4] British Heart Foundation, Accessed: 22/01/2025

MOTIVATION

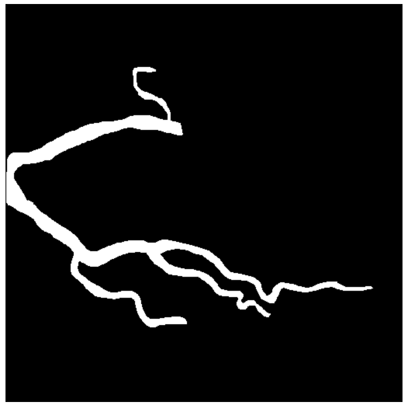
Doing **3D coronary artery tree reconstruction from two ICA images** helps:

- Reduce the likelihood of subjective interpretation of 3D geometry from 2D projections
- Reduce extra contrast injected and extra X-ray radiation dose exposed
- **Deep Learning** helps:
  - 3D reconstruction in real time
  - **Implicitly compensate** for the non-rigid cardiac and respiratory motions



CHALLENGES

- **Non-rigid** cardiac and respiratory motions due to **non-simultaneous image acquisition**, causing vessels to misalign between projections
- Possible patient and device movements between non-simultaneous scans
- Foreshortening, vessel overlap and complex vessel shape
- Only **two** projections acquired and some parts of the vessels in projection images may be incomplete
- Intensity values in projections do not provide additional information due to contrast injected
- **No 3D ground truth** and the number of real clinical 2D ICA data is also **limited**



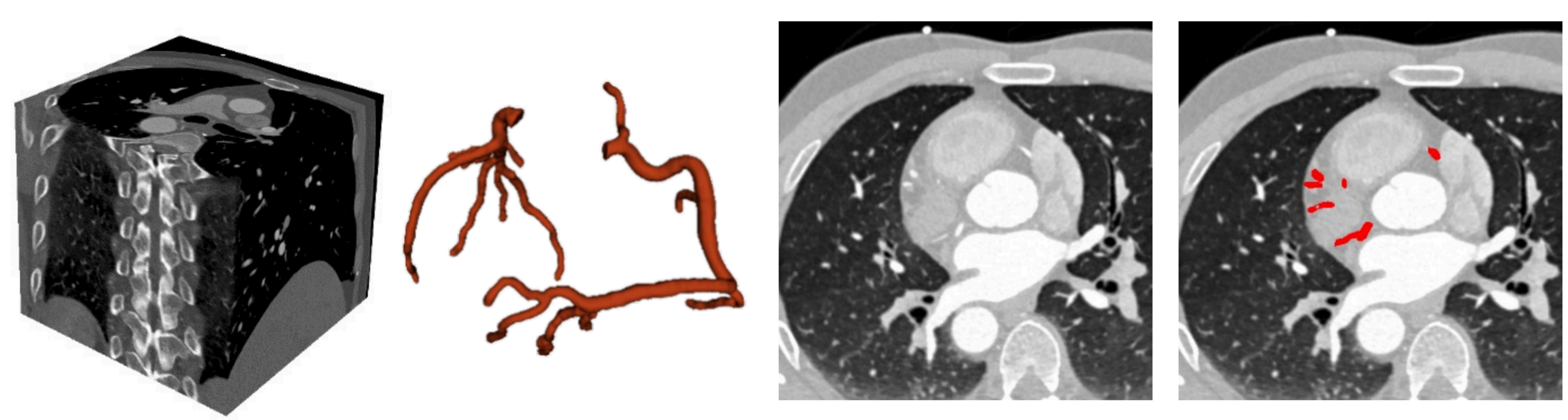
RELATED WORK

- Traditional Methods:
  - Usually require substantial manual annotations
  - Cannot handle non-rigid cardiac motion
- Deep Learning Approaches:
  - Based on synthetic data or Coronary Computed Tomography Angiography (CCTA) data only
  - Use real ICA data from bi-planar scans
  - None of which suffers from **non-rigid motion** between projections

DATA

REAL CCTA DATA

- Issues:
  - No public ICA image datasets with projection geometry information
  - Hard to build the accurate 3D coronary artery tree ground truth even given several real 2D angiograms
- Solution:
  - Public datasets[1] of segmented CCTA data of 1000 patients containing both right coronary artery (**RCA**) and the left anterior descending artery (LAD)

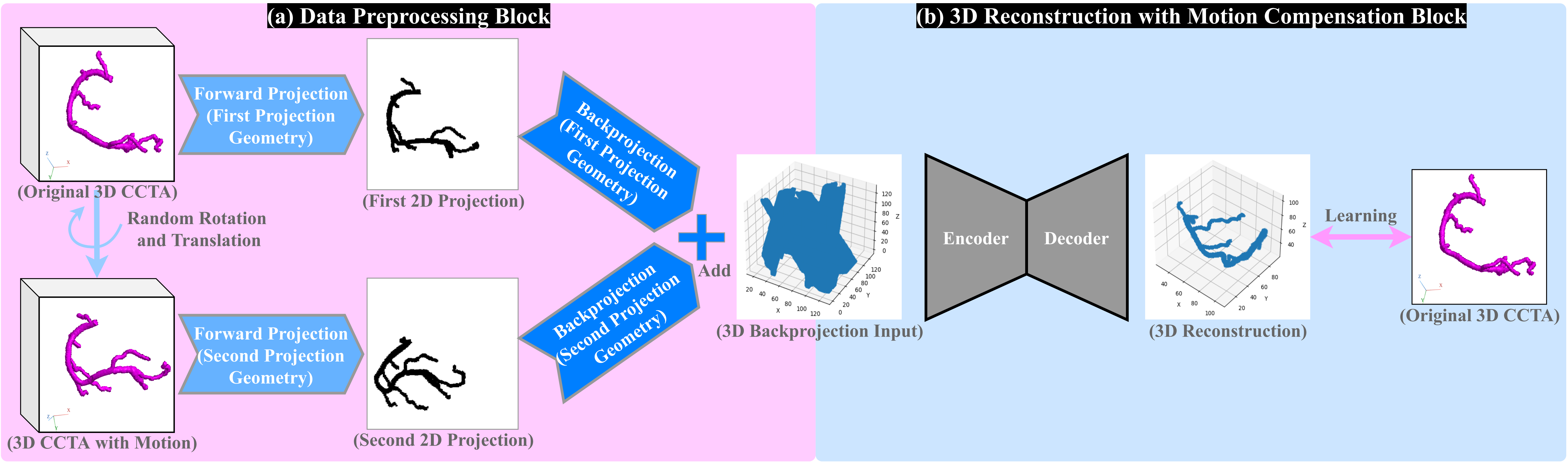


CT Label CT slice Labels in CT slice

[1] Zeng et al., 2023

METHOD

OUR PROPOSED PIPELINE



(a) **Data preprocessing block:**

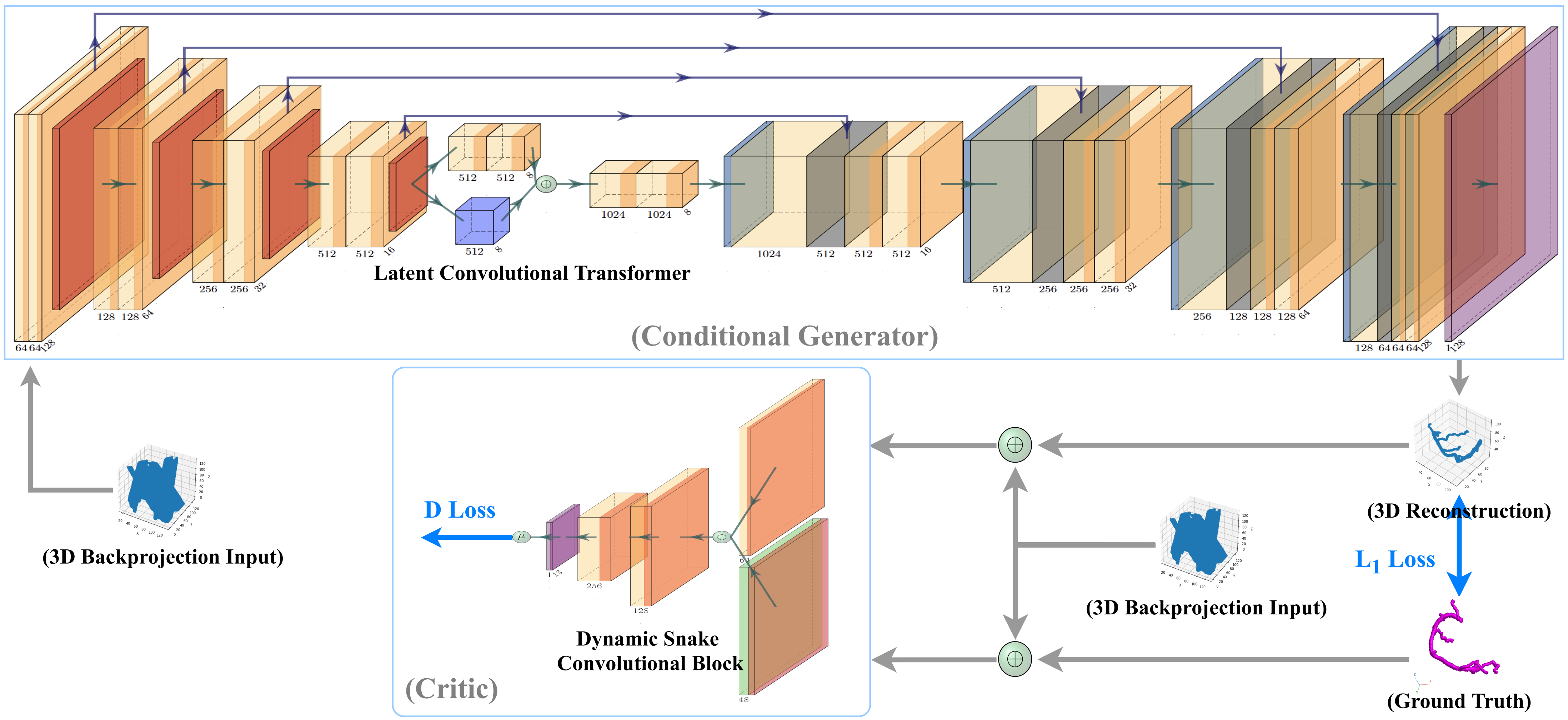
- Two simulated projections from CCTA data, including simulated motion
- Model input via performing backprojection on two simulated projections

(b) **3D reconstruction with motion compensation block:**

- A deep neural network for 3D coronary artery tree reconstruction

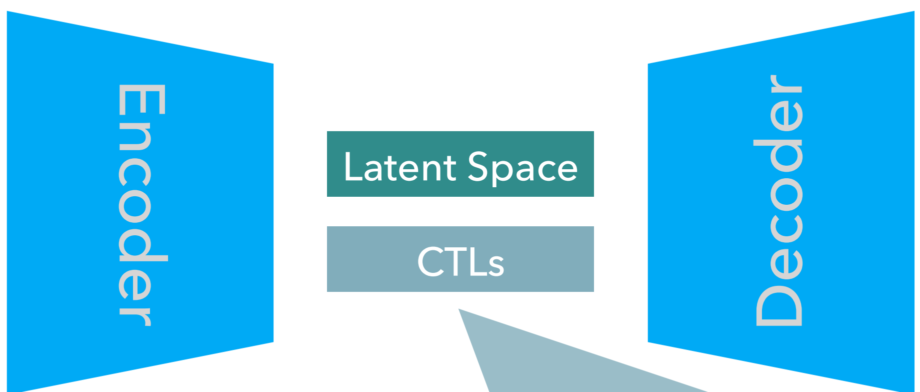
OUR PROPOSED MODEL

- Based on Wasserstein conditional generative adversarial network with gradient penalty (**WGP**), latent convolutional transformer layers (**CTLs**), and a dynamic snake convolutional critic (**DSCC**).



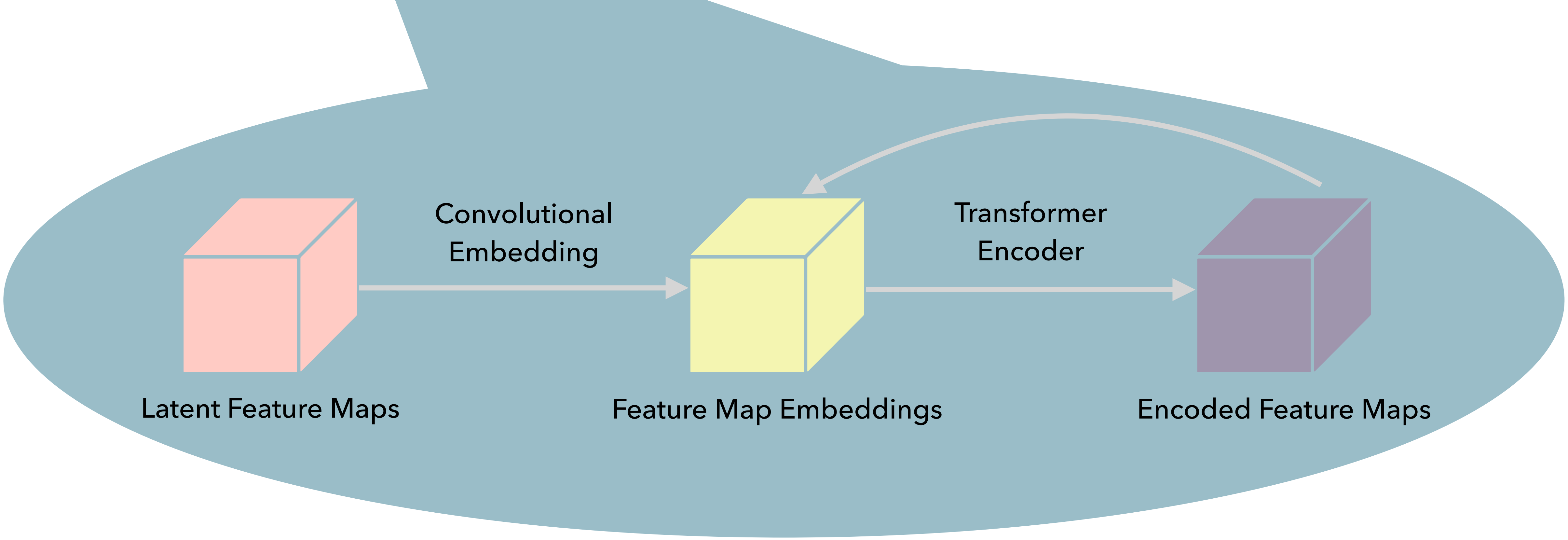
[1] Cicek et al., 2016

LATENT CONVOLUTIONAL TRANSFORMERS

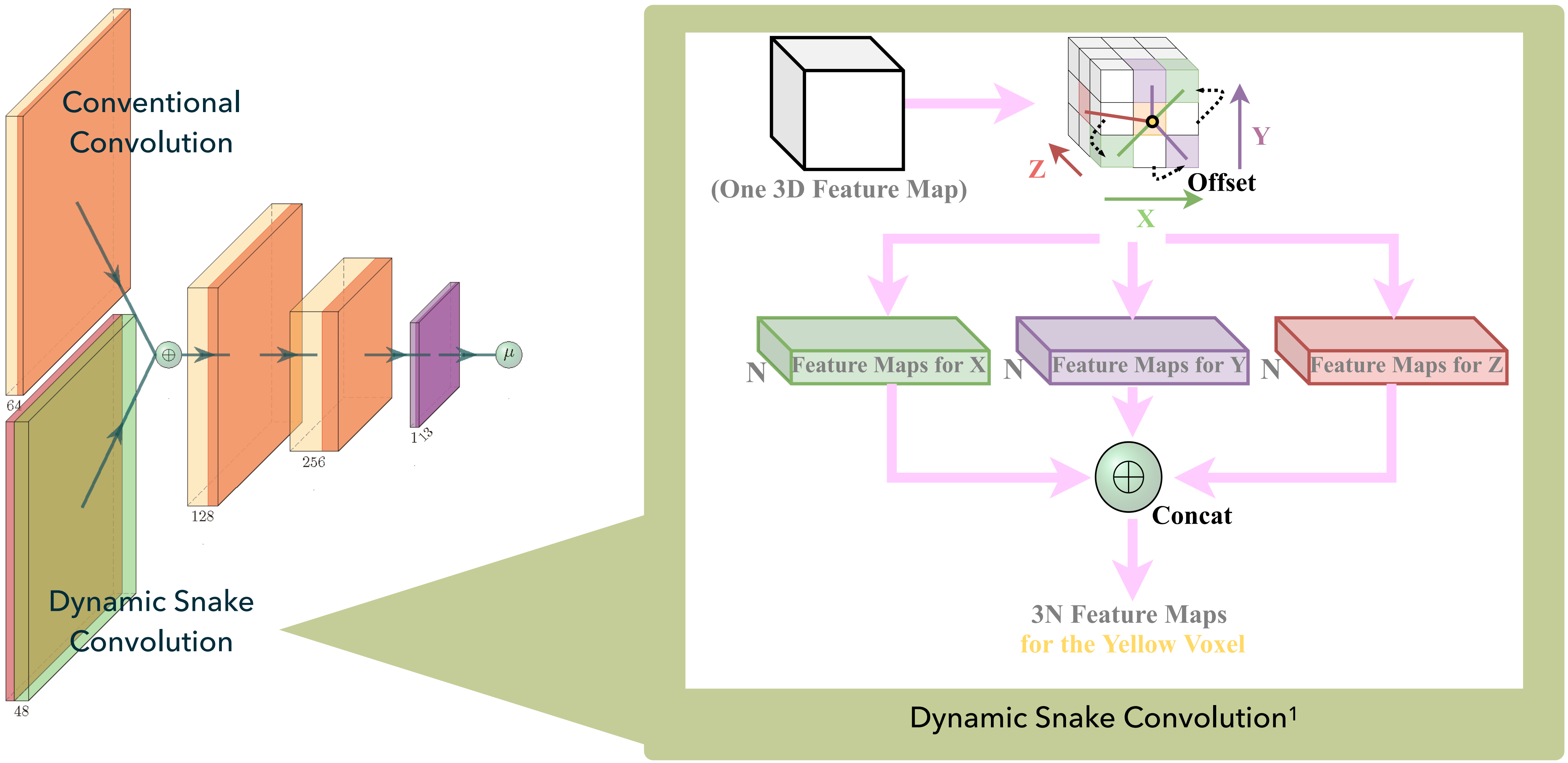


3D U-Net With Latent Convolutional Transformer Layers

- Since our data contain large empty background, usual patch embeddings are not suitable
- The latent convolutional transformers are built on **convolutional embeddings** following transformer layers
- Do not require positional embeddings as the latent feature maps are order invariant



DYNAMIC SNAKE CONVOLUTIONAL CRITIC



Dynamic Snake Convolution[1]

- The proposed critic can effectively **distinguish vessel tubular structures**:
  - **Dynamic snake convolution** to extract global **tubular** features
  - Traditional convolution to extract essential local features

[1] Qi et al., 2023

EVALUATION

DATASETS

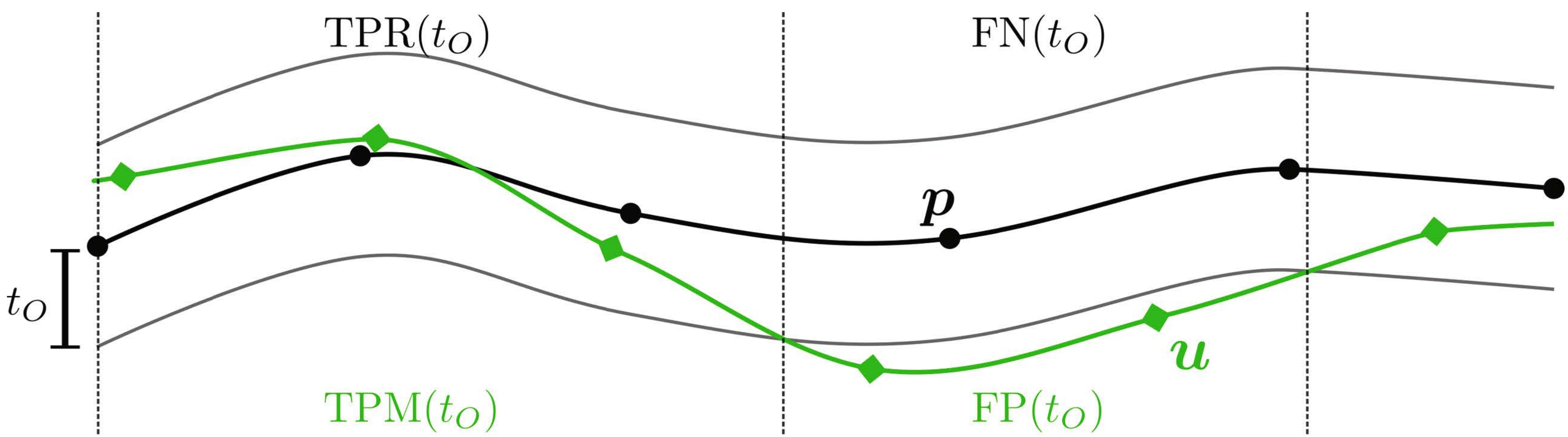
- We use **a public CCTA dataset**, ImageCAS[1], containing 3D binary segmented coronary artery trees for training in our study.
- We also collect **a clinical ICA dataset** of 8 patients for evaluation, who were admitted at the Oxford John Radcliffe Hospital and provided informed consent.

[1] Zeng et al., 2023

METRICS

- **Overlap using a sweeping distance threshold Ot**(t_0)[1], where points of the prediction (**green**) and ground truth (**black**) vessels are labeled as true and false positives or negatives depending on the sweeping test distance $\mathbf{t_0}$ (*mm*)
- **Chamfer ℓ_2 distance** (**CD(ℓ2)**) for measuring the corresponding prediction errors (*mm*)

$$\mathrm{Ot}(t_0) = \frac{|\mathrm{TPM}(t_0)| + |\mathrm{TPR}(t_0)|}{|\mathrm{TPM}(t_0)| + |\mathrm{TPR}(t_0)| + |\mathrm{FN}(t_0)| + |\mathrm{FP}(t_0)|}$$



[1] Çimen et al., 2017

EVALUATION PROCESS

- For the CCTA test dataset, validate 3D results directly after **rigidly registering** the ground truth to the predicted reconstruction
- For real clinical ICA data:
  - Measure the **Dice** score (same as Ot(0)) between the ICA data and reprojections of our reconstruction on the **first** projection plane
  - For the **second** and any **additional** projection planes, compute Ot(t_0) and CD$(\ell 2)$ between the ICA data and reprojections **after rigid registration**

RESULTS

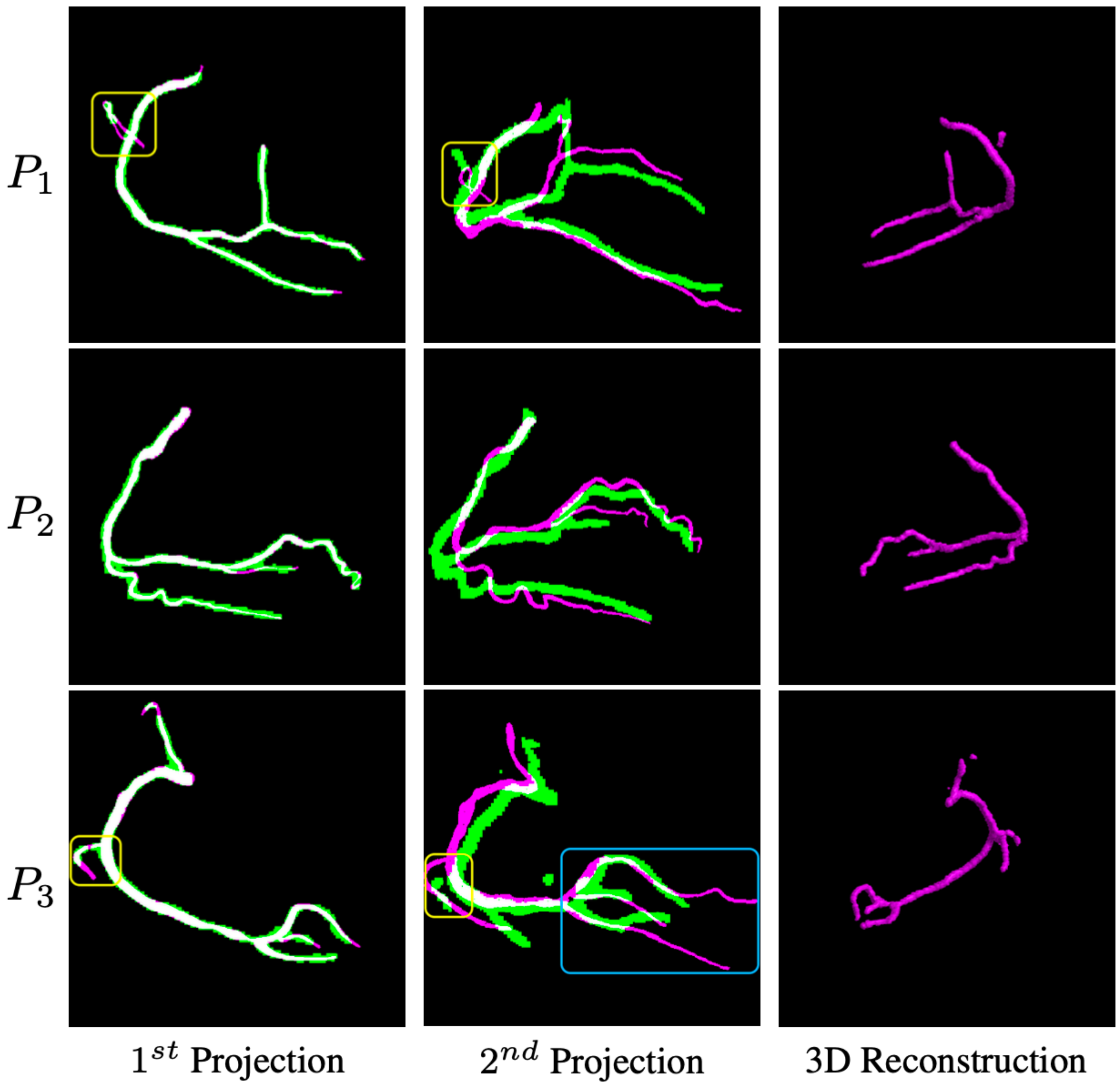
QUANTITATIVE RESULTS

Model	3D CCTA Test Dataset		
	$Ot(1)\uparrow$	$Ot(2)\uparrow$	$CD(\ell_2)\downarrow$
WGP	$62.06_{\pm 10.61}$	$74.38_{\pm 10.01}$	$3.43_{\pm 1.29}$
+CTLs	$62.87_{\pm 11.68}$	$74.39_{\pm 10.70}$	$3.24_{\pm 1.23}$
+DSCC	$63.46_{\pm 10.85}$	$75.14_{\pm 10.00}$	$3.24_{\pm 1.23}$
DeepCA	$\mathbf{64.21}_{\pm 10.78}$	$\mathbf{76.25}_{\pm 9.72}$	$\mathbf{3.22}_{\pm 1.20}$

Quantitative performance in terms of **Ot**(t_0) (%) and **CD(ℓ2)** (mm) for 3 ablation models (**left**) and 4 baseline models (**bottom**)

Model	3D CCTA Test Dataset			2D Real Clinical ICA Dataset (Unseen Domain)							
				1^{st}	2^{nd} Projection			Additional Projection			
	$Ot(1)\uparrow$	$Ot(2)\uparrow$	$CD(\ell_2)\downarrow$	Dice $\uparrow$	$Ot(1)\uparrow$	$Ot(2)\uparrow$	$CD(\ell_2)\downarrow$	$Ot(1)\uparrow$	$Ot(2)\uparrow$	$CD(\ell_2)\downarrow$
U-Net++	51.99 (±12.17)	64.75 (±13.28)	4.64 (±2.01)	65.42 (±6.68)	22.97 (±10.82)	31.05 (±12.76)	12.79 (±4.61)	25.25 (±18.40)	39.37 (±20.75)	8.49 (±3.26)
U-Net+++	55.10 (±10.72)	68.69 (±10.96)	4.49 (±1.67)	62.23 (±9.49)	22.27 (±8.30)	30.19 (±10.51)	12.20 (±3.77)	32.92 (±23.99)	42.37 (±26.30)	7.70 (±1.59)
Dynamic Snake Convolution Net	61.74 (±14.28)	72.21 (±13.31)	3.49 (±1.68)	**83.59** (±4.01)	30.66 (±11.30)	42.74 (±11.68)	7.81 (±2.19)	53.26 (±6.74)	67.90 (±4.77)	3.92 (±0.48)
Convolutional Vision Transformer GAN	61.53 (±11.49)	73.71 (±10.75)	3.51 (±1.36)	76.84 (±5.73)	32.98 (±12.29)	44.85 (±15.85)	8.23 (±3.73)	49.50 (±0.82)	64.63 (±3.05)	4.22 (±0.51)
DeepCA	**64.21** (±10.78)	**76.25** (±9.72)	**3.22** (±1.20)	83.31 (±4.32)	**45.70** (±6.79)	**58.39** (±8.42)	**4.51** (±1.29)	**58.58** (±4.01)	**72.88** (±0.90)	**2.81** (±0.06)

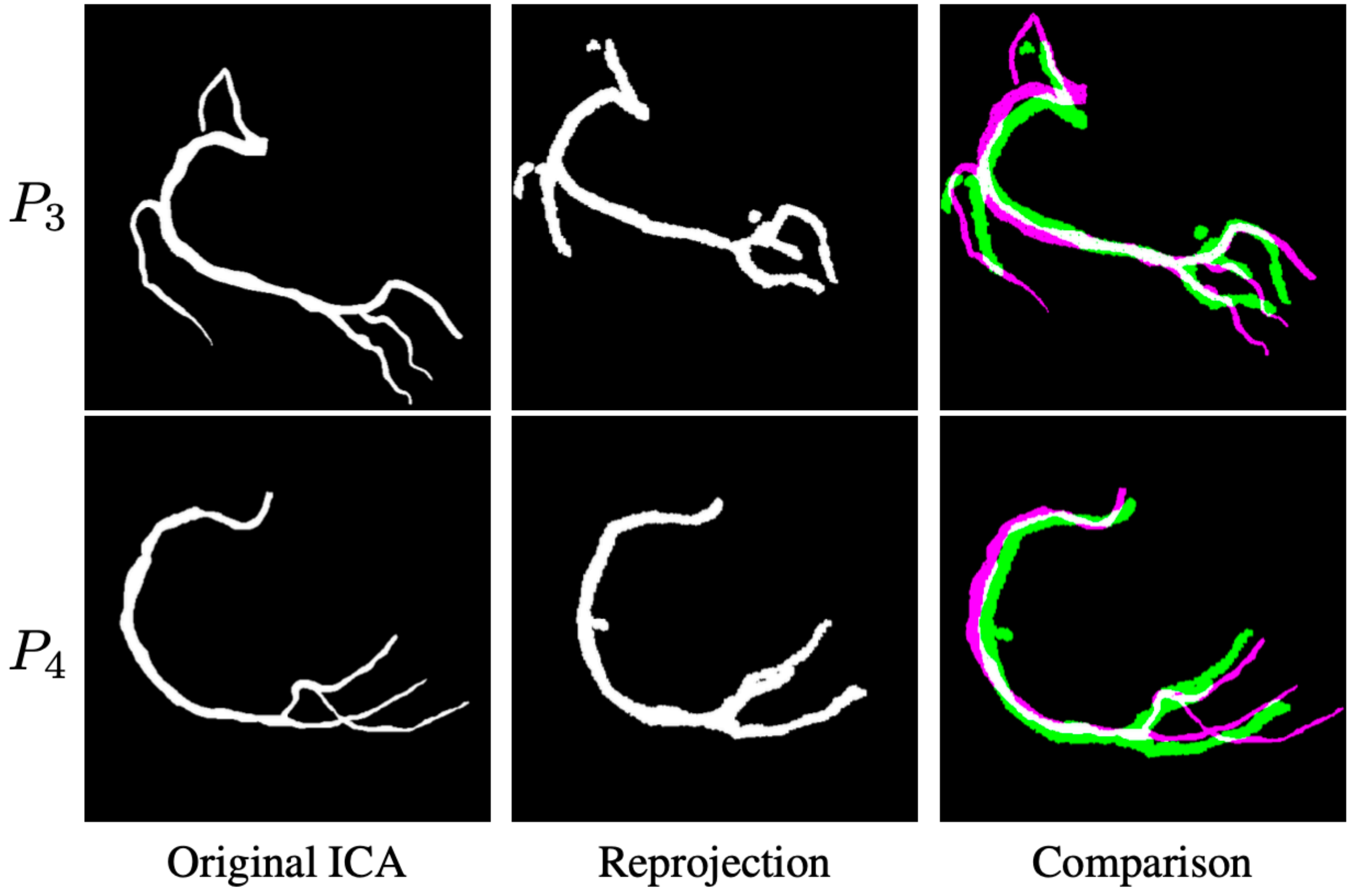
QUALITATIVE RESULTS FOR 1ST & 2ND PROJECTIONS



- From left to right: comparisons of three patients $P_{1,2,3}$ between the real ICA data and our reprojections on the **first** and **second** planes **after rigid registration**, and our DeepCA model's **3D reconstruction**
- Colour **purple** represents ICA data, **green** the reprojection, and **white** the overlap

2D EXTRA PROJECTION EVALUATION

- From left to right: original ICA data, reprojections on **the additional projection plane**, and comparisons between them **after rigid registration** of two patients $P_{3,4}$
- Colour **purple** represents ICA data, **green** the reprojection, and **white** the overlap



CONCLUSION

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- Through simulating projections from CCTA data, we achieve generalisation on non-simultaneous ICA data, **implicitly compensating for non-rigid motion**
- Together with automated coronary vessels segmentation, our model can allow end-to-end automated real-time 3D coronary tree reconstruction during cardiac interventions

THANK YOU

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