FREQUENCY DOMAIN ADVERSARIAL TRAINING FOR ROBUST VOLUMETRIC MEDICAL SEGMENTATION

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Introduction

- Semantic segmentation of organs, anatomical structures, or anomalies in medical images (e.g. CT or MRI scans) remains one of the fundamental tasks in medical image analysis.
- Deep learning and volumetric medical image segmentation
- Adversarial vulnerability of volumetric medical image segmentation
- Adversarial robustness of medical image models
- Understanding the vulnerability and robustness of medical image models

Contributions

- Volumetric Adversarial Frequency Attack (VAFA)
- Volumetric Adversarial Frequency Training (VAFT)

Voxel-domain Attacks vs. Frequency-domain Attacks

- Voxel-domain Attacks: Directly perturb input space
- Frequency-domain Attacks: Preturb the frequency-domain representation of an image e.g. DCT

Method

- **V**olumetric **A**dversarial **F**requency domain **A**ttack (**VAFA**)
- **V**olumetric **A**dversarial **F**requency domain **T**raining (**VAFT**)

Volumetric Adversarial Frequency Domain Attack (VAFA)

Volumetric Adversarial Frequency Domain Attack (VAFA)

$$\mathbf{x} \mapsto \mathcal{D}(\mathbf{x}) \mapsto \underbrace{\varphi(\mathcal{D}(\mathbf{x}), \mathbf{q})}_{\substack{\text{quantization,} \\ \text{rounding and} \\ \text{de-quantization}}} \mapsto \mathcal{D}_I(\varphi(\cdot)) \mapsto \mathbf{x}'$$

Volumetric Adversarial Frequency Domain Attack (VAFA)

$$\varphi(\mathcal{D}(\mathbf{x}), \mathbf{q}) := \left\lfloor \frac{\mathcal{D}(\mathbf{x})}{\mathbf{q}} \right\rfloor \odot \mathbf{q}$$

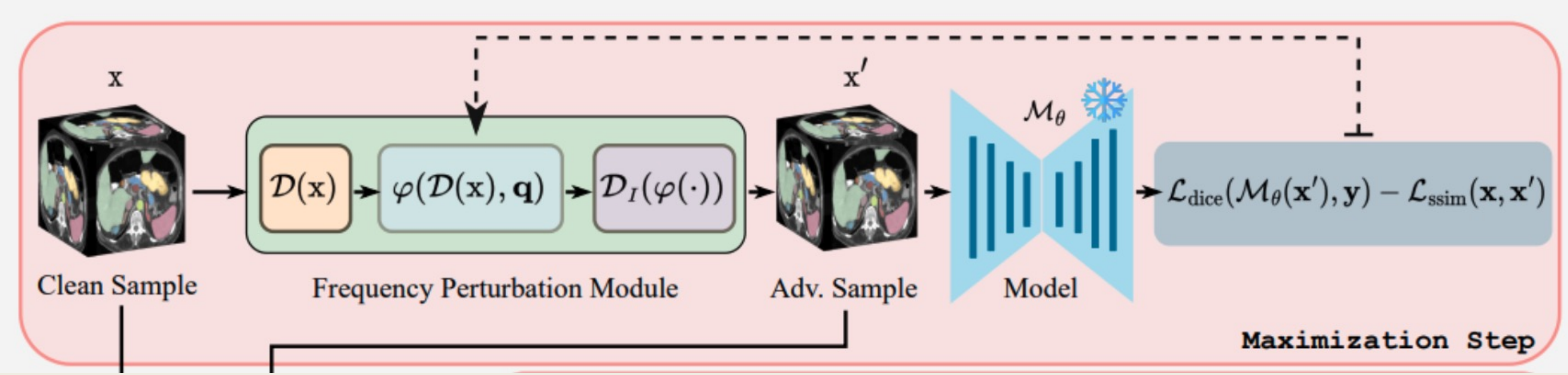
$$\mathbf{q} \in \mathbb{Z}^{h \times w \times d}$$

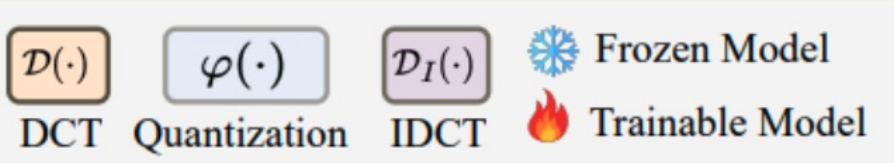
Volumetric Adversarial Frequency Domain Attack (VAFA)

$$\underset{\mathbf{q}}{\text{maximize}} \quad \mathcal{L}_{\text{dice}}(\mathcal{M}_\theta(\mathrm{X}'), \mathrm{Y}) - \mathcal{L}_{\text{ssim}}(\mathrm{X}, \mathrm{X}')$$

$$\text{s.t.} \quad \|\mathbf{q}\|_\infty \leq q_{\max},$$

Volumetric Adversarial Frequency Domain Attack (VAFA)





Volumetric Adversarial Frequency Domain Attack (VAFA)

Algorithm 1 Volumetric Adversarial Frequency Attack (**VAFA**)

Number of Steps: T, Quantization Threshold: $q_{\max}$
Input: $\mathrm{X} \in \mathbb{R}^{H \times W \times D}, \mathrm{Y} \in \{0,1\}^{\mathrm{NumClass} \times H \times W \times D}$ **Output:** $\mathrm{X}' \in \mathbb{R}^{H \times W \times D}$
function VAFA(X,Y)
  $\mathbf{q}_i \leftarrow \mathbf{1} \quad \forall\, i \in \{1, 2, \ldots, n\}$ ▷ Initialize all *quantization tables* with ones.
  for $t \leftarrow 1$ to T **do**
    $\{\mathbf{x}_i\}_{i=1}^{n} \leftarrow \mathrm{Split}(\mathrm{X})$ ▷ Split X into 3D patches of size $(h \times w \times d)$
    $\mathbf{x}'_i \leftarrow \mathcal{D}_I\big(\, \varphi(\mathcal{D}(\mathbf{x}_i), \mathbf{q}_i)\,\big) \quad \forall\, i \in \{1, 2, \ldots, n\}$ ▷ Frequency Perturbation
    $\mathrm{X}' \leftarrow \mathrm{Merge}(\{\mathbf{x}'_i\}_{i=1}^{n})$ ▷ Merge all adversarial patches to form X′
    $\mathcal{L}(\mathrm{X}, \mathrm{X}', \mathrm{Y}) = \mathcal{L}_{\mathrm{dice}}(\mathcal{M}_\theta(\mathrm{X}'), \mathrm{Y}) - \mathcal{L}_{\mathrm{ssim}}(\mathrm{X}, \mathrm{X}')$
    $\mathbf{q}_i \leftarrow \mathbf{q}_i + \mathrm{sign}(\nabla_{\mathbf{q}_i} \mathcal{L}) \quad \forall\, i \in \{1, 2, \ldots, n\}$
    $\mathbf{q}_i \leftarrow \mathrm{clip}(\mathbf{q}_i,\ \mathrm{min}{=}1,\ \mathrm{max}{=}q_{\max}) \quad \forall\, i \in \{1, 2, \ldots, n\}$
  end for
end function
Return X′

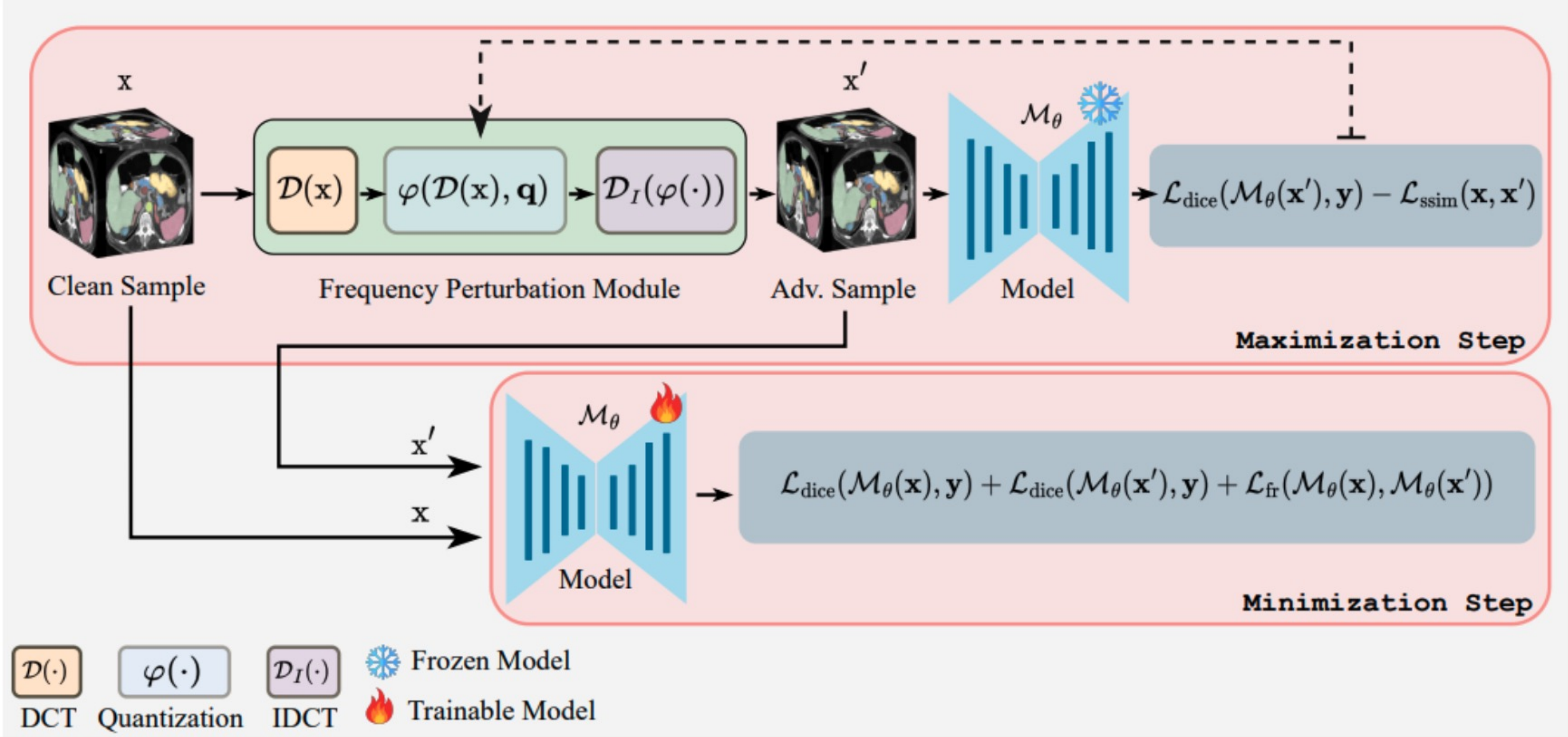
Volumetric Adversarial Frequency Domain Training (VAFT)

Volumetric Adversarial Frequency Domain Training (VAFT)

$$\underset{\theta}{\text{minimize}}\ \mathcal{L}_{\text{dice}}(\mathcal{M}_\theta(\mathrm{X}), \mathrm{Y}) + \mathcal{L}_{\text{dice}}(\mathcal{M}_\theta(\mathrm{X}'), \mathrm{Y}) + \mathcal{L}_{\text{fr}}(\mathcal{M}_\theta(\mathrm{X}), \mathcal{M}_\theta(\mathrm{X}')),$$

$$\mathcal{L}_{\text{fr}}(\mathcal{M}_\theta(\mathrm{X}), \mathcal{M}_\theta(\mathrm{X}')) = \|\mathcal{D}(\mathcal{M}_\theta(\mathrm{X})) - \mathcal{D}(\mathcal{M}_\theta(\mathrm{X}'))\|_1$$

Volumetric Adversarial Frequency Domain Training (VAFT)



Volumetric Adversarial Frequency Domain Training (VAFT)

Algorithm 2 Volumetric Adversarial Frequency Training (**VAFT**)

Train Dataset: $\mathcal{X} = \{(\mathrm{X}_i, \mathrm{Y}_i)\}_{i=1}^{N}, \ \ \mathrm{X}_i \in \mathbb{R}^{H \times W \times D}, \ \ \mathrm{Y}_i \in \{0,1\}^{\mathrm{NumClass} \times H \times W \times D}$

NumSamples$=N$, BatchSize$=B$, Target Model: $\mathcal{M}_\theta$, AT Robust Model: $\mathcal{M}_{\text{🛡}}$

for $i \leftarrow 1$ to NumEpochs **do**

    for $j \leftarrow 1$ to $\lfloor N/B \rfloor$ **do**

        Sample a mini-batch $\mathcal{B} \subseteq \mathcal{X}$ of size B

        $\mathrm{X}' \leftarrow \mathbf{VAFA}(\mathrm{X}, \mathrm{Y}) \ \ \forall (\mathrm{X}, \mathrm{Y}) \in \mathcal{B}$ ▷ Adv. Freq. Attack on clean images.

        $\mathcal{L} = \mathcal{L}_{\mathrm{dice}}(\mathcal{M}_\theta(\mathrm{X}), \mathrm{Y}) + \mathcal{L}_{\mathrm{dice}}(\mathcal{M}_\theta(\mathrm{X}'), \mathrm{Y}) + \mathcal{L}_{\mathrm{fr}}(\mathcal{M}_\theta(\mathrm{X}), \mathcal{M}_\theta(\mathrm{X}'))$

        Backward pass and update $\mathcal{M}_\theta$

    end for

end for

$\mathcal{M}_{\text{🛡}} \leftarrow \mathcal{M}_\theta$ ▷ AT robust model after training completion.

Return $\mathcal{M}_{\text{🛡}}$

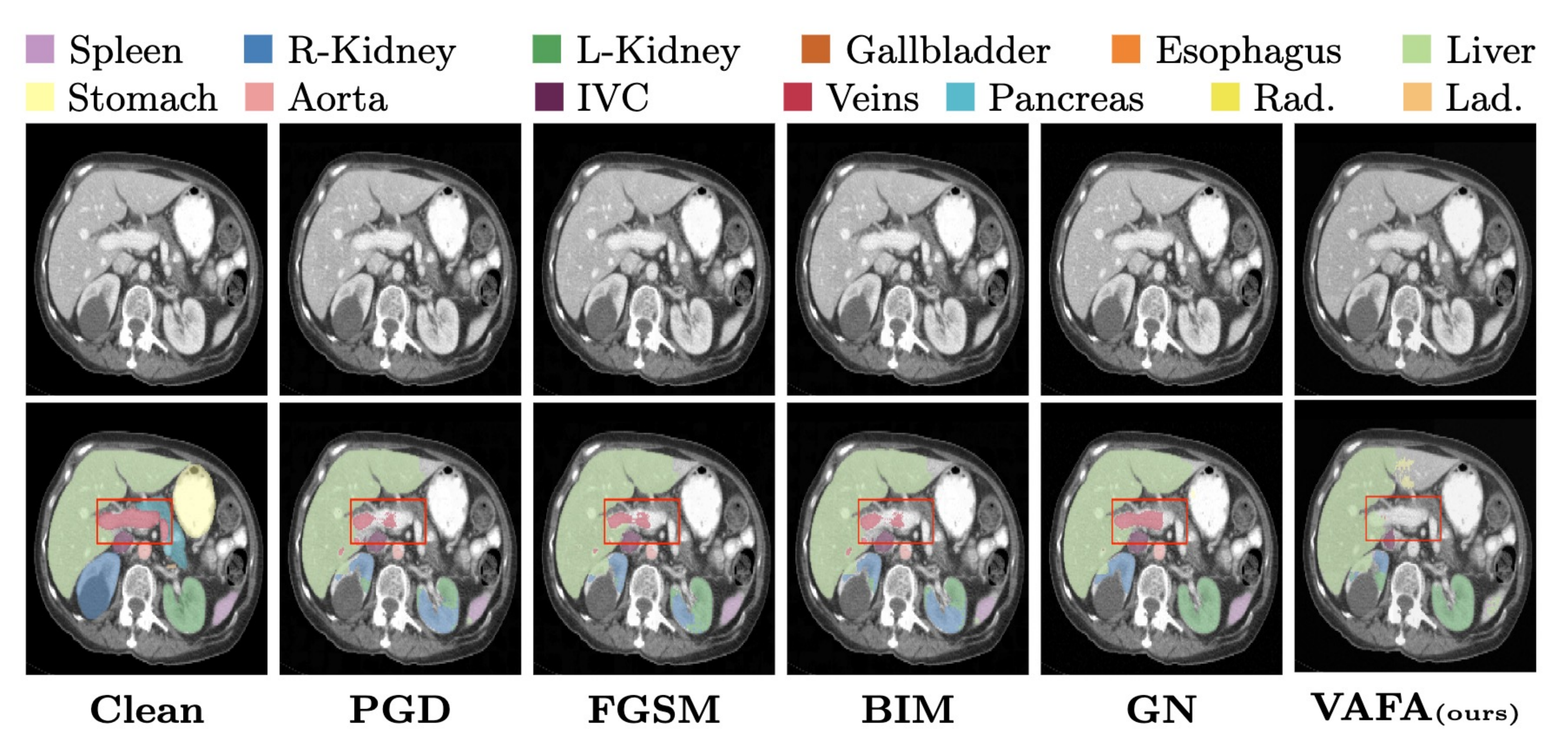
Results

- **Segmentation Models:** UNETR and UNETR++
- **Datasets:** Synapse and ACDC
- **Baseline Attacks:** PGD, FGSM, BIM, GN
- **Evaluation Metrics:** Dice Score, HD95 Distance, LPIPS
- **Programming Framework:** Pytorch

Volumetric Adversarial Frequency Domain Attack (VAFA)

Models → Attacks ↓	UNETR			UNETR++		
	DSC↓	HD95↑	LPIPS↑	DSC↓	HD95↑	LPIPS↑
Clean Images	74.3	14.0	-	84.7	12.7	-
PGD ($\epsilon = 4/8$)	62.7/50.8	40.4/64.5	**98.9**/95.3	77.5/67.1	48.1/78.3	95.7/85.1
FGSM ($\epsilon = 4/8$)	62.8/53.9	34.8/48.7	98.8/94.7	73.1/67.1	37.3/43.2	94.7/82.2
BIM ($\epsilon = 4/8$)	62.8/50.7	39.9/**65.8**	98.8/95.3	77.3/66.8	46.6/78.1	**95.8**/85.3
GN ($\sigma = 4/8$)	74.2/73.9	17.0/15.4	97.7/91.1	84.7/84.3	12.3/13.4	93.3/78.2
VAFA ($q_{\max} = 20/30$)	**32.2**/**29.8**	**57.6**/59.9	97.5/**96.9**	**45.3**/**39.3**	**73.9**/**85.2**	94.2/**94.7**

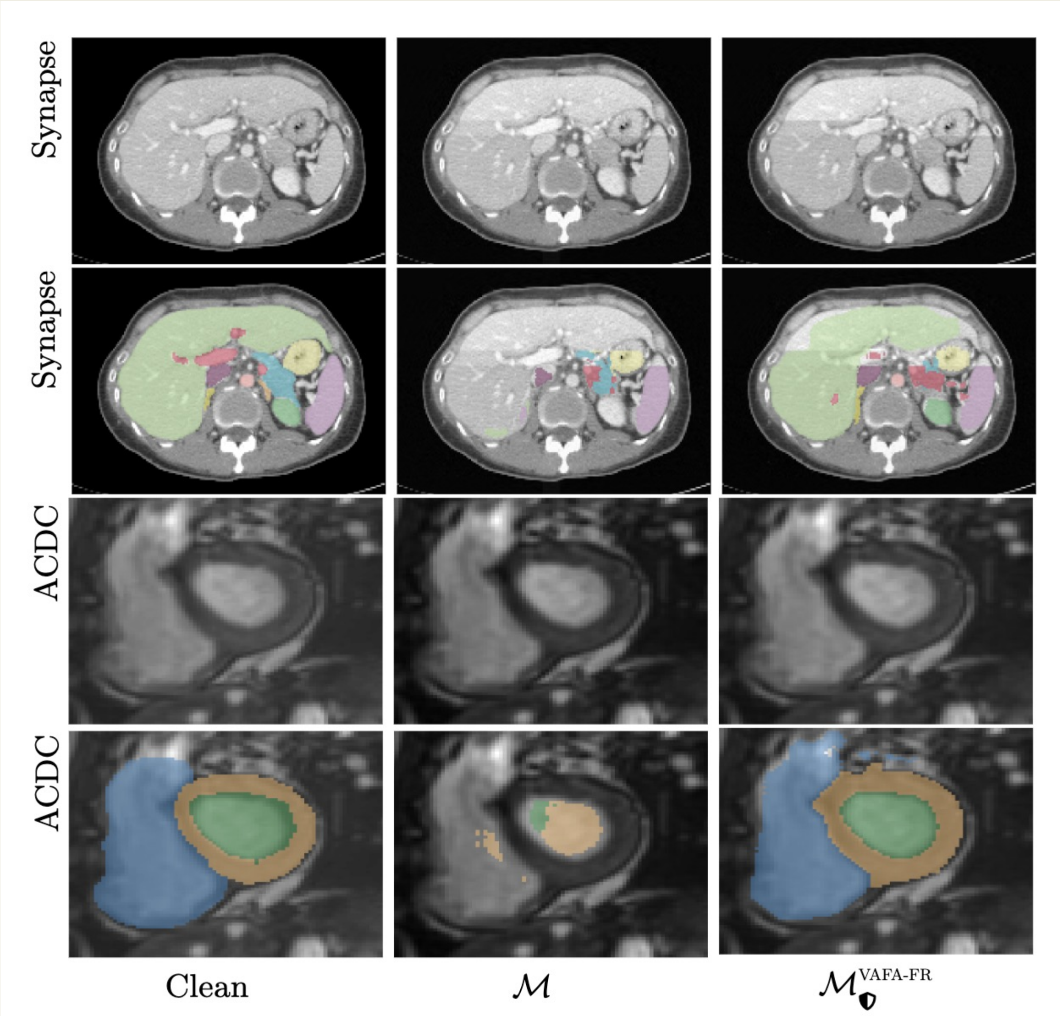
Volumetric Adversarial Frequency Domain Attack (VAFA)



Volumetric Adversarial Frequency Domain Training (VAFT)

	Attacks → Models ↓	UNETR					UNETR++				
		Clean	PGD	FGSM	BIM	VAFA	Clean	PGD	FGSM	BIM	VAFA
Synapse	$\mathcal{M}^{\text{PGD}}$	73.47	65.53	65.68	65.51	42.47	75.43	67.81	67.82	67.80	38.22
	$\mathcal{M}^{\text{FGSM}}$	72.44	64.80	66.31	64.76	39.02	81.06	73.84	74.76	73.77	37.48
	$\mathcal{M}^{\text{BIM}}$	75.12	67.78	68.32	67.78	45.97	74.80	67.58	67.46	67.57	35.72
	$\mathcal{M}^{\text{GN}}$	73.17	61.40	61.77	61.29	30.00	80.05	76.23	70.96	74.51	41.44
	$\mathcal{M}^{\text{VAFA}}$	74.67	64.83	65.49	64.73	66.31	81.88	69.09	65.40	68.90	76.47
	$\mathcal{M}^{\text{VAFA-FR}}$	**75.66**	65.90	66.79	65.83	66.33	**82.65**	70.61	67.00	70.41	78.19
ACDC	$\mathcal{M}^{\text{VAFA}}$	81.95	60.77	68.16	60.75	69.76	89.00	76.28	80.41	76.56	88.45
	$\mathcal{M}^{\text{VAFA-FR}}$	**83.44**	60.63	69.33	60.61	73.05	**91.36**	85.42	87.42	83.90	91.23

Volumetric Adversarial Frequency Domain Training (VAFT)



Github Repository

https://github.com/asif-hanif/vafa

Thank you !

VAFA – Ablation Study

- Impact of quantization threshold
- Impact of steps
- Impact of patch size

VAFA – Ablation Study
Impact of Quantization Threshold: $q_{\max}$

$q_{\max}$	DSC↓	HD95↑	LPIPS↑
-	74.31	14.03	-
10	65.95	26.25	**99.10**
20	56.24	35.92	98.70
30	50.96	44.09	98.33
40	49.58	43.66	97.90
60	48.83	44.55	96.60
80	**48.76**	**45.30**	94.50

VAFA – Ablation Study
Impact of Steps

Steps	DSC↓	HD95↑	LPIPS↑
-	74.31	14.03	-
10	61.33	33.20	**98.85**
20	56.24	35.92	98.70
30	54.37	38.00	98.64
40	53.31	37.76	98.59
50	52.97	**39.23**	98.54
60	**52.25**	39.19	98.52

VAFA – Ablation Study
Impact of Patch-Size

Patch Size	DSC↓	HD95↑	LPIPS↑
-	74.31	14.03	-
$(4 \times 4 \times 4)$	63.48	32.63	**98.90**
$(8 \times 8 \times 8)$	56.24	35.92	98.70
$(16 \times 16 \times 16)$	41.30	45.98	98.14
$(32 \times 32 \times 32)$	32.40	56.64	97.49
$(48 \times 48 \times 48)$	28.19	**66.08**	97.16
$(96 \times 96 \times 96)$	**28.08**	59.09	96.47