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Spherical Procrustes Alignment for Reliable Medical Audio Diagnosis

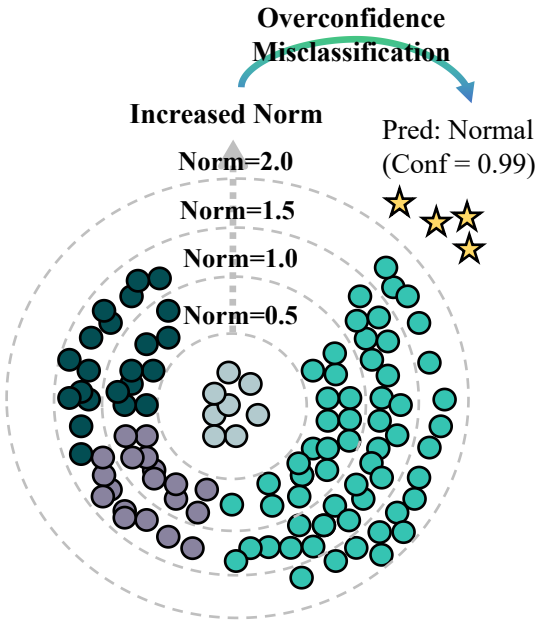
Ying Wang[1], Guoheng Huang[2], Chan-Tong Lam[1], Xiaochen Yuan[1]

[1]Macao Polytechnic University, xcyuan@mpu.edu.mo

Code: github.com/wangying1586/SPA

Motivation – The Overconfidence Problem

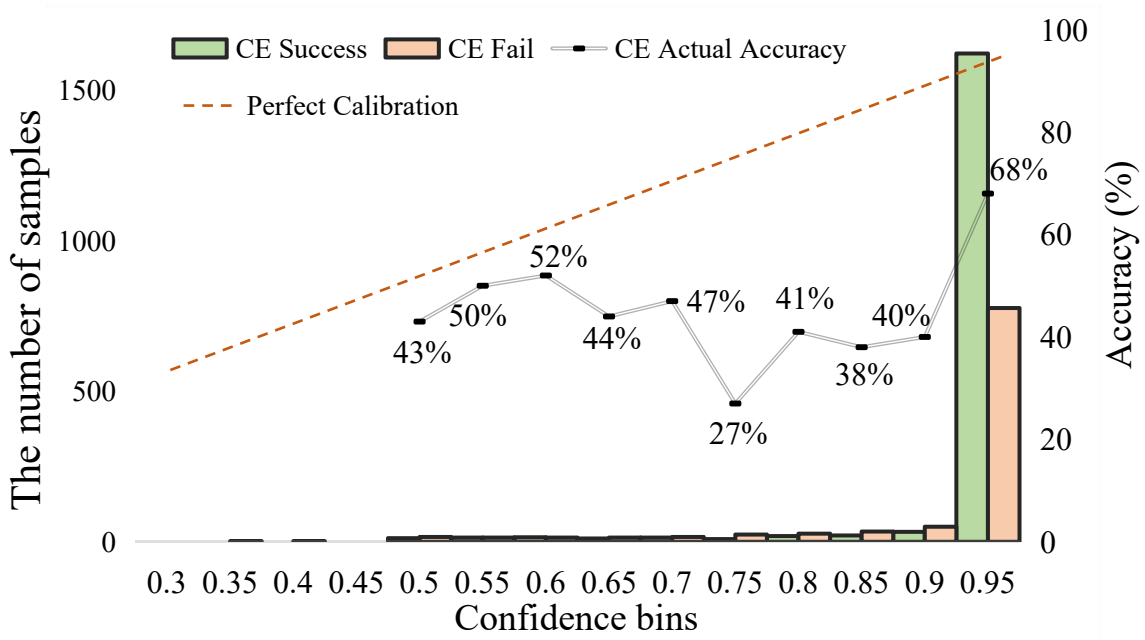
norm-biased radial space
→ high-norm noise triggers 0.99 confidence



(a) **CE**

Reliability diagram (CE baseline)
→ far from diagonal (Perfect Calibration)

CE's true accuracy is around 60%, but most of the confidence distribution is at 0.95.

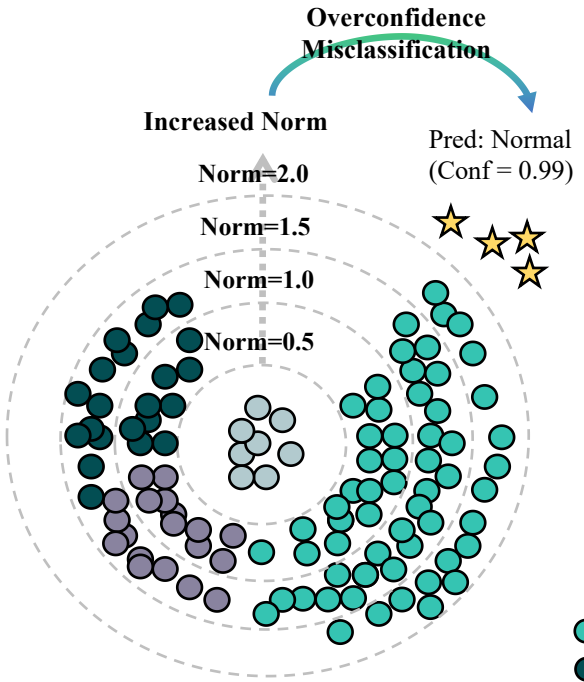


(c) **CE vs. SPA**

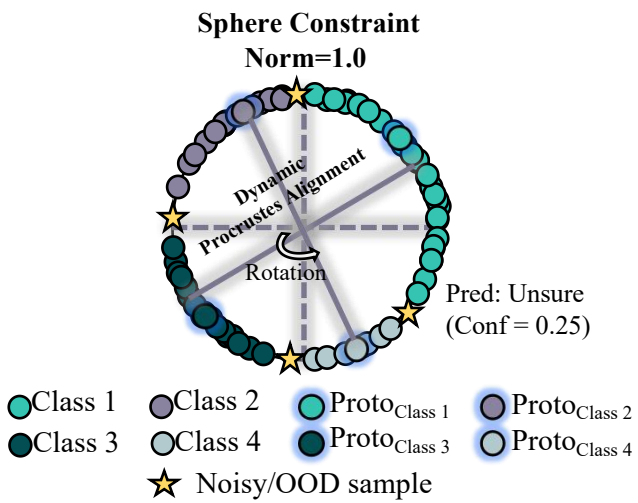
Clinical diagnosis needs both accuracy and well-calibrated confidence.

Root Cause & Our Insight

Root cause: Norm bias – logit magnitude dominates, not semantic alignment
Why existing methods fail: Loss-level or post-hoc; ignore geometric pathology

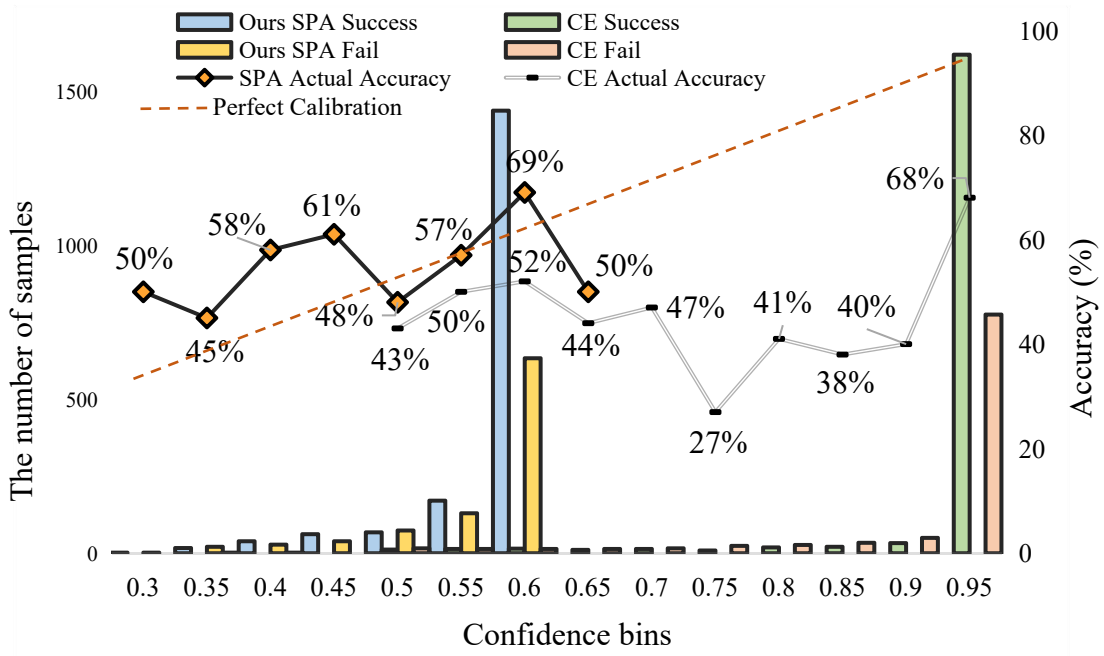


(a) **CE**



(b) **SPA**

Ours SPA is closer to the diagonal (Perfect Calibration).



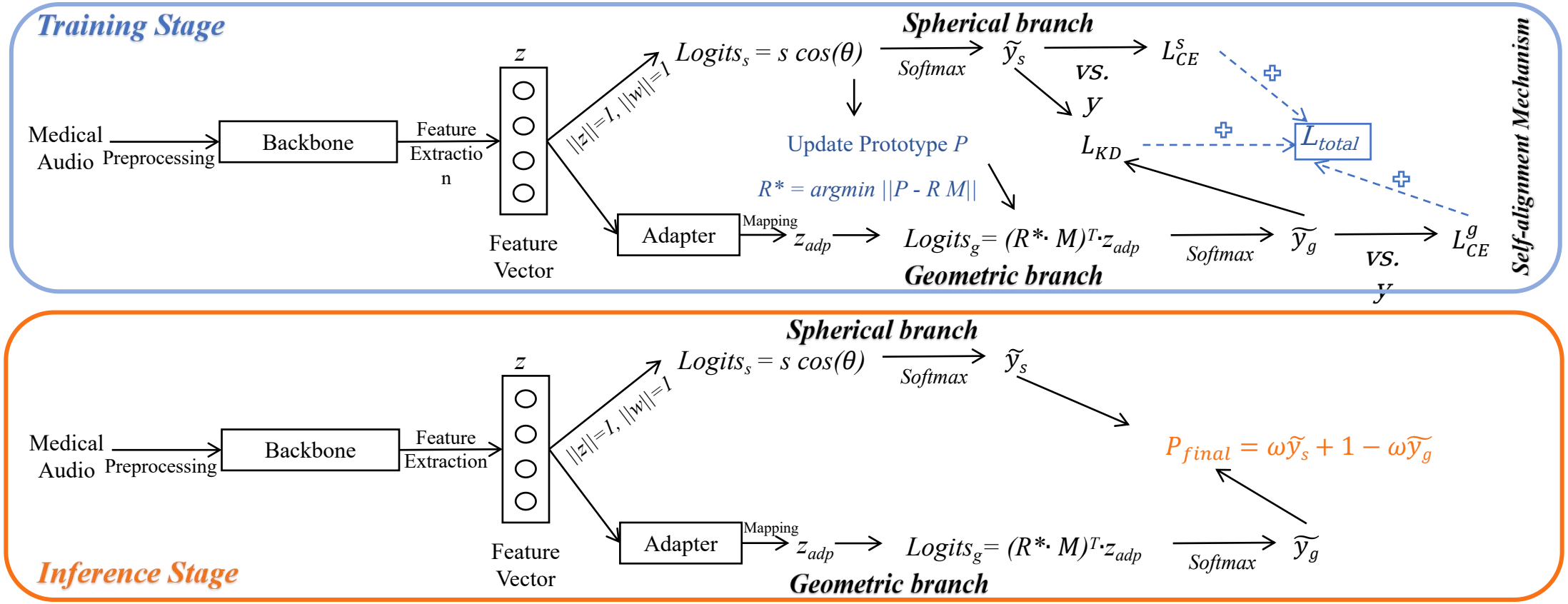
(c) **CE vs. SPA**

Our insight - Enforce spherical constraint plus dynamic geometric alignment with ETF

Spherical Procrustes Alignment Overview

Training stage:

- **Spherical branch:** unit hypersphere, eliminate norm bias
- **Geometric branch:** fixed ETF plus dynamic Procrustes alignment
- **Self-alignment Mechanism:** fuse via KL divergence



Inference stage: weighted fusion

Spherical Procrustes Alignment – Dual branch architecture

Spherical Branch – Decouple Norm

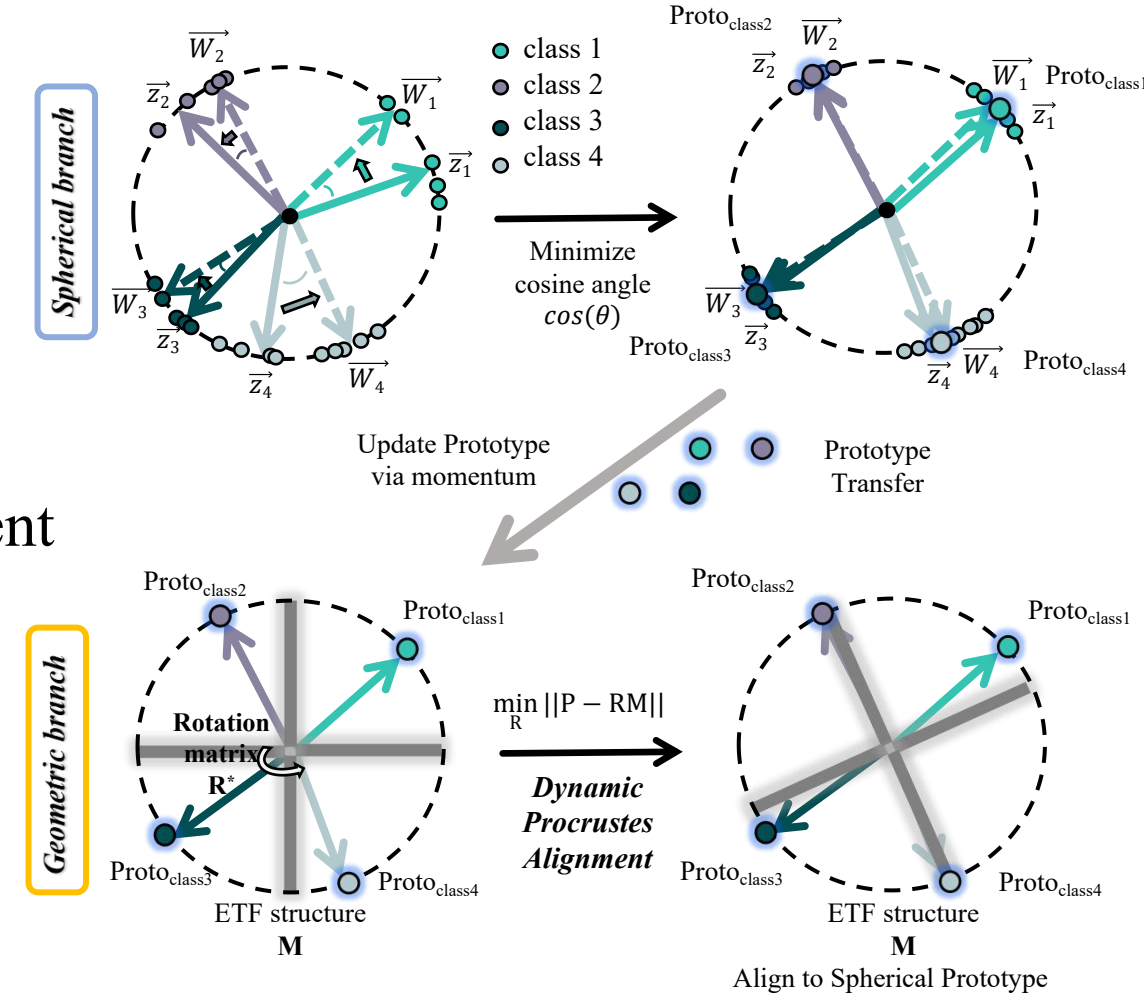
- Normalize features $\tilde{z}$ and weights $\widetilde{W}$
- Logit = $s \cdot \cos\theta \rightarrow$ confidence purely angular

Momentum prototype update for stability

Geometric Branch – Dynamic Procrustes Alignment

- Fixed Simplex ETF M (maximally separated)
- Solve Orthogonal Procrustes:
- $min_R \parallel P - RM \parallel_F \rightarrow R^* = UV^\top$ via SVD

Avoid gradient jitter
→ stable geometry even on small/noisy data



Spherical Procrustes Alignment – Training & Inference

Joint loss: $\mathcal{L}_{total} = \gamma\left(\mathcal{L}_{CE}^{s} + \mathcal{L}_{CE}^{g}\right) + \lambda\mathcal{L}_{KD}$

Inference: $P_{final} = \omega \cdot \sigma(logits_s) + (1 - \omega) \cdot \sigma\left(logits_g\right)$

No extra inference cost

Main Results – ICBHI & CirCor & Calibration Methods

ICBHI (BEATs): AS ↑ 65.27%, ECE ↓ from 23.36% to **6.05%**

Backbone	Method	Classification Performance			Reliability
		Se (%) ↑	Sp (%) ↑	AS (%) ↑	ECE (%) ↓
CNN6	+ CE Loss (Kong et al., 2020b)	$35.56_{\pm 4.99}$	$81.75_{\pm 4.33}$	$58.66_{\pm 0.54}$	$23.53_{\pm 5.01}$
	+ Focal Loss (Lin et al., 2017)	$35.11_{\pm 5.36}$	$79.18_{\pm 5.01}$	$57.14_{\pm 0.58}$	$17.51_{\pm 2.24}$
	+ LDAM-DRW (Cao et al., 2019)	$33.37_{\pm 3.96}$	$80.49_{\pm 4.13}$	$56.93_{\pm 0.85}$	$17.47_{\pm 3.85}$
	+ SPA (Ours)	$35.24_{\pm 2.92}$	$82.96_{\pm 4.82}$	**59.10**$_{\pm 1.24}$	**7.51**$_{\pm 0.72}$
AST	+ CE Loss (Gong et al., 2021)	$42.58_{\pm 2.71}$	$79.52_{\pm 2.07}$	$61.05_{\pm 0.54}$	$21.59_{\pm 6.99}$
	FBS (Fraihi et al., 2025)	$43.22_{\pm 2.44}$	$84.19_{\pm 3.08}$	$64.28_{\pm 1.09}$	$19.82_{\pm 5.13}$
	FBS + SPA (Ours)	$44.81_{\pm 2.65}$	$84.92_{\pm 3.19}$	**65.01**$_{\pm 2.77}$	**5.49**$_{\pm 1.13}$
BEATs	+ CE Loss (Chen et al., 2023)	$50.60_{\pm 1.79}$	$77.20_{\pm 3.22}$	$63.90_{\pm 1.15}$	$28.51_{\pm 4.91}$
	+ SPA (Ours)	$49.77_{\pm 2.17}$	$79.06_{\pm 2.81}$	**64.42**$_{\pm 0.78}$	**4.44**$_{\pm 1.02}$
	PAFA (Jeong & Kim, 2025)	$48.72_{\pm 3.75}$	$80.19_{\pm 4.07}$	$64.45_{\pm 0.52}$	$23.36_{\pm 7.83}$
	PAFA + SPA (Ours)	$49.34_{\pm 4.12}$	$81.21_{\pm 4.48}$	**65.27**$_{\pm 0.57}$	**6.05**$_{\pm 3.63}$

CirCor (M2D): Wacc ↑ 84.23%, ECE ↓ to **4.63%**

Backbone	Method	Classification		Reliability
		W_{acc} (%) ↑	UAR (%) ↑	ECE (%) ↓
Previous Studies				
Wav2vec	Panah et al. (Panah et al., 2023)	80.0	70.0	-
HSMM	CUED Acoustics (McDonald et al., 2022)	80.0	68.0	-
Pre-trained extractors				
CNN14	+ CE Loss (Kong et al., 2020a)	$57.47_{\pm 3.25}$	$53.63_{\pm 2.89}$	$11.24_{\pm 2.14}$
	+ SPA (Ours)	**58.32**$_{\pm 2.47}$	**54.47**$_{\pm 2.18}$	**6.08**$_{\pm 1.24}$
BYOL-A	+ CE Loss (Niizumi et al., 2021)	$54.34_{\pm 3.71}$	$54.81_{\pm 2.67}$	$12.13_{\pm 2.53}$
	+ SPA (Ours)	**55.73**$_{\pm 2.85}$	**55.52**$_{\pm 2.36}$	**6.42**$_{\pm 1.47}$
AST	+ CE Loss (Gong et al., 2021)	$64.12_{\pm 2.38}$	$66.38_{\pm 2.95}$	$10.35_{\pm 1.87}$
	+ SPA (Ours)	**65.24**$_{\pm 1.96}$	**66.91**$_{\pm 2.07}$	**5.58**$_{\pm 1.12}$
M2D	+ CE Loss (Niizumi et al., 2024)	$83.51_{\pm 1.92}$	$72.14_{\pm 2.14}$	$9.17_{\pm 1.65}$
	+ SPA (Ours)	**84.23**$_{\pm 1.53}$	**72.96**$_{\pm 1.78}$	**4.63**$_{\pm 0.89}$

Method	AS (%) ↑	ECE (%) ↓	Inf. Time (ms)
CE Loss	$63.90_{\pm 1.15}$	$28.51_{\pm 4.91}$	4.1
Label Smoothing	$62.58_{\pm 0.59}$	$33.91_{\pm 4.41}$	4.1
Mixup	$62.16_{\pm 0.66}$	$8.67_{\pm 6.29}$	4.1
Post-hoc & Sampling Methods			
Temperature Scaling	$63.90_{\pm 1.15}$	$21.99_{\pm 6.97}$	4.1
MC Dropout (5 passes)	$63.82_{\pm 0.89}$	$25.90_{\pm 4.18}$	19.1
Deep Ensembles (5 models)	$64.40_{\pm 0.93}$	$22.29_{\pm 4.89}$	20.5
SPA (Ours)	**64.42**$_{\pm 0.78}$	**4.44**$_{\pm 1.02}$	**4.2**

Outperforms Label Smoothing, Mixup, Temperature Scaling, MC Dropout, and Deep Ensembles

without consuming extra inference

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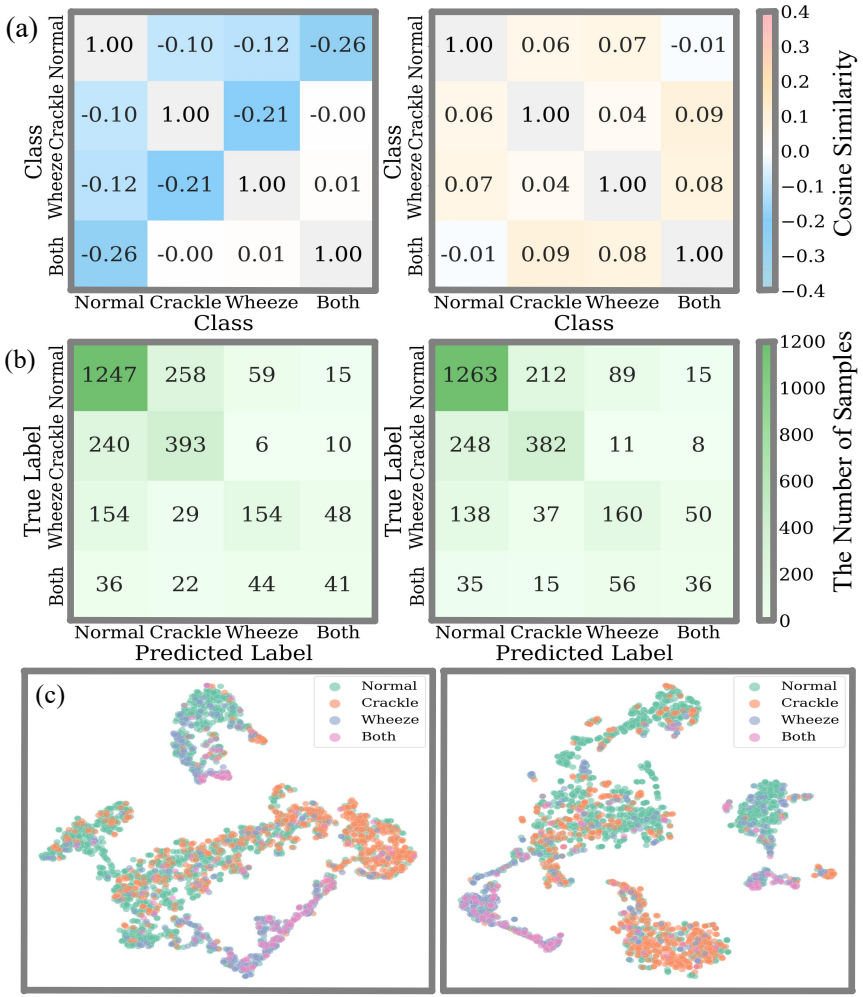
Visualization

Comparison on ICBHI



(a) Cosine similarity heatmap

SPA *enforces near-zero inter-class correlation*

(b) Confusion matrix

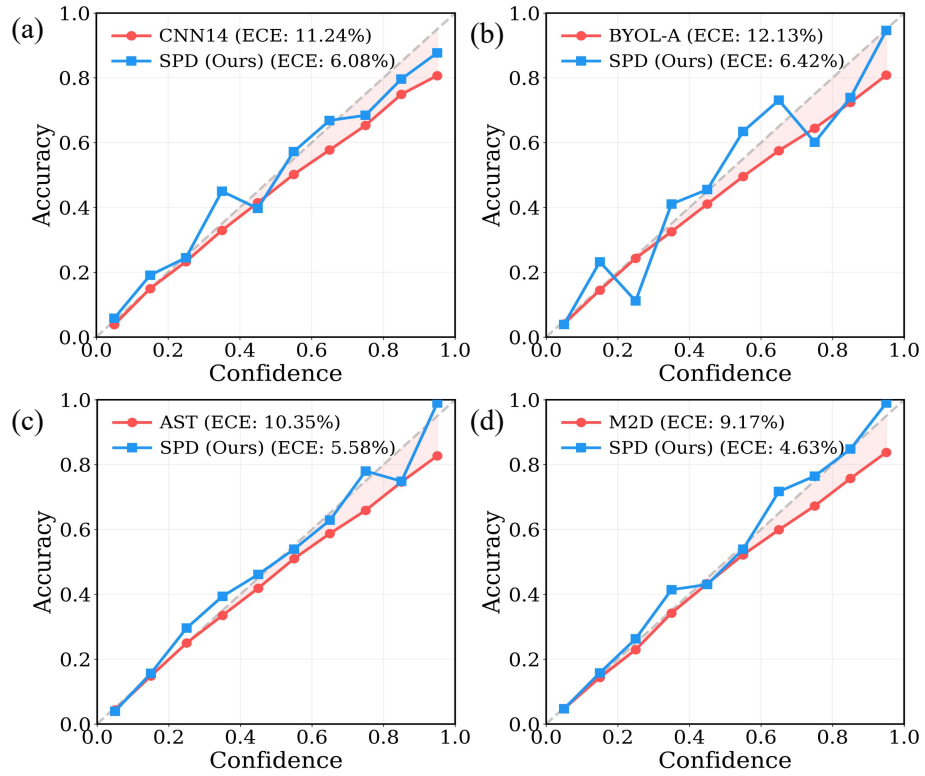
SPA *improves minority recall without hurting majority*

(c) t-SNE projection

SPA *yields compact, angularly separated clusters*

Reliability diagram on CirCor

SPA (blue) aligns near diagonal vs. baseline (red)



Conclusion

Norm bias is the geometric root of overconfidence in medical audio

SPA: spherical constraints plus dynamic Procrustes alignment

SOTA accuracy and calibration, no extra inference cost

Future Work

Robust prototype estimation, OOD detection

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