

Supplementary information

Supplementary Table 1. Imaging protocols and interpretation criteria for multimodal plaque assessment

Modality	Imaging protocol / system	Assessed features	Interpretation criteria / role in consensus
B-mode ultrasound	Canon Aplio 500 with 14L5 probe; Canon Aplio i900 with 11L3 probe; GE LOGIQ E9 with 9L-D probe; Philips EPIQ 5 / EPIQ 7 / EPIQ 7c / EPIQ CVx with L12-3 probe; Siemens ACUSON S3000 with 9L4 probe; Esaote MyLab Twice with LA332E probe; Mindray Resona R8 Pro with L15-3WU probe. Standardized carotid scanning protocol across centers.	Plaque presence, morphology, luminal surface appearance, echogenicity, calcification pattern, and stenosis category.	Plaque was defined as focal wall thickening ≥ 1.5 mm, or ≥ 0.5 mm / $\geq 50\%$ greater than adjacent intima-media thickness. Stenosis was categorized using duplex velocity criteria corresponding to NASCET-equivalent categories. B-mode ultrasound was not used to assign IPH, LRNC, or fibrous-cap status.
CEUS	Canon Aplio i900 with 11L3 probe; GE LOGIQ E9 with 9L-D probe; Philips EPIQ 7c with L12-3 probe. Contrast-specific ultrasound imaging using SonoVue 2.4 mL intravenous bolus injection.	Intraplaque neovascularization.	CEUS positivity was defined as visible intraplaque contrast enhancement.
CTA	Carotid CTA was performed using multidetector CT scanners, including Siemens SOMATOM Force dual-source CT, Siemens SOMATOM Definition Flash 64-row/128-slice CT, and GE Optima CT620 systems. Intravenous iodinated contrast, including iodixanol, was administered according to standardized institutional CTA protocols. Axial source images and multiplanar reconstructions were reviewed.	Luminal stenosis, calcification, plaque morphology, surface ulceration or luminal surface defect	Surface ulceration or luminal defect was defined as a focal luminal surface defect or contrast-filled outpouching on reconstructed CTA images. CTA was not used to assign IPH or fibrous-cap status.
MRA-only	MRA was performed on 3.0-T Siemens or Philips MRI systems using 8-channel carotid coils or 20-channel head-neck phased-array coils. MRA-only examinations included TOF-MRA and/or contrast-enhanced MRA. A typical TOF-MRA protocol was performed without ECG gating, with TR/TE of approximately 20/3.6-5.5 ms, field of view of approximately 160×160 to 220×198 mm, and slice thickness of 0.8-1.2 mm. When contrast-enhanced MRA was performed, gadolinium-based contrast was administered according to institutional protocols.	Luminal stenosis and surface-contour assessment.	MRA-only examinations were used for luminal or surface-contour assessment only and were not used to assign plaque-composition features, including IPH, LRNC, or fibrous-cap status.
HR-VWI	HR-VWI was performed on 3.0-T Siemens or Philips MRI systems using 8-channel carotid coils or 20-channel head-neck phased-array coils. Protocols included fat-suppressed T1-weighted 3D vessel-wall imaging, including SPACE or equivalent vendor-specific sequences, and additional T1-weighted and T2-weighted vessel-wall sequences according to institutional protocols and image availability.	IPH, LRNC, and fibrous-cap rupture or thinning.	Plaque-composition features were assigned according to predefined sequence-specific HR-VWI criteria. Features were recorded as non-assessable when required sequences or image quality were insufficient.

Abbreviations: CEUS, contrast-enhanced ultrasound; CTA, computed tomography angiography; HR-VWI, high-resolution magnetic resonance vessel-wall imaging; IPH, intraplaque hemorrhage; LRNC, lipid-rich necrotic core; MRA, magnetic resonance angiography; MRI, magnetic resonance imaging; NASCET, North American Symptomatic Carotid Endarterectomy Trial; TOF, time-of-flight.

Note: For B-mode ultrasound and CEUS, depth, focal zone, gain, dynamic range, and time-gain compensation were adjusted by experienced operators according to patient anatomy and plaque location under the standardized acquisition protocol. B-mode ultrasound and CEUS were interpreted by senior ultrasound physicians, whereas CTA and MR-based carotid imaging were interpreted by vascular radiologists. Discordant, incomplete, or indeterminate findings were resolved by consensus or multidisciplinary panel adjudication. Not all participants underwent all advanced imaging modalities; vulnerability labels were assigned using the available modality or modalities according to the prespecified consensus process. MR-based carotid imaging included MRA-only examinations and HR-VWI; MRA-only examinations were used only for luminal or surface-contour assessment and were not used to assign plaque-composition vulnerability features.

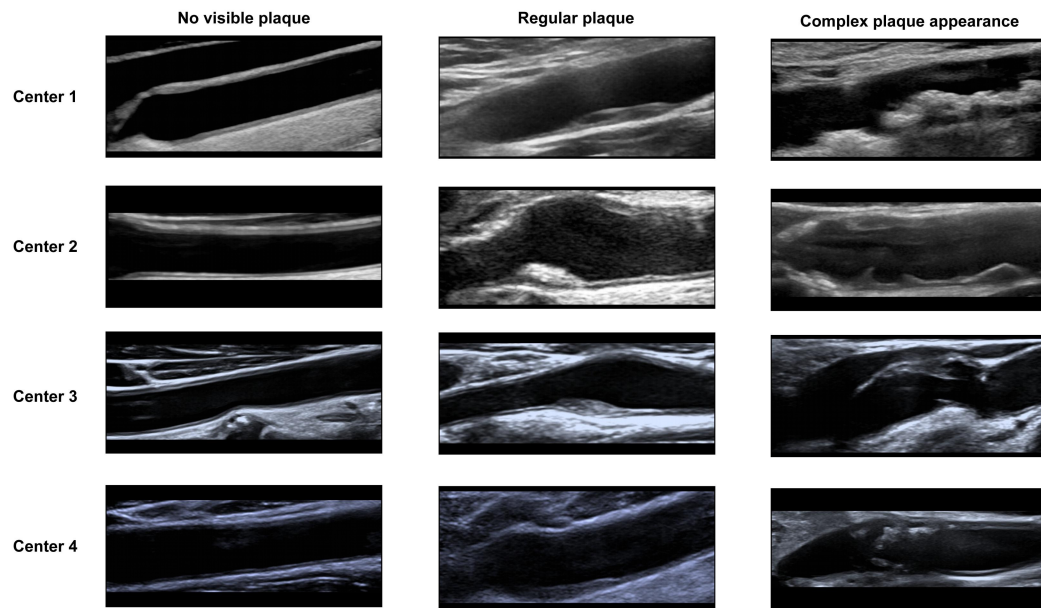
Supplementary Table 2. Number of vulnerable plaque images confirmed by B-mode ultrasound and advanced imaging modalities across centers

	Center 1	Centers 2-4
	(image)	(image)
Vulnerable plaques confirmed jointly by B-mode and advanced imaging	1466	1001
B-mode and CEUS	360	282
B-mode and CTA	825	529
B-mode and MR-based carotid imaging	281	190
Vulnerable plaques confirmed by B-mode and advanced imaging via expert panel arbitration	358	416
B-mode and CEUS	118	176
B-mode and CTA	186	199
B-mode and MR-based carotid imaging	54	41
Total vulnerable plaques	1824	1417

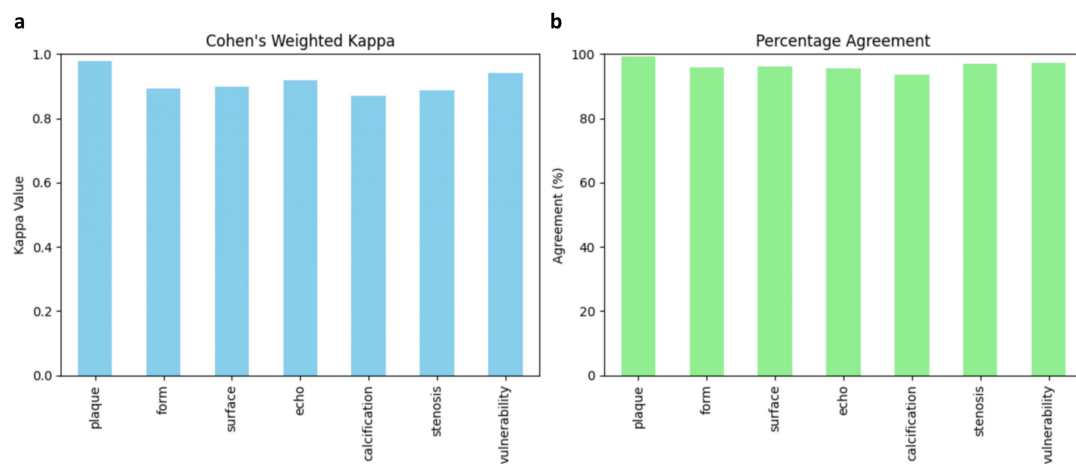
Supplementary Table 3. Sensitivity analyses stratified by supporting imaging evidence and agreement status

Dataset	Positive subgroup	Positive n	AUC (95% CI)
Internal test	Overall consensus	644	0.901 (0.887-0.916)
	CEUS-supported	178	0.894 (0.868-0.917)
	CTA-supported	334	0.915 (0.900-0.930)
	MR-supported	132	0.877 (0.845-0.904)
	Concordant B-mode/advanced imaging	497	0.919 (0.905-0.933)
	Expert panel-arbitrated	147	0.842 (0.813-0.872)
External test	Overall consensus	1417	0.883 (0.871-0.893)
	CEUS-supported	458	0.882 (0.864-0.899)
	CTA-supported	728	0.879 (0.864-0.894)
	MR-supported	231	0.897 (0.875-0.916)
	Concordant B-mode/advanced imaging	1001	0.908 (0.896-0.919)
	Expert panel-arbitrated	416	0.821 (0.798-0.841)
Pooled held-out test	Overall consensus	2061	0.885 (0.876-0.894)
	CEUS-supported	636	0.882 (0.867-0.896)
	CTA-supported	1062	0.887 (0.876-0.898)
	MR-supported	363	0.881 (0.862-0.898)
	Concordant B-mode/advanced imaging	1498	0.908 (0.898-0.917)
	Expert panel-arbitrated	563	0.823 (0.805-0.841)

Note: AUCs were calculated among plaque-positive images in the held-out test cohorts. For each positive subgroup, the negative group was all consensus non-vulnerable plaque-positive images from the same dataset. CEUS-, CTA-, and MR-supported subgroups indicate consensus vulnerable plaques for which the corresponding advanced imaging modality contributed positive support to the final multimodal label. Concordant B-mode/advanced imaging and expert panel-arbitrated subgroups were defined according to whether B-mode ultrasound and advanced imaging findings were concordant or required expert consensus adjudication.

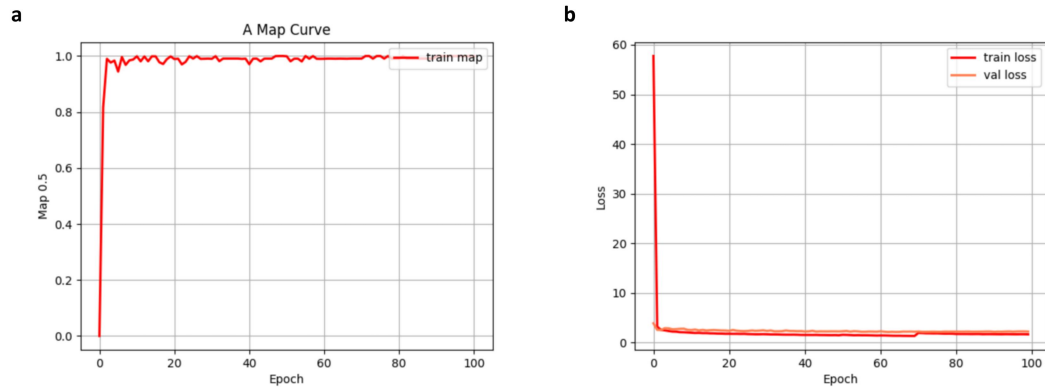


Supplementary Figure 1. Representative multicenter carotid B-mode ultrasound images.
De-identified long-axis B-mode images from Centers 1-4 show representative plaque-negative, regular plaque, and complex plaque appearances. Arrows or dashed boxes indicate plaque regions where present.



Supplementary Figure 2. Inter-Observer Agreement Metrics for Vulnerable Plaque Annotations

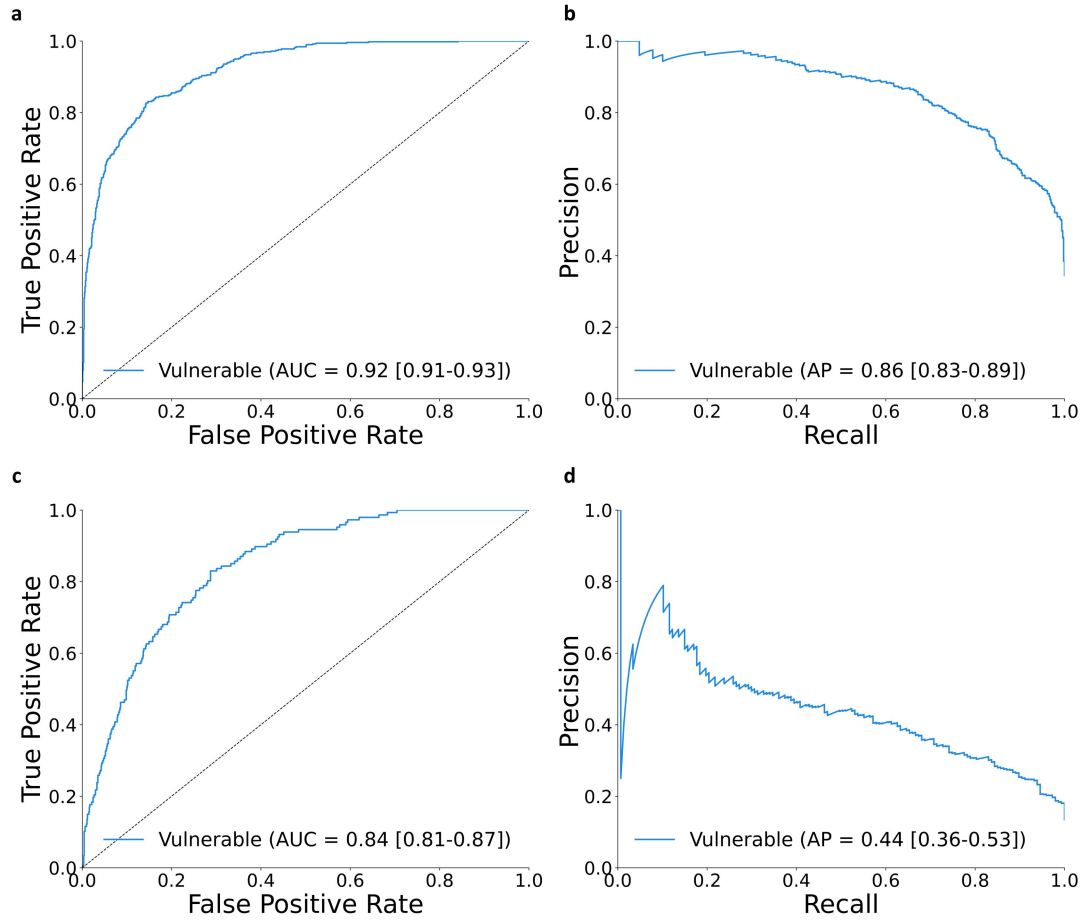
- (a) Cohen's weighted kappa values assessing consistency among experts for plaque features, including presence, surface, morphology, echo, calcification, stenosis, and vulnerability.
- (b) Percentage agreement scores corresponding to the kappa metrics



Supplementary Figure 3. Training performance of the YOLOv8 ROI detection model.

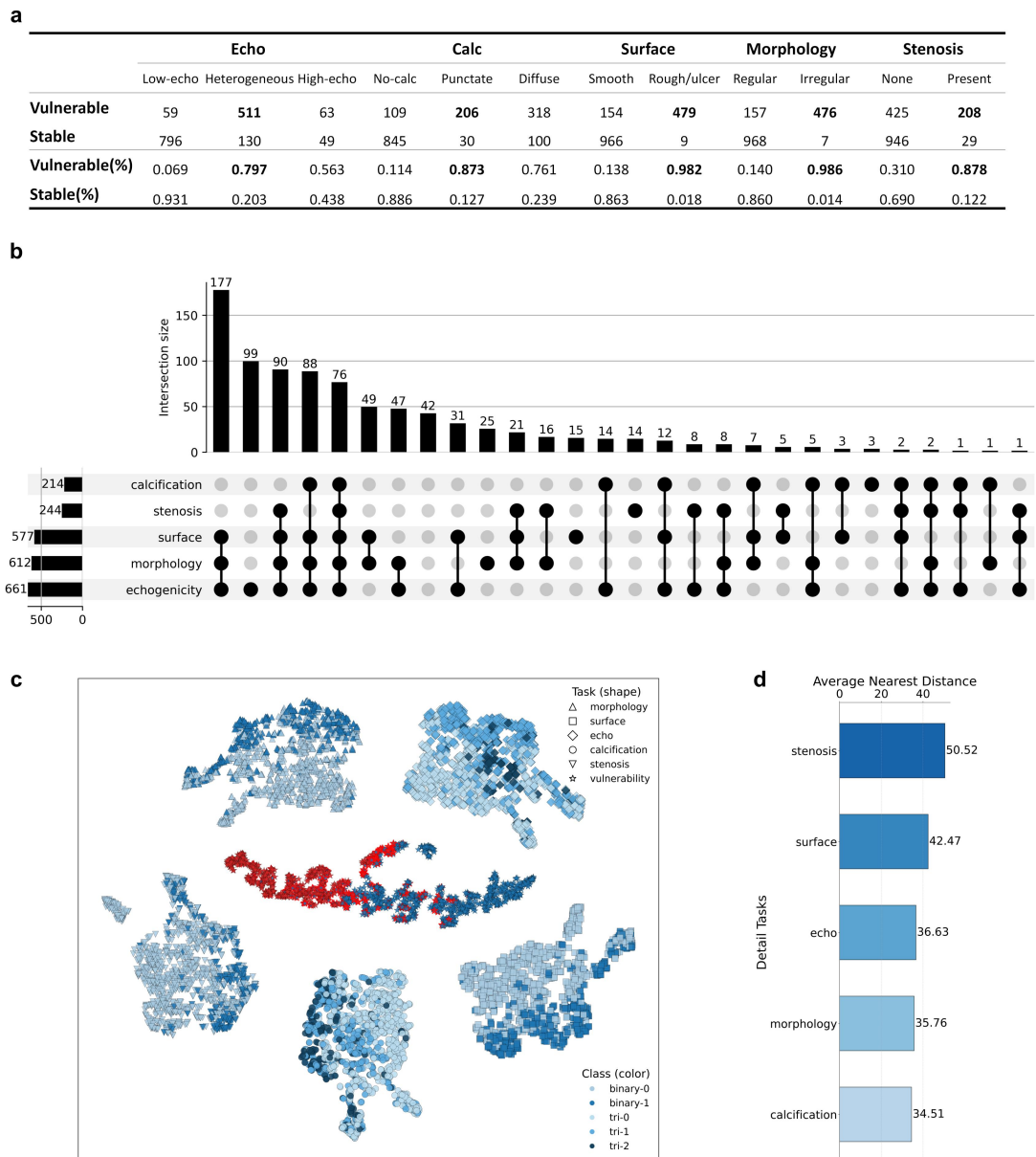
(a) Mean Average Precision (mAP) at IoU threshold of 0.5 (mAP@0.5) across training epochs, showing convergence to a high value (final mAP@0.5 = 0.9998 on the test set).

(b) Total loss curve over epochs, demonstrating steady decrease and stabilization (final loss = 2.203).



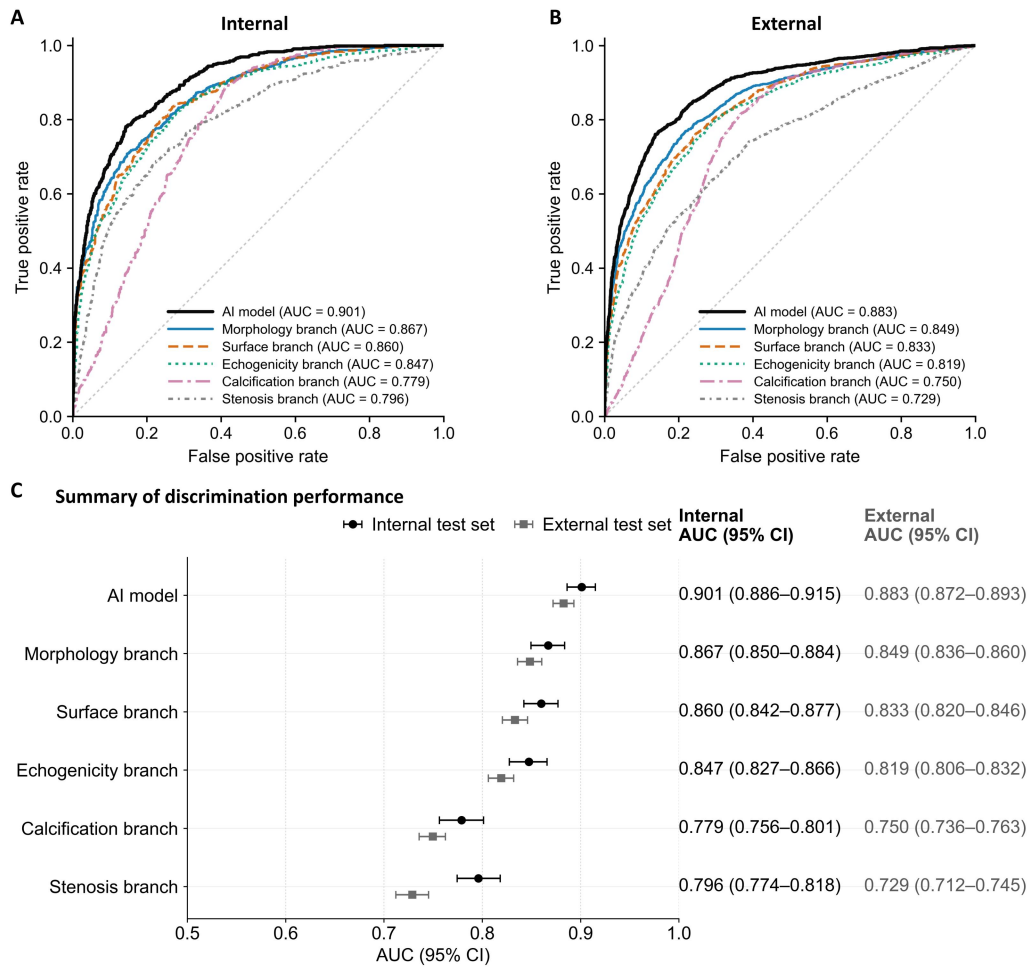
Supplementary Figure 4. Subgroup performance for vulnerable plaque classification.

(a, b) ROC and PR curves for plaques with vulnerable features on both B-mode ultrasound and advanced imaging. (c, d) ROC and PR curves for plaques with vulnerable features on advanced imaging but without identifiable vulnerability features on B-mode ultrasound.



Supplementary Figure 5. Feature patterns and embedding analysis of the cascaded model.

(a) Distribution of plaque-detail features among predicted vulnerable and stable plaques. (b) UpSet plot of high-risk feature combinations contributing to vulnerability assessment. (c) t-SNE visualization of feature embeddings for plaque-detail tasks and vulnerability. (d) Mean distances between vulnerability and detail-task embeddings in the t-SNE space.



Supplementary Figure 6. Branch-specific discrimination of multimodal consensus plaque vulnerability.

a,b, ROC curves comparing the full AI vulnerability score with individual B-mode feature-branch scores in the internal (a) and external (b) test cohorts. c, AUCs and bootstrap 95% confidence intervals for each score. The multimodal consensus vulnerability label was used as the reference standard, and analyses were restricted to plaque-positive images.