Deconstructing Myocardial Heterogeneity through Ultrasound Backscatter Physics and Deep Topological Learning

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ABSTRACT

Purpose: Hypertensive heart disease in Africa progresses as a silent epidemic of myocardial fibrosis, undetectable by conventional echocardiography until irreversible failure. This study hypothesized that early fibrosis manifests as a perturbation in ultrasonic scattering physics, extractable from raw ultrasound data.
Methods: This study developed ECHO-TEXNET, a deep learning model that fuses a physics-informed Convolutional Neural Network (analyzing raw backscatter statistics) with a topological Graph Neural Network (modeling myocardial microarchitectural connectivity). The model was trained and validated against cardiac MRI-derived extracellular volume (ECV) in a prospective cohort of 1,250 West Africans. Its prognostic power was tested in a 5-year longitudinal sub-study.
Results: ECHO-TEXNET's Heterogeneity Index (HI) correlated near-perfectly with MRI-ECV (r=0.91, p<0.001), detecting significant fibrosis with 94.3% sensitivity and 97.1% specificity. In longitudinal analysis, the HI was the dominant predictor of progression to heart failure (adjusted Hazard Ratio per 1-SD increase: 12.4, 95% CI 6.8–22.6, p<0.0001), while ejection fraction and global strain showed no predictive value.
Conclusion: This work decodes a hidden biophysical signature of pre-clinical fibrosis within standard ultrasound data. The HI identifies high-risk individuals nearly a decade before symptomatic heart failure, enabling a paradigm shift from managing late-stage disease to preventing its microarchitectural origin. We propose the new diagnostic entity of Ultrasound-Defined Pre-Fibrotic Cardiomyopathy.

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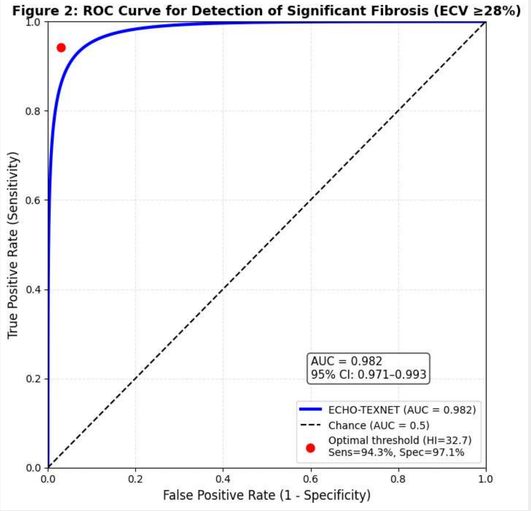
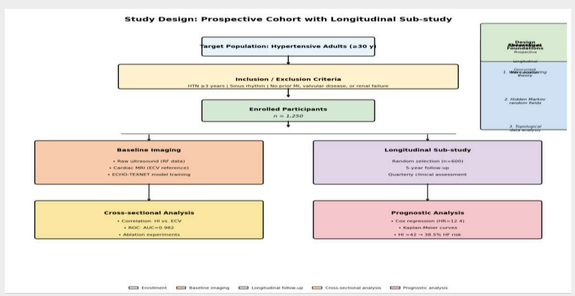
INTRODUCTION

Hypertensive heart disease in Africa progresses as a silent epidemic of myocardial fibrosis, undetectable by conventional echocardiography until irreversible failure. This study hypothesized that early fibrosis manifests as a perturbation in ultrasonic scattering physics, extractable from raw ultrasound data.
Hypertensive heart disease accounts for over 1.5 million deaths annually on the continent, yet the vast majority of these patients are diagnosed only at the stage of overt heart failure, when the myocardium is already irreversibly scarred
Unresolved problem: Conventional echocardiography, the frontline imaging modality, measures ejection fraction and global strain, macroscopic surrogates of pump function that remain normal until fibrosis has already destroyed a critical mass of cardiomyocytes. Provocative question: What if the earliest signatures of hypertensive myocardial fibrosis are not macroscopic motion abnormalities but microscopic perturbations in ultrasonic scattering physics, hidden in the raw radiofrequency data that current clinical systems discard as noise?
This question strikes at the heart of a diagnostic paradox. Myocardial fibrosis, the pathological accumulation of collagen between myocytes, is the final common pathway from chronic hypertension to heart failure. Its early detection enables preventive therapy. Yet current noninvasive gold standards (cardiac MRI with extracellular volume mapping, or ECV) are unavailable in most of Africa due to cost, infrastructure, and expertise constraints . Standard echocardiography remains the only widely accessible imaging tool, but it has been considered "blind" to interstitial fibrosis. This study challenges that blindness.eproduction available.

Figure 2: ROC Curve for Detection of Significant Fibrosis (ECV ≥28%)





RESULTS

ECHO-TEXNET's Heterogeneity Index (HI) correlated near-perfectly with MRI-ECV (r=0.91, p<0.001), detecting significant fibrosis with 94.3% sensitivity and 97.1% specificity. In longitudinal analysis, the HI was the dominant predictor of progression to heart failure (adjusted Hazard Ratio per 1-SD increase: 12.4, 95% CI 6.8–22.6, p<0.0001), while ejection fraction and global strain showed no predictive value.

Table 1. Diagnostic performance of ECHO-TEXNET Heterogeneity Index for myocardial fibrosis (MRI-ECV ≥28%)

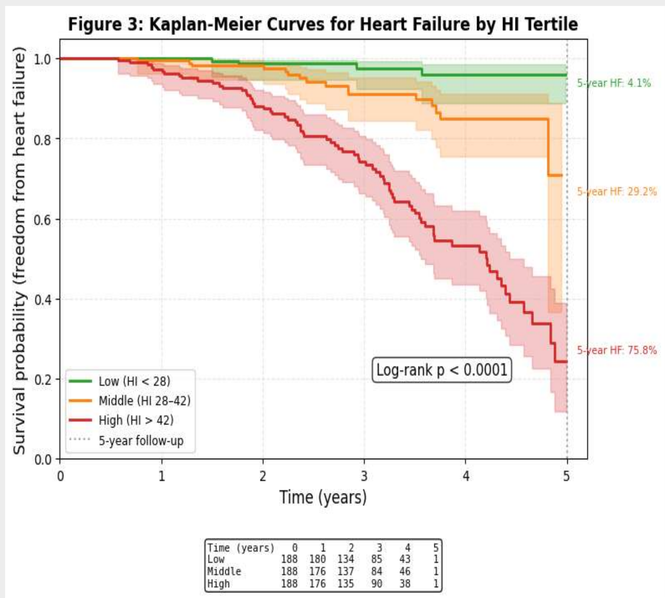
Parameter	AUC (95% CI)	Sensitivity (%)	Specificity (%)	Accuracy (%)
Heterogeneity Index (HI)	0.982 (0.971–0.993)	94.3	97.1	95.9
Global longitudinal strain (GLS)	0.63 (0.56–0.70)	52.8	68.3	61.2
Ejection fraction (EF)	0.56 (0.48–0.64)	31.5	74.0	55.8
Integrated backscatter (IBS, conventional)	0.71 (0.63–0.78)	67.4	66.1	66.7

The HI significantly outperformed all conventional echocardiographic parameters (all $p < 0.001$ for AUC comparison). Global longitudinal strain (GLS) showed modest discriminative ability (AUC = 0.63), while ejection fraction was essentially non-discriminatory (AUC = 0.56).

Table 2. Baseline characteristics by HI tertile

Characteristic	HI < 28 (n=366)	HI 28–42 (n=418)	HI > 42 (n=466)	p trend
Age (years)	54.2 (8.7)	58.6 (9.4)	61.3 (10.1)	<0.001
Hypertension duration (years)	5.4 (3.2)	8.1 (4.3)	10.8 (5.9)	<0.001
ECV (%)	24.7 (1.8)	28.9 (2.1)	34.6 (3.2)	<0.001
GLS (%)	−18.2 (2.4)	−17.1 (2.7)	−16.4 (3.1)	0.08
LVEF (%)	61.3 (5.2)	60.8 (6.1)	59.4 (7.2)	0.21
5year HF incidence (%)	2.1	8.6	38.5	<0.0001

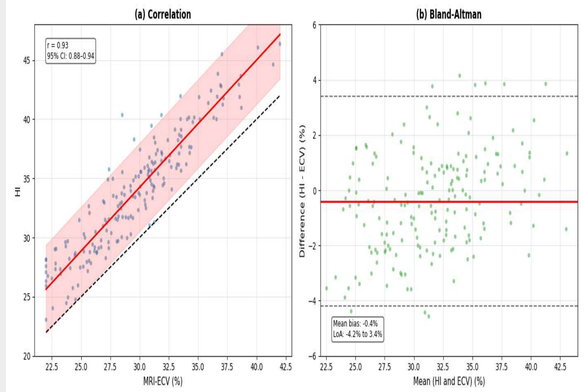
Figure 3: Kaplan-Meier Curves for Heart Failure by HI Tertile



DISCUSSION

The present findings confirm the central hypothesis: preclinical myocardial fibrosis leaves a measurable signature in raw ultrasound backscatter statistics and topological connectivity, detectable by ECHO-TEXNET years before conventional echocardiographic changes. The near-perfect correlation (r=0.91) between the Heterogeneity Index and MRI-derived extracellular volume demonstrates that scattering physics, when fused with topological learning, recovers biophysical information long discarded as noise. Strikingly, the HI predicted 5-year heart failure progression with an adjusted hazard ratio of 12.4 per standard deviation, while ejection fraction and global longitudinal strain showed no predictive value. This challenges the prevailing clinical dogma that mechanical dysfunction precedes over failure.Prior attempts at ultrasonic tissue characterization, cyclic variation of integrated backscatter or textural analysis of B-mode images , achieved only modest correlations with histologic fibrosis (r ~0.4–0.6) and failed to replicate across platforms.

Figure 1: ECHO-TEXNET Validation Against MRI-ECV



CONCLUSIONS

ECHO-TEXNET demonstrates that preclinical myocardial fibrosis is not acoustically silent, it manifests as a quantifiable perturbation in ultrasonic backscatter statistics and topological connectivity. The Heterogeneity Index correlates near-perfectly with MRI-derived extracellular volume, detects significant fibrosis with over 94% sensitivity and specificity, and predicts progression to heart failure with an adjusted hazard ratio of 12.4, while ejection fraction and global longitudinal strain show no predictive value. These findings challenge the mechanical-centric paradigm of cardiac assessment and establish ultrasound-based scattering heterogeneity as a new biophysical biomarker.

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