Role of Echocardiography and Cardiac Magnetic Resonance Imaging in the Evaluation of Atrial Cardiomyopathy: Evidence from the ES2CRYP Cohort

Rôle de l'échocardiographie et de l'imagerie par résonance magnétique cardiaque dans l'évaluation de la cardiomyopathie auriculaire : données de la cohorte ES2CRYP

Amine Bahloul [1], Oussama Haddar [1], Nadia Bouattour[2] , Mariem Jabeur[1], Selma Charfeddine[1], Mariem Dammak[2], Leila Abid [1]

1. *Hedi Chaker University Hospital, Cardiology Department, Sfax, Tunisia*
2. *Habib Bourguiba University Hospital, Neurology department, Sfax, Tunisia*

SUMMARY

This paper reviewed conventional echocardiographic markers of atrial remodeling, including left atrial volume index, atrial function, Doppler-derived parameters and left atrial strain imaging as a sensitive marker of atrial mechanical dysfunction. These variables provide insight into the structural and functional consequences of atrial disease.

In our cohort, patients with cardioembolic stroke exhibited more pronounced structural and functional atrial abnormalities. Although conventional echocardiographic variables were associated with cardioembolic mechanisms, they were ultimately outperformed by left atrial strain parameters.

Peak atrial longitudinal strain (PALS) reflects atrial compliance, reservoir function, and the cumulative effects of fibrosis and remodeling. In our prospective cohort, PALS ≤26.5% emerged as the strongest independent predictor of cardioembolic stroke and occult atrial fibrillation. This parameter received the highest weighting in the ES²CRYP score, emphasizing the pivotal role of atrial mechanical dysfunction in the pathophysiology of atrial cardiomyopathy.

MRI-derived fibrosis quantification provides a unique opportunity to visualize the pathological substrate underlying atrial cardiomyopathy. Although MRI was not systematically performed in our cohort, the abnormalities identified through ECG, Holter monitoring, and strain imaging strongly suggest the presence of advanced fibrotic remodeling. The ES²CRYP score can therefore be viewed as a practical clinical surrogate of the fibrotic atrial substrate (1–4).

Reminder: ES²CRYP Components

• Age ≥75 years • Female sex • PALS ≤26.5% • Absence of coronary artery disease • PAC burden ≥400/day • P-wave dispersion ≥55 ms • PTFV1 ≥3100 ms·µV

This paper introduces the structural substrate that ultimately culminates in the mechanical dysfunction quantified by PALS, the most powerful imaging component of the ES²CRYP score.

KEYWORDS

Atrial cardiomyopathy - Cardioembolic stroke - Occult atrial fibrillation - Left atrial strain - Peak atrial longitudinal strain (PALS) - Atrial fibrosis - Echocardiography 6 ES²CRYP score

RÉSUMÉ

Cet article passe en revue les marqueurs échocardiographiques conventionnels du remodelage atrial, notamment l'index du volume de l'oreillette gauche, la fonction atriale, les paramètres Doppler et l'imagerie du strain atrial gauche, considérée comme un marqueur sensible du dysfonctionnement mécanique atrial. Ces variables permettent d'appréhender les conséquences structurelles et fonctionnelles de la maladie atriale.

Dans notre cohorte, les patients présentant un AVC cardioembolique avaient des anomalies structurelles et fonctionnelles atriales plus marquées. Bien que les variables échocardiographiques conventionnelles aient été associées aux mécanismes cardioemboliques, elles ont finalement été surpassées par les paramètres du strain atrial gauche.

Le strain longitudinal atrial maximal (Peak Atrial Longitudinal Strain, PALS) reflète la compliance atriale, la fonction réservoir et les effets cumulés de la fibrose et du remodelage atrial. Dans notre cohorte prospective, un PALS ≤ 26,5 % est apparu comme le prédicteur indépendant le plus puissant de l'AVC cardioembolique et de la fibrillation atriale occulte. Ce paramètre a reçu la pondération la plus élevée dans le score ES²CRYP, soulignant le rôle central du dysfonctionnement mécanique atrial dans la physiopathologie de la cardiomyopathie atriale.

La quantification de la fibrose par imagerie par résonance magnétique (IRM) offre une opportunité unique de visualiser le substrat pathologique sous-jacent de la cardiomyopathie atriale. Bien que l'IRM n'ait pas été réalisée de manière systématique dans notre cohorte, les anomalies identifiées par l'électrocardiogramme, l'enregistrement Holter et l'imagerie du strain suggèrent fortement la présence d'un remodelage fibrotique avancé. Le score ES²CRYP peut ainsi être considéré comme un substitut clinique pratique du substrat atrial fibrotique (1–4).

Rappel : Composantes du score ES²CRYP

• Âge ≥ 75 ans • Sexe féminin • PALS ≤ 26,5 % • Absence de maladie coronarienne • Charge en extrasystoles atriales (PAC burden) ≥ 400/jour • Dispersion de l'onde P ≥ 55 ms • PTFV1 ≥ 3100 ms·µV

Cet article présente le substrat structurel qui aboutit finalement au dysfonctionnement mécanique quantifié par le PALS, le composant d'imagerie le plus puissant du score ES²CRYP.

MOTS-CLÉS

Cardiomyopathie atriale - Accident vasculaire cérébral cardioembolique - Fibrillation atriale occulte - Strain atrial gauche - Strain longitudinal atrial maximal (PALS) -Fibrose atriale - Échocardiographie - Score ES²CRYP

Correspondance

Amine Bahloul

INTRODUCTION

Echocardiography is the cornerstone of atrial imaging and remains the first-line modality for the evaluation of atrial structure and function. It is widely available, non-invasive, reproducible, and capable of providing comprehensive information regarding atrial remodeling (1,5–8).

Atrial cardiomyopathy affects multiple dimensions of atrial physiology, including:

- Structural remodeling
- Mechanical dysfunction
- Electromechanical abnormalities

Hemodynamic consequences

- Thrombogenic remodeling (Figure 1)

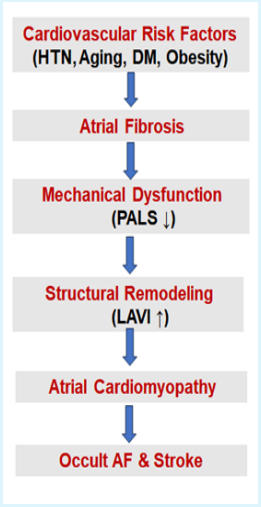

Figure 1. Continuum of Atrial Remodeling

No single echocardiographic parameter can fully characterize atrial disease. Therefore, a multiparametric approach is required (1,2).

Left atrial strain has emerged as the most sensitive echocardiographic marker of atrial cardiomyopathy. Unlike volume measurements, strain detects dysfunction before structural enlargement develops and may therefore identify patients at an earlier stage of atrial remodeling (9–12).

Cardiac magnetic resonance (CMR) has emerged as the reference non-invasive imaging modality for comprehensive characterization of atrial structure and tissue composition. While echocardiography remains the first-line tool for evaluating atrial size and function, CMR provides superior spatial resolution and unique tissue characterization capabilities that allow direct visualization of atrial remodeling (13–16).

The role of CMR in atrial cardiomyopathy extends beyond simple chamber quantification. It enables assessment of atrial anatomy, fibrosis burden, atrial appendage morphology, and potentially thromboembolic risk.

ECHOCARDIOGRAPHIC ASSESSMENT OF ATRIAL CARDIOMYOPATHY

Left Atrial Size: The First Marker of Remodeling

We present the case of a 27-year-old woman referred for acute heart failure due to severe aortic regurgitation. Her medical history was unremarkable; however, her family history was notable for multiple cases of aortic aneurysm and dissection: her father, paternal aunt, and a first cousin underwent surgical repair for thoracic aortic aneurysm, while a brother and another cousin died suddenly due to aortic rupture.

On admission, the patient exhibited signs of left-sided heart failure. There were no phenotypic stigmata suggestive of a syndromic connective tissue disorder.

Transthoracic echocardiography (TTE) revealed a tricuspid aortic valve with preserved leaflet morphology but significant annulo-aortic ectasia leading to severe central aortic regurgitation. The sinus of Valsalva measured 38 mm, the sino-tubular junction 49 mm, and the ascending aorta 66 mm. Left ventricular dilation with a reduced ejection fraction of 40% was observed (Figures 1 and 2).

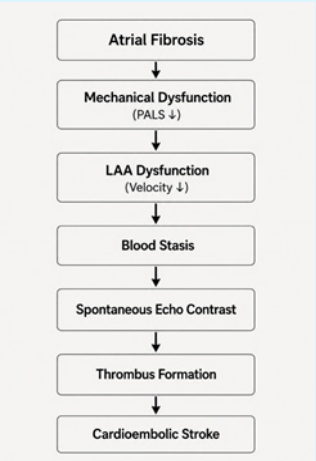

Figure 2. Thrombogenic Remodeling in Atrial Cardiomyopathy

The left atrium acts as a chronic barometer of left ventricular filling pressures. Unlike Doppler indices that fluctuate according to loading conditions, left atrial enlargement reflects cumulative exposure to hypertension, diastolic dysfunction,

obesity, diabetes mellitus, sleep apnea, heart failure and atrial fibrillation. For this reason, left atrial enlargement is often described as the "HbA1c of diastolic dysfunction" (17).

Moreover, left atrial enlargement integrates the long-term consequences of hemodynamic stress and therefore reflects the cumulative burden of cardiovascular risk factors over time (17–19).

Several epidemiological studies have demonstrated that increasing atrial size is associated with incident atrial fibrillation, ischemic stroke, heart failure and cardiovascular mortality (18–21).

Left Atrial Diameter

Historically, left atrial diameter measured in parasternal long-axis view was widely used to assess atrial remodeling. Normal Values are < 40 mm in men and < 38 mm in women

The left atrium enlarges asymmetrically during the remodeling process. Consequently, a single linear measurement may underestimate the true extent of atrial enlargement.

Current ASE and EACVI guidelines therefore recommend volumetric assessment rather than simple diameter measurements (6,7).

Left Atrial Volume Index (LAVI)

LAVI is currently considered the reference echocardiographic parameter for assessing atrial size and structural remodeling (6,7).

Calculation :Biplane Simpson method:

- Apical four-chamber view
- Apical two-chamber view

Volume indexed to body surface area.

Cut-Off Values (ASE / ESC Recommendations) are :

- LAVI ≤34 mL/m^2 : Normal
- LAVI 35–41 mL/m^2 : Mild enlargement
- LAVI 42–48 mL/m^2 : Moderate enlargement
- LAVI >48 mL/m^2 : Severe enlargement

Numerous studies have demonstrated that elevated LAVI predicts incident atrial fibrillation , cardioembolic stroke, heart failure and ardiovascular mortality

The Framingham Heart Study demonstrated that every incremental increase in left atrial size is associated with a substantial increase in AF risk (20).

Similarly, ARIC investigators reported a strong association between atrial enlargement and future ischemic stroke, even in the absence of documented AF (18,21).

LAVI primarily reflects structural remodeling. However, atrial enlargement is generally considered a relatively late manifestation of atrial disease. Mechanical dysfunction and fibrosis frequently precede volumetric enlargement (1,2,10).

This limitation has stimulated growing interest in strain imaging and other functional markers capable of detecting earlier stages of atrial cardiomyopathy.

Left Atrial Emptying Fraction (LAEF)

LAEF evaluates global atrial pump function and integrates reservoir, conduit and contractile performance.

Formula : (Maximum LA Volume – Minimum LA Volume) ÷ Maximum LA Volume ×100

Normal Value is > 55%

Abnormal Values :

- LAEF 45–55% : Mild dysfunction
- LAEF 35–45% : Moderate dysfunction
- LAEF < 35% : Severe dysfunction

Reduced LAEF predicts atrial fibrillation, ischemic stroke and heart failure hospitalization

Several studies have demonstrated significant correlations between reduced LAEF and atrial fibrosis burden assessed by MRI (15,16,22).

Consequently, LAEF is increasingly recognized as a functional marker of atrial cardiomyopathy.

Phasic Left Atrial Function

The left atrium performs three complementary physiological functions during the cardiac cycle.

- Reservoir Function : Occurs during ventricular systole. It represents atrial filling and storage of pulmonary venous return.

Influenced by atrial compliance, myocardial fibrosis and left ventricular longitudinal function.

Reservoir dysfunction is often the earliest functional manifestation of atrial cardiomyopathy (9–12).

- Conduit Function : Occurs during early diastole. It represents passive transfer of blood from the pulmonary veins into the left ventricle.

Conduit dysfunction is closely linked to abnormalities of ventricular relaxation and elevated filling pressures.

- Booster Pump Function :Occurs during late diastole. It represents active atrial contraction.

This component becomes progressively impaired with advancing fibrosis and is frequently lost after the development of atrial fibrillation.

Doppler Assessment

Doppler echocardiography remains essential for evaluating the hemodynamic consequences of atrial remodeling.

Mitral Inflow

- E Wave : Represents early ventricular filling.
- A Wave : Represents atrial contraction.
- E/A Ratio : Provides important information regarding diastolic function and filling pressures.

Tissue Doppler Imaging

- e' : Reflects myocardial relaxation.
- E/e' : Provides an estimate of left ventricular filling pressure.

Chronically elevated filling pressures contribute directly to atrial stretch, fibrosis, and structural remodeling (17,23). Several studies have shown that elevated E/e' is independently associated with incident AF and progressive atrial dysfunction (23,24).

Atrial Electromechanical Delay (AEMD)

AEMD measures the interval between electrical activation and mechanical contraction of the atrium. It represents a unique bridge between Electrical Remodeling and Mechanical Dysfunction.

Prolonged AEMD has been associated with atrial fibrosis, AF recurrence after catheter ablation, and occult AF after ischemic stroke (25–27).

It therefore represents an attractive marker integrating electrical and structural aspects of atrial cardiomyopathy.

Measurement :Using Tissue Doppler Imaging. Usually measured at septal annulus, lateral annulus and tricuspid annulus

Normal Values is <30–35 ms . Several studies suggest that values exceeding 40 ms are associated with atrial fibrillation, electrical remodeling, fibrosis and cardioembolic stroke (25–27);

Left Atrial Appendage Function

The left atrial appendage (LAA) is increasingly recognized as a central component of atrial cardiomyopathy and thromboembolic risk. More than 90% of intracardiac thrombi in non-valvular atrial fibrillation originate from the LAA, highlighting its importance in stroke pathophysiology (28,29).

Beyond its role as a thrombus reservoir, the appendage reflects the severity of atrial remodeling. Structural fibrosis, impaired contractility, endothelial dysfunction, and blood stasis progressively affect appendage function as atrial cardiomyopathy advances (1,3).

- LAA Emptying Velocity

Assessment ! Measured using pulsed-wave Doppler during transesophageal echocardiography. Normal value is >40 cm/s while LAA Empty velocity < 20 cm/sec is associated with high risk of atrial fibrillation

Reduced appendage velocity is associated with spontaneous echo contrast, left atrial thrombus formation, cardioembolic stroke, and future atrial fibrillation (figure 2).

Several studies have demonstrated a close relationship between reduced appendage flow velocities and atrial fibrosis burden assessed by cardiac MRI (28–31).

- Spontaneous Echo Contrast

Spontaneous echo contrast (SEC) appears as a dynamic smoke-like echogenicity within the atrial cavity. SEC reflects blood stasis, hypercoagulability and ndothelial dysfunction.

These mechanisms correspond closely to the thrombogenic phenotype of atrial cardiomyopathy described by Kamel and colleagues (2). SEC is associated with LAA thrombus, cardioembolic stroke and increased mortality. Its presence strongly suggests advanced atrial disease.

Three-Dimensional Echocardiography

Three-dimensional echocardiography overcomes several limitations of conventional two-dimensional imaging.

The left atrium is a highly asymmetrical structure that cannot be accurately characterized using geometric assumptions.

3D echocardiography provides:

- More accurate volume assessment
- Better reproducibility
- Improved evaluation of atrial remodeling (32–34)

Several studies suggest that 3D-derived atrial volumes correlate more closely with MRI measurements than conventional 2D echocardiography (32–34).

Although not routinely available, 3D imaging represents an important step toward comprehensive atrial phenotyping.

Left Atrial Strain Imaging (figure 3)

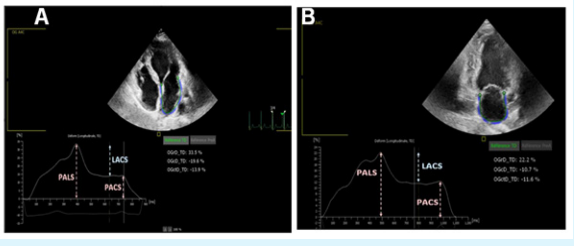

Figure 3. Left atrial strain parameters from four chamber view (A) and two chamber view (B)

Among all echocardiographic parameters currently available, left atrial strain imaging has emerged as the most sensitive marker of atrial cardiomyopathy (9–12).

Speckle-tracking echocardiography allows direct quantification of atrial myocardial deformation and provides a functional assessment of atrial tissue properties.

Unlike volume measurements, strain detects dysfunction before structural enlargement becomes evident.

Atrial strain reflects myocardial deformation during the cardiac cycle.

Fibrosis progressively reduces atrial compliance, elasticity and reservoir capacity.

Consequently: Increasing fibrosis → Reduced atrial compliance → Reduced deformation → Reduced strain values (figure 4).

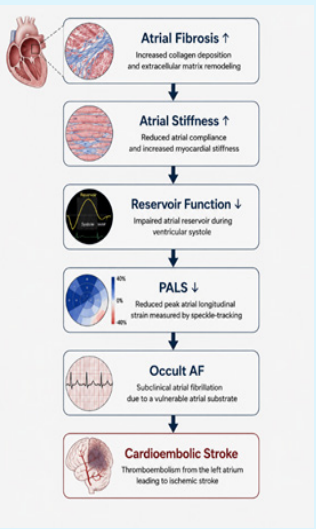

Figure 4. Left atrial strain parameters from four chamber view (A) and two chamber view (B)

- Peak Atrial Longitudinal Strain (PALS)

PALS corresponds to the maximal atrial deformation reached during ventricular systole.

It reflects reservoir function, atrial compliance and myocardial elasticity.

According to contemporary meta-analyses normal value is PALS >35–40% (9)

Pathological Values :

- 30–35% : Mild dysfunction
- 25–30% : Moderate dysfunction
- <25% :Severe dysfunction

Several MRI studies demonstrated a strong inverse relationship between PALS and atrial fibrosis burden (15,16,35).

Reduced PALS predicts incident AF, AF recurrence after ablation, cardioembolic stroke, ESUS-related atrial cardiopathy and cardiovascular mortality (9–12,35–38)

Numerous investigations suggest that PALS outperforms conventional echocardiographic variables including LA diameter , LAVI and LAEF for identifying advanced atrial disease.

ES^{2}CRYP Cohort Findings

In our prospective bicentric cohort, PALS emerged as the strongest imaging predictor of:

- Cardioembolic stroke
- Occult atrial fibrillation

Patients with PALS ≤26.5% exhibited:

- Higher prevalence of cardioembolic stroke
- Greater atrial ectopic burden
- Increased incidence of occult AF
- More severe electrical remodeling

This threshold was incorporated into the ES^{2}CRYP score and assigned the highest weight among all variables.

PALS likely represents the final common pathway of atrial remodeling.

Unlike isolated structural markers, strain integrates:

Structural Component : Fibrosis

Mechanical Component : Reduced compliance

Electrical Component : AF substrate

Thrombogenic Component : Blood stasis

Consequently, strain may function as a global surrogate of atrial cardiomyopathy severity.

Echocardiographic Severity Classification of Atrial Cardiomyopathy

Based on current literature and findings from our cohort, atrial cardiomyopathy may be conceptualized as a continuum witch can be classified in 4 stages :

- Mild atrial cardiomyopathy : Normal LAVI, mildly reduced PALS
- Moderate cardiomyopathy : LAVI enlargement, PALS 25–30%
- Advanced cardiomyopathy : Severe LA enlargement, PALS <25%, LAEF reduction
- End-Stage cardiomyopathy : Severe dysfunction, AF, LAA abnormalities

CARDIAC MRI AND ATRIAL FIBROSIS

For decades, atrial fibrillation was considered a purely electrical disease. However, advances in histopathology and imaging have demonstrated that atrial fibrosis constitutes the fundamental substrate underlying atrial remodeling, arrhythmogenesis, and thromboembolic risk (1–4).

Atrial fibrosis is characterized by collagen deposition, myocyte degeneration, fibroblast activation, extracellular matrix expansion and conduction heterogeneity.

These abnormalities lead to progressive impairment of atrial structure and function.

Cardiac MRI has revolutionized the evaluation of atrial cardiomyopathy by allowing direct in vivo visualization of atrial fibrosis (5–8).

Multiple cardiovascular conditions contribute to fibrotic remodeling including aging, hypertension, diabetes mellitus, obesity, Sleep apnea, heart failure, inflammation and oxidative stress. These factors activate transforming growth factor β (TGF-β), renin–angiotensin–aldosterone system, and nflammatory pathways resulting in progressive extracellular matrix deposition (2,3).

Consequences of Fibrosis :

- Electrical Consequences : conduction slowing, conduction block , electrical anisotropy and re-entry circuits
- Mechanical Consequences : reduced compliance, reduced reservoir function, reduced strain, reduced appendage function
- Thrombogenic Consequences :blood stasis, endothelial dysfunction and hypercoagulability.

These abnormalities collectively define atrial cardiomyopathy (1,4).

Late Gadolinium Enhancement MRI

Late gadolinium enhancement (LGE) imaging is currently the most widely used technique for visualization of atrial fibrosis.

Following intravenous gadolinium administration:

- Normal myocardium rapidly washes out contrast.
- Fibrotic tissue retains gadolinium longer.

As a result:

- Normal myocardium appears dark.
- Fibrotic tissue appears bright. (5–8)

LGE allows direct fibrosis visualization, quantification of fibrosis burden ,regional fibrosis mapping and risk stratification.

No other imaging modality currently provides equivalent tissue characterization

Several technical challenges remain:

- Thin atrial wall
- Motion artifacts
- Limited spatial resolution
- Lack of universal standardization

Despite these limitations, LGE-CMR remains the reference technique for atrial fibrosis assessment.

Utah Classification

The Utah classification was developed to standardize quantification of atrial fibrosis.

Utah I : Fibrosis <5% , inimal remodeling

Utah II : Fibrosis 5–20% , Mild remodeling

Utah III : Fibrosis 20–35%, Moderate remodeling

Utah IV : Fibrosis >35% , Severe remodeling (5,9)

Clinical Significance

Increasing Utah stage is associated with:

- Higher AF burden
- Increased AF recurrence
- Reduced ablation success
- Greater stroke risk
- More advanced atrial cardiomyopathy (5,9–11)

The DECAAF Program

The Delayed Enhancement MRI Determinant of Successful Catheter Ablation of Atrial Fibrillation (DECAAF) study represented a major breakthrough in atrial imaging.

Marrouche and colleagues demonstrated that fibrosis burden independently predicts recurrence after AF ablation (10).

The DECAAF II trial further confirmed the prognostic importance of fibrosis burden.

Although fibrosis-guided ablation did not improve overall outcomes, the study reinforced the concept that fibrosis represents a major determinant of AF progression and procedural success (11).

The DECAAF program established that:

Fibrosis is not merely a consequence of AF.

Fibrosis is a primary disease process driving AF initiation, AF maintenance, Stroke risk and Progressive atrial dysfunction.

Emerging MRI Biomarkers

- T1 Mapping

T1 mapping provides quantitative assessment of diffuse myocardial fibrosis.

Advantages:

- Quantitative
- Reproducible
- Detects diffuse fibrosis

Potential future applications include earlier identification of atrial cardiomyopathy before overt fibrosis develops (12).

- Extracellular Volume Fraction (ECV)

ECV quantifies expansion of the extracellular matrix.

Increased ECV reflects:

- Fibrosis
- Matrix remodeling
- Advanced atrial disease

Several studies have demonstrated correlations between ECV, AF burden, and reduced atrial strain (12,13).

MRI and echocardiography provide complementary information.

MRI measures fibrosis burden and tissue composition while Echocardiography measures

mechanical consequences and Functional impairment. The strongest relationship identified to date is between Atrial Fibrosis augmentation and PALS diminution (13–15).

Several studies have demonstrated strong inverse correlations between MRI fibrosis burden and atrial strain measurements (13–15).

Although MRI was not systematically performed in our cohort, the ES^{2}CRYP score likely identifies patients with advanced MRI-defined atrial fibrosis.

Each ES^{2}CRYP component reflects a manifestation of fibrosis (Table 1) :

Table 1. Fibrosis manifestations in ES^{2}CRYP Components

ES^{2}CRYP Component	Fibrosis Manifestation
PTFV1	Electrical remodeling
P-wave dispersion	Conduction heterogeneity
PAC burden	Arrhythmogenic substrate
PALS	Mechanical dysfunction
Advanced age	Fibrosis accumulation
Female sex	Remodeling susceptibility
No CAD	Non-ischemic atrial disease phenotype

Thus, the ES^{2}CRYP score may represent a practical bedside approximation of MRI-defined atrial cardiomyopathy.

The contemporary evaluation of atrial cardiomyopathy should integrate (figure 5):

- ECG : PTFV1, P-wave dispersion and Interatrial block
- Holter Monitoring : PAC burden, ESVEA, Short atrial runs and HRV abnormalities
- Echocardiography : LAVI, LAEF and PALS
- Cardiac MRI : Fibrosis burden, Utah stage, ECV and T1 mapping.

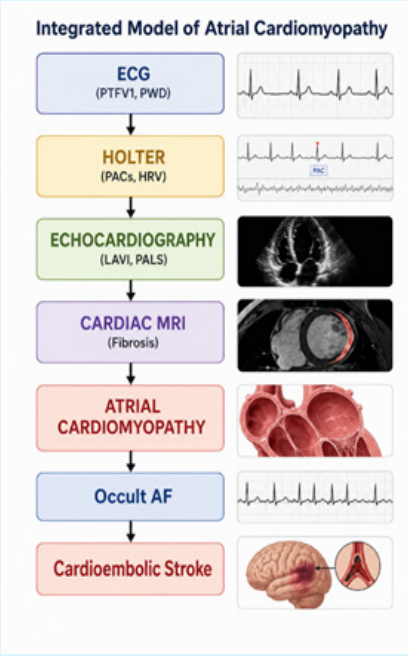

Figure 5. Integrated Multimodality Assessment of Atrial Cardiomyopathy

CONCLUSION

The contemporary concept of atrial cardiomyopathy extends far beyond simple atrial enlargement and encompasses a complex spectrum of structural, mechanical, electrical, autonomic, and thrombogenic remodeling. Echocardiography and cardiac magnetic resonance imaging have become essential tools for characterizing this evolving disease process and identifying patients at increased risk of atrial fibrillation and cardioembolic stroke.

Conventional echocardiographic parameters, particularly left atrial volume index (LAVI), left atrial emptying fraction (LAEF), and left atrial appendage function, provide important insights

into the progression of atrial remodeling. However, left atrial strain imaging has emerged as the most sensitive marker of early atrial dysfunction, capable of detecting impairment before the development of overt atrial enlargement. Peak atrial longitudinal strain (PALS) reflects the reservoir function of the left atrium and appears to represent the functional expression of the underlying fibrotic substrate.

In our prospective bicentric stroke cohort, PALS ≤26.5% was the strongest echocardiographic predictor of occult atrial fibrillation and cardioembolic stroke, highlighting the central role of mechanical dysfunction in the pathophysiology of atrial cardiomyopathy. This observation justified the inclusion of PALS as the highest-weighted imaging variable within the ES^2CRYP score.

Cardiac magnetic resonance imaging provides complementary information by directly visualizing atrial fibrosis, which is increasingly recognized as the anatomical hallmark of atrial cardiomyopathy. Studies such as DECAAF and DECAAF II have demonstrated that the extent of atrial fibrosis is closely associated with atrial fibrillation burden, treatment outcomes, and thromboembolic risk. MRI therefore offers a unique opportunity to identify the structural substrate responsible for the electrical and mechanical abnormalities observed on ECG, Holter monitoring, and echocardiography.

Taken together, echocardiography, strain imaging, and cardiac MRI support a continuum of atrial disease progressing from fibrosis and increased atrial stiffness to impaired reservoir function, reduced PALS, atrial enlargement, left atrial appendage dysfunction, occult atrial fibrillation, and ultimately cardioembolic stroke. This integrated multimodality approach reinforces the concept that atrial cardiomyopathy is a distinct clinical entity capable of promoting thromboembolism even in the absence of documented atrial fibrillation.

Future advances combining multimodal imaging, artificial intelligence, and clinical risk stratification may enable earlier identification of vulnerable atrial phenotypes and facilitate personalized strategies for stroke prevention. Within this framework, the ES^2CRYP score may serve as a practical clinical surrogate of the underlying atrial cardiomyopathy substrate, bridging advanced imaging findings with everyday clinical decision-making.

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