Imaging of left heart intracardiac thrombus: clinical needs, current imaging, and emerging cardiac magnetic resonance techniques

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Abstract: Intracardiac thrombus in the left atrium and atrial appendage (LA/LAA) and left ventricle (LV) increases the risk of systemic thromboembolism and causes potentially devastating diseases such as ischemic stroke and acute ischemia in abdominal organs and lower extremities. Detecting the presence and monitoring the resolution of left heart intracardiac thrombus are of vital importance for stratifying patients and guiding treatment decisions. Currently, echocardiography is the most frequently used method for the above clinical needs, followed by computed tomography. An increasing number of studies have been performed to investigate the value of cardiac magnetic resonance (CMR) as an alternative imaging modality given its several unique strengths. This article provides an overview of the clinical relevance of the LA/LAA and LV thrombus as well as the diagnostic performance of the current imaging modalities and emerging CMR techniques.

Keywords: cardiac magnetic resonance, intracardiac thrombus, left heart

Introduction

Assessment of intracardiac masses is a critical part of cardiac imaging. Intracardiac thrombus is the most common type of cardiac mass. Thrombus in the left ventricle (LV) or left atrium is of particular clinical concern due to significant risk of embolic events in the brain or other organs resulting in significant morbidity and mortality.1 Left atrium and atrial appendage (LA/LAA) thrombus is prevalent in patients with atrial fibrillation (AF) and also may be associated with valvular disease.2,3 LV thrombus is associated with severe myocardial dysfunction, which may occur in both ischemic and non-ischemic etiologies.4 The presence of LA/LAA or LV thrombus typically requires adjustment in clinical management, and therefore detection and assessment of left chamber intracardiac thrombus are highly clinically relevant.4

There are multiple modalities currently available for imaging of intracardiac thrombus. Transthoracic echocardiography (TTE) and transesophageal echocardiography (TEE) are the most frequently used methods.5,6 TTE is inferior to TEE in visualizing LA/LAA thrombus, and apical thrombus may also be obscured by near-field clutter artifacts.7,8 However, access to TEE is limited by its moderately invasive nature and is contraindicated in patients with significant esophageal disease.9

Contrast-enhanced cardiac computed tomography (CCT) identifies masses with high precision; however, tissue characterization is limited, as the appearance of tumor and thrombus is similar.10 In addition, the risks of ionizing radiation exposure and contrast-related nephropathy limit broad application. Over the past decade, studies have demonstrated that cardiac magnetic resonance (CMR) has the potential to safely and accurately identify intracardiac thrombus without invasive measurement, radiation, or iodinated contrast exposure.11,12 The aim of this article is to provide an overview of the clinical relevance of LA/LAA and LV thrombus and review the diagnostic performance of the current imaging modalities and emerging CMR techniques.
emerging CMR techniques for the identification of LA/LAA and LV thrombus.

**Left atrial thrombus**

**Pathophysiology of LA/LAA thrombus**

AF is one of the most common cardiac arrhythmias in the world. The worldwide prevalence of AF in 2017 was estimated at 37,574 million cases in 2017. Thromboembolic complications, especially stroke, are the main cause of death and disability in patients with AF, at a rate of nearly fivefold the general population. Thrombus most frequently forms in the LAA due to poor blood movement during AF. While other left atrial locations are possible in the setting of concurrent pathology (e.g. valvular disease), more than 90% of atrial thrombi in patients with non-valvular AF are located in the LAA. Compared with non-AF-related stroke, AF-related stroke showed more severe disability, higher fatality, and recurrence rate.

The diagnosis of LA/LAA thrombus impacts clinical care. Anticoagulation is recommended for the treatment of confirmed thrombus in patients with AF, as well as prophylactic therapy in most patients. However, approximately one-third of eligible AF patients do not receive appropriate anticoagulant therapy. Nearly half of the cases were due to the physicians’ clinical judgment, which may not always be based on evidence-based risk schemes and guidelines. Even with appropriate medical therapy, 20–40% of AF patients with LAA thrombus have persistent thrombus. Thus, accurate and non-invasive imaging techniques may be beneficial to monitor treatment response for intensification or alteration of therapy. On the other hand, ruling out the presence of LAA thrombus is of vital importance in patients prior to electrocardioversion, radiofrequency ablation, and LAA occlusion procedures due to risk of intraprocedural thromboembolic events.

**Conventional diagnostic modalities for LA/LAA thrombus**

TEE is considered the gold standard for the detection of LA/LAA thrombus in patients with AF who are selected for undergoing electrocardioversion or pulmonary vein isolation. A thrombus appears as an echo-dense material acoustically separate from the endocardium (Figure 1). Previous studies have shown that the prevalence of LAA thrombus detected by TEE is around 3.6–8.8% in AF patients under anticoagulation therapy. Compared with TTE, TEE provides superior visualization of the LAA, with sensitivity and specificity as high as 100% and 99%, respectively. However, TEE requires esophageal intubation which has rare but potentially serious complications like esophageal perforation. Furthermore, the procedure requires experienced echocardiographers and support staff, is time-consuming, may cause patient discomfort, and has significant financial cost. TEE also cannot provide essential information about pulmonary vein anatomy for pulmonary vein isolation studies, which frequently benefit from volumetric views of the pulmonary venous anatomy.

The utility of TTE in the detection of LA/LAA thrombus is limited due to its low sensitivity. However, with continued technological development and the use of harmonic imaging and administration of ultrasound contrast agents, the visualization and delineation of the LAA on TTE have been substantially improved. Agoston et al. showed that three-dimensional (3D) TTE has a better detection rate for LAA compared with two-dimensional (2D) TTE (68.1% versus 45.5%) in 204 consecutive patients. In a subgroup of 37 patients, thrombus was detected in 8 patients using both 3D TTE and TEE (kappa = 1.0). Karakus et al. suggested that combined 2D TTE and 3D TTE may have comparable accuracy to TEE in evaluating LAA thrombus; however, this approach has not yet experienced significant clinical uptake, as the clinical consequences of missing intracardiac thrombus are high.

As CCT is often performed prior to AF ablation to assess the number, location, and size of the pulmonary veins, as well as the size and morphology of LA/LAA, many studies had proposed to use CCT as a non-invasive alternative method for screening LA/LAA thrombus. With the use of contrast medium, thrombus is detected as a filling defect on initial and delayed image acquisition (Figure 2). Delayed image acquisition is critical, as reduced LAA filling rates can cause false-positive filling defects during first-pass perfusion. A meta-analysis published in 2013 demonstrated that the mean sensitivity and specificity of CCT in assessing LA/LAA thrombus were 96% and 92%, whereas the positive
predictive value and negative predictive value were 41% and 99%, respectively. The diagnostic accuracy significantly improved from 94% to 99% in a sub-analysis of studies in which delayed imaging was performed. A recent study by Spagnolo et al. evaluated the optimal delay time for data acquisition in a cohort of consecutive patients with persistent AF referred for radiofrequency ablation to differentiate between thrombus and effects of slow LAA filling. The study reported that 10 (4%) out of 260 patients were diagnosed with LAA thrombi. Among 63 patients with LAA early filling defects on CCT, 15 had a persistent defect at 1 min, 12 at 3 min, and 10 at 6 min after contrast injection. The sensitivity, specificity, and positive and negative predictive values were all 100% at 6-min delayed phase. In comparison with TEE, CCT has high temporal and spatial resolution, yet additional radiation burden and potential nephrotoxicity caused by required iodinated contrast agents cannot be ignored. Furthermore, irregular and fast heart rates in patients with AF can reduce the probability of high-quality image acquisition on CCT.

**CMR diagnosis of LA/LAA thrombus**

CMR can be used for LA/LAA thrombus detection with or without contrast medium. The utility of non-enhanced turbo spin-echo double- or triple-inversion recovery sequences for the assessment of thrombus in the LAA was explored by Ohyama et al. in 50 patients with nonrheumatic continuous AF and a history of cardioembolic stroke. CMR was found to have high intra- and interobserver reproducibility, with a high agreement in detecting LAA thrombus compared with TEE (overall kappa = 0.876, SE = 0.068). The authors also noticed that the thrombus sizes detected on CMR were consistently ≈20% larger than those on TEE. Another early study showed that the diagnostic accuracy of contrast-enhanced CMR in ruling out LAA thrombus was low due to insufficient spatial resolution. Compared with TEE, the sensitivity of 2D saturation-recovery steady-state free precession sequence and 3D turbo fast low-angle shot in detecting LAA thrombus was 47% and 35%, respectively, and the specificity was 50% and 67%, respectively. Both 2D and 3D techniques overestimated the size of the thrombus compared with TEE measurements by 66% and 25%, respectively.

With recent advances in sequence development combined with the ability of paramagnetic contrast agents, an increasing number of studies have shown the improvement of CMR in diagnostic accuracy. Rathi et al. compared the performance of 2D non-contrast cine images, 2D/3D
contrast-enhanced CMR sequences, and TEE for the detection of LAA thrombus in 97 patients with AF. Both 2D and 3D contrast-enhanced CMR were positive for thrombus in 2 of the 97 patients with 100% concordance to TEE, whereas 2D cine-CMR was indeterminate in 6 patients. Kitkungvan et al.⁴⁹ used TEE as a reference standard to study the diagnostic performance of different CMR techniques in the detection of LAA thrombus in 261 patients for pulmonary venous anatomy mapping. Nine patients were diagnosed with LA/LAA thrombus using TEE. Long inversion time delayed enhancement CMR (DE-CMR) had the highest diagnostic accuracy (99.2%), sensitivity (100%), and specificity (99.2%), followed by contrast-enhanced magnetic resonance angiography (MRA) (accuracy, 94.3%; sensitivity, 66.7%; and specificity, 95.2%) and cine-CMR (accuracy, 91.6%; sensitivity, 66.7%; and specificity, 92.5%) with excellent interobserver agreement in all three techniques. The findings suggest that CMR could be an alternative imaging modality to TEE for the assessment of LA/LAA thrombus. The characteristics of the studies are summarized in Table 1. Relevant studies between 1 January 1972 and 1 January 2022 were searched on PubMed, Embase, Cochrane Library, and Medline. The detailed literature search strategy is shown in Figure 3.

A major advantage of CMR over echocardiography and CCT is its ability to characterize tissue, including differentiation of tissue and thrombus and identification of myocardial tissue scarring through delayed enhancement imaging.⁵⁰ DE-CMR now has high enough resolution to visualize scar in the LA wall.⁵¹ Several studies have shown the feasibility of using DE-CMR to localize and quantify LA fibrosis that is associated with increased risk of cerebro-cardiovascular diseases and is a helpful indicator of the severity and prognosis of AF.⁵²-⁵⁶

Figure 3. Flow diagram of literature search strategy.
LV thrombus may lead to embolic complications such as stroke, with devastating consequences. The main risk factors for LV thrombus development are the duration of myocardial ischemia, infarct size, and reduced cardiac function. Ventricular cavity dilation, wall akinesia and dyskinesia, and the formation of LV aneurysm all result in stasis of blood within the LV, which leads to LV thrombus formation. The incidence of LV thrombus after myocardial infarction ranges from under 2% to over 34%. In patients with significant LV dysfunction, the incidence of LV thrombus ranges from 7% to 26%, and it can reach as high as 57.1% in patients with left ventricular ejection fraction (LVEF) below 20%. LV thrombus has a dynamic nature of development and resolution, which requires active monitoring to guide anticoagulation therapy to balance risks of embolization versus bleeding.

Conventional diagnostic modalities for LV thrombus
TTE is currently the first choice for assessing the structural consequences of myocardial infarction owing to its wide availability and excellent cost-effectiveness balance. LV thrombus is identified as a discrete echocardiographic mass seen in the LV with well-defined margins that are distinct from the endocardium and seen throughout systole and diastole in an area with corresponding significant LV regional or global wall motion abnormalities (Figure 4). Unfortunately, routine TTE detects LV thrombus only based on anatomic appearance, resulting in low sensitivity. Compared with DE-CMR, the sensitivity and specificity of TTE in diagnosing LV thrombus were 33% and 91% in patients with impaired systolic function (LVEF < 50%). Intravenous echo contrast is frequently used during TTE to improve the diagnostic assessment of LV thrombus. Studies reported contrast echo sensitivity of 61–64% compared with 33–35% of non-contrast echo. Mural thrombus and small thrombus are still sub-optimally visualized by TTE.

Table 1. Summary of the characteristics of the LAA thrombus study.

| Source           | n   | Study population                        | Modality                  | CMR Protocol                     | Findings                                                                 |
|------------------|-----|-----------------------------------------|---------------------------|----------------------------------|--------------------------------------------------------------------------|
| Ohyama et al.    | 50  | NVAF or cardioembolic stroke            | CMR (1.5 T), TEE          | Double- and triple-IR sequence   | TEE identified 16 LAA thrombi; CMR identified 19 LAA thrombi             |
| Mohrs et al.     | 25  | NVAF                                    | CMR (1.5 T), TEE          | 2D True-FISP, 3D turbo FLASH      | TEE identified 17 LAA thrombi                                           |
| Rathi et al.     | 97  | NVAF                                    | CMR (1.5 T), TEE          | 2D non-contrast cine, 2D/3D contrast-enhanced CMR | TEE and CMR identified 2 LAA thrombi                                    |
| Kitkungvan et al.| 261 | NVAF                                    | CMR (1.5 T or 3.0 T), TEE | Cine, CE-MRA, long TI DE-CMR     | TEE identified 9 LAA thrombi                                           |

3D turbo FLASH, three-dimensional turbo fast low-angle shot; CE-MRA, contrast-enhanced magnetic resonance angiography; CMR, cardiac magnetic resonance; IR, inversion recovery; LAA, left atrial appendage; long TI DE, long inversion time delayed enhancement; NPV, negative predictive value; NVAF, nonvalvular atrial fibrillation; PPV, positive predictive value; Sn, sensitivity; Sp, specificity; TEE, transesophageal echocardiography; True-FISP, true fast imaging with steady state precession.
TEE has a limited role in the detection of LV thrombus because the apex is farthest from the transducer, and the apex is often foreshortened and not well visualized.\textsuperscript{66} In 361 patients with ischemic heart disease who had surgical and pathological confirmation of the presence (106, 29\%) or absence of LV thrombus, TEE showed 40 ± 14\% sensitivity and 96 ± 3.6\% specificity for thrombus detection.\textsuperscript{68}

CCT is a straightforward and widely available diagnostic tool with less operator/patient dependency compared with TTE.\textsuperscript{10} A quantitative study of 31 patients found that the CT attenuation of the myocardial wall was significantly higher than that of the thrombus.\textsuperscript{71} A threshold of 65 HU yielded sensitivity, specificity, and positive and negative predictive values of 94\%, 97\%, 94\%, and 97\%, respectively, to differentiate LV thrombus from the myocardial wall. A few case reports showed the use of CCT in detecting LV thrombus that was initially missed by echocardiography.\textsuperscript{72,73}

**CMR diagnosis of LV thrombus**

CMR is considered the reference technique in detecting LV thrombus.\textsuperscript{74} With a high spatial resolution for morphological definition of the LV thrombus and high soft-tissue contrast, CMR showed higher sensitivity for detecting LV thrombus when compared with TTE. A meta-analysis recently reported that the incidence of LV thrombus detected by CMR in ST-elevation myocardial infarction (STEMI) and anterior STEMI patients was 6.3\% and 12.2\%, respectively,\textsuperscript{11} which is more than twice the incidence reported by TTE.\textsuperscript{75} The study also showed that the sensitivity of TTE to detect LV thrombus was 29\% with a specificity of 98\%.\textsuperscript{11} In a retrospective study of 171 patients with a history of coronary artery disease, contrast-enhanced CMR sequences were compared with TTE for diagnostic accuracy.\textsuperscript{76} TTE revealed LV thrombus formation in 35 patients, while 43 were identified by CMR. LV thrombus was missed by TTE in one patient with an LVEF of 30–40\% and in seven patients with an LVEF <30\%. These results suggest that TTE may be suboptimal for diagnosis, particularly in significantly reduced ejection fraction. Srichai \textit{et al.}\textsuperscript{68} found that in 361 patients with surgically and pathologically confirmed presence or absence of LV thrombus, contrast-enhanced CMR provided the highest sensitivity and specificity (88 ± 9\% and 99 ± 2\%, respectively) compared with TTE and TEE. Among different CMR sequences, contrast-enhanced inversion recovery gradient-echo fast low-angle-shot sequence was found to be superior to dark-blood-prepared half-Fourier acquisition single-shot turbo spin-echo sequence and fast imaging steady-state free precession cine sequence in revealing intracardiac free precession sequence in revealing intracardiac thrombi.\textsuperscript{77} A systematic review analyzed seven studies and found that DE-CMR was the most accurate modality in detecting LV thrombus, with a sensitivity of 88\% and specificity of 99\%, followed by cine-CMR with a sensitivity of 58–79\% and specificity of 99\%.\textsuperscript{78} The result is in line with the study by Surder \textit{et al.}\textsuperscript{79} that DE-CMR was superior to cine-CMR in the detection of LV thrombus. The characteristics of the studies are summarized in Table 2. The detailed literature search strategy is shown in Figure 3.

CMR can also be used in evaluating the evolution of LV thrombus. In 194 STEMI patients who had undergone primary percutaneous coronary intervention (PCI) with stent implantation, CMR was performed at 2–7 days and repeated at 4 months after primary PCI.\textsuperscript{67} At baseline, 17 (8.8\%) patients had LV thrombus. At 4-month follow-up, LV thrombus persisted in only 2 of the original 17 patients but spontaneously occurred in an additional 12 patients. Another study of 392 STEMI patients showed that 5\% of the patients displayed LV thrombus at 1 week, three-quarters of which resolved by 6 months.\textsuperscript{80} Moreover, LV thrombus was newly detected in 2\% of the total patients at 6 months.

The use of CMR in evaluating the age of thrombus has also been explored, which may help assess the risk of embolism. An acute thrombus usually has intermediate signal intensity on both T1- and T2-weighted images, but it is rare to obtain MR images at the very acute phase. In the subacute phase, thrombus is typically T1- and T2-hyperintense. In chronic thrombi, the signal intensity decreases on both T1- and T2-weighted images (Figure 5). It has been shown that T1 mapping may differentiate between recent (<1 week) and old (>1 month) thrombi.\textsuperscript{81}

CMR has been investigated for its capability of detecting the cardioembolic sources of ischemic stroke.\textsuperscript{82} In a study of 106 patients (85 with ischemic stroke and 21 with transient ischemic attack), TTE detected LV thrombus in two patients, while two
Additional cases were detected after the use of cine- and DE-CMR. The value of contrast-enhanced CMR in etiology workup was further explored in a cohort of 797 consecutive ischemic stroke patients. Sixty patients who had previous myocardial infarction or LV dysfunction (LVEF <50%) underwent contrast-enhanced CMR, and LV thrombus was seen in 12 patients, whereas only 1 had been detected on TTE. The findings suggest that CMR might be a more sensitive diagnostic method for LV thrombus in the diagnostic workup in patients with potential cardioembolic stroke.

### Challenges of CMR in clinical practice

So far, no large prospective study involving multiple centers has compared the diagnostic value of CMR and conventional imaging modalities for intracardiac thrombus detection. There is also no consensus regarding the use of CMR for an...
efficient and comprehensive assessment of left heart intracardiac thrombus. Despite the high diagnostic accuracy of CMR, current barriers include long acquisition time and breath-holding, which can be difficult for severely ill patients. In addition, cost, availability, renal dysfunction, and technical expertise may also limit its widespread use. However, given these barriers to LA/LAA and LV thrombus detection, improving access and performance of CMR is critical, as well as identifying optimal patients for imaging by CMR.

Conclusion
Detection of intracardiac thrombus has a major impact on clinical care of patients with AF and patients at risk of LV thrombus, with changes in care necessary for protecting against cardioembolic morbidity and mortality. Our literature review suggests that CMR is the most accurate modality for detecting LV thrombus. Although echocardiography is currently the most widely used imaging modality in detecting LA/LAA thrombus, with the development of new techniques, CMR may provide an alternative diagnostic modality without the need for esophageal intubation, thus improving safety and patient comfort.

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References
1. Wendelboe AM and Raskob GE. Global burden of thrombosis: epidemiologic aspects. Circ Res 2016; 118: 1340–1347.

2. Lip GY, Hammerstingl C, Marin F, et al. Left atrial thrombus resolution in atrial fibrillation or flutter: results of a prospective study with rivaroxaban (X-TRA) and a retrospective observational registry providing baseline data (CLOT-AF). Am Heart J 2016; 178: 126–134.

3. Whitlock RP, Sun JC, Frenses SE, et al. Antithrombotic and thrombolytic therapy for valvular disease: antithrombotic therapy and prevention of thrombosis, 9th ed: American college of chest physicians evidence-based clinical practice guidelines. Chest 2012; 141(2Suppl): e576S–e600S.

4. Delevi R, Zijlstra F and Piek JJ. Left ventricular thrombus formation after acute myocardial infarction. Heart 2012; 98: 1743–1749.

5. Kirkpatrick JN, Wong T, Bednarz JE, et al. Differential diagnosis of cardiac masses using contrast echocardiographic perfusion imaging. J Am Coll Cardiol 2004; 43: 1412–1419.

6. Daniel WG and Mugge A. Transesophageal echocardiography. N Engl J Med 1995; 332: 1268–1279.

7. Bertrand PB, Levine RA, Isselbacher EM, et al. Fact or artifact in two-dimensional echocardiography: avoiding misdiagnosis and missed diagnosis. J Am Soc Echocardiogr 2016; 29: 381–391.

8. de Bruijn SF, Agema WR, Lammers GJ, et al. Transesophageal echocardiography is superior to transthoracic echocardiography in management of patients of any age with transient ischemic attack or stroke. Stroke 2006; 37: 2531–2534.

9. Hilberath JN, Oakes DA, Sherman SK, et al. Safety of transesophageal echocardiography. J Am Soc Echocardiogr 2010; 23: 1115–1127; quiz 1220–1221.

10. Doherty JU, Kort S, Mehran R, et al. ACC/AATS/AHA/ASE/ASNC/HRS/SCAI/SCCT/SCMR/STS 2019 appropriate use criteria for multimodality imaging in the assessment of cardiac structure and function in nonvalvular heart disease: a report of the American College of Cardiology Appropriate Use Criteria Task Force, American Association for Thoracic Surgery, American Heart Association, American Society of Echocardiography, American Society of Nuclear Cardiology, Heart Rhythm Society, Society for Cardiovascular Angiography and Interventions, Society of Cardiovascular Computed Tomography, Society for Cardiovascular Magnetic Resonance, and the Society of Thoracic Surgeons. J Am Coll Cardiol 2019; 73: 488–516.

11. Bulluck H, Chan MHH, Paradies V, et al. Incidence and predictors of left ventricular thrombus by cardiovascular magnetic resonance in acute ST-segment elevation myocardial infarction treated by primary percutaneous coronary intervention: a meta-analysis. J Cardiovasc Magn Reson 2018; 20: 72.

12. Vira T, Pechlivanoglou P, Connelly K, et al. Cardiac computed tomography and magnetic resonance imaging vs. transoesophageal echocardiography for diagnosing left atrial appendage thrombi. Europace 2019; 21: e1–e10.

13. Andrade J, Khairy P, Dobrev D, et al. The clinical profile and pathophysiology of atrial fibrillation: relationships among clinical features,
epidemiology, and mechanisms. Circ Res 2014; 114: 1453–1468.

14. Chugh SS, Havmoeller R, Narayanan K, et al. Worldwide epidemiology of atrial fibrillation: a Global Burden of Disease 2010 Study. Circulation 2014; 129: 837–847.

15. Wolf PA, Abbott RD and Kannel WB. Atrial fibrillation as an independent risk factor for stroke: the Framingham Study. Stroke 1991; 22: 983–988.

16. Beigel R, Wunderlich NC, Ho SY, et al. The left atrial appendage: anatomy, function, and noninvasive evaluation. JACC Cardiovasc Imaging 2014; 7: 1251–1265.

17. Ramlawi B, Abu Saleh WK and Edgerton J. The left atrial appendage: target for stroke reduction in atrial fibrillation. Methodist DeBakey Cardiovasc J 2015; 11: 100–103.

18. Gattellari M, Goumas C, Aitken R, et al. Outcomes for patients with ischaemic stroke and atrial fibrillation: the PRISM study (A program of research informing stroke management). Cerebrovasc Dis 2011; 32: 370–382.

19. Marini C, De Santis F, Sacco S, et al. Contribution of atrial fibrillation to incidence and outcome of ischemic stroke: results from a population-based study. Stroke 2005; 36: 1115–1119.

20. Kakkar AK, Mueller I, Bassand JP, et al. Risk profiles and antithrombotic treatment of patients newly diagnosed with atrial fibrillation at risk of stroke: perspectives from the international, observational, prospective GARFIELD registry. PLoS ONE 2013; 8: e63479.

21. Wu MS, Gabriels J, Khan M, et al. Left atrial thrombus despite continuous direct oral anticoagulant or warfarin therapy in patients with atrial fibrillation: insights into rates and timing of thrombus resolution. J Intero Card Electrophysiol 2018; 53: 159–167.

22. Jaber WA, Prior DL, Thamilarasan M, et al. Efficacy of anticoagulation in resolving left atrial and left atrial appendage thrombi: a transesophageal echocardiographic study. Am Heart J 2000; 140: 150–156.

23. Glikson M, Wolff R, Hindricks G, et al. EHRA/EAPCI expert consensus statement on catheter-based left atrial appendage occlusion – an update. Eurointervention 2020; 15: 1133–1180.

24. Calkins H, Kuck KH, Cappato R, et al. 2012 HRS/EHRA/ECAS expert consensus statement on catheter and surgical ablation of atrial fibrillation: recommendations for patient selection, procedural techniques, patient management and follow-up, definitions, endpoints, and research trial design: a report of the Heart Rhythm Society (HRS) task force on catheter and surgical ablation of atrial fibrillation. Developed in partnership with the European Heart Rhythm Association (EHRA), a registered branch of the European Society of Cardiology (ESC) and the European Cardiac Arrhythmia Society (ECAS); and in collaboration with the American College of Cardiology (ACC), American Heart Association (AHA), the Asia Pacific Heart Rhythm Society (APHRS), and the Society of Thoracic Surgeons (STS). Endorsed by the governing bodies of the American College of Cardiology Foundation, the American Heart Association, the European Cardiac Arrhythmia Society, the European Heart Rhythm Association, the Society of Thoracic Surgeons, the Asia Pacific Heart Rhythm Society, and the Heart Rhythm Society. Heart Rhythm 2012; 9: 632–696.

25. Piccini JP, Stevens SR, Lokhnygina Y, et al. Outcomes after cardioversion and atrial fibrillation ablation in patients treated with rivaroxaban and warfarin in the ROCKET AF trial. J Am Coll Cardiol 2013; 61: 1998–2006.

26. Fukuda S, Watanabe H, Shimada K, et al. Left atrial thrombus and prognosis after anticoagulation therapy in patients with atrial fibrillation. J Cardiol 2011; 58: 266–277.

27. Bertaglia E, Anselmino M, Zorzi A, et al. NOACs and atrial fibrillation: incidence and predictors of left atrial thrombus in the real world. Int J Cardiol 2017; 249: 179–183.

28. Niku AD, Shiota T, Siegel RJ, et al. Prevalence and resolution of left atrial thrombus in patients with nonvalvular atrial fibrillation and flutter with oral anticoagulation. Am J Cardiol 2019; 123: 63–68.

29. Kapa S, Martinez MW, Williamson EE, et al. ECG-gated dual-source CT for detection of left atrial appendage thrombus in patients undergoing catheter ablation for atrial fibrillation. J Interv Card Electrophysiol 2010; 29: 75–81.

30. Jaber WA, White RD, Kuzmiak SA, et al. Comparison of ability to identify left atrial thrombus by three-dimensional tomography versus transesophageal echocardiography in patients with atrial fibrillation. Am J Cardiol 2004; 93: 486–489.

31. Daniel WG, Erbel R, Kasper W, et al. Safety of transesophageal echocardiography. A multicenter survey of 10,419 examinations. Circulation 1991; 83: 817–821.
32. Gula LJ, Massel D, Redfearn DP, et al. Impact of routine transesophageal echocardiography on safety, outcomes, and cost of pulmonary vein ablation: inferences drawn from a decision analysis model. *EuroIntervention* 2010; 12: 1550–1557.

33. Wood MA, Wittkamp M, Henry D, et al. A comparison of pulmonary vein ostial anatomy by computerized tomography, echocardiography, and venography in patients with atrial fibrillation having radiofrequency catheter ablation. *Am J Cardiol* 2004; 93: 49–53.

34. Shrestha NK, Moreno FL, Narciso FV, et al. Two-dimensional echocardiographic diagnosis of left-atrial thrombus in rheumatic heart disease. A clinicopathologic study. *Circulation* 1983; 67: 341–347.

35. Kumar V and Nanda NC. Is it time to move on from two-dimensional tranesophageal to three-dimensional transthoracic echocardiography for assessment of left atrial appendage? Review of existing literature. *Echocardiography* 2012; 29: 112–116.

36. Sallach JA, Puwanant S, Drinko JK, et al. Comprehensive left atrial appendage optimization of thrombus using surface echocardiography: the CLOTS multicenter pilot trial. *J Am Soc Echocardiogr* 2009; 22: 1165–1172.

37. Agoston I, Xie T, Tiller FL, et al. Assessment of left atrial appendage by live three-dimensional echocardiography: early experience and comparison with tranesophageal echocardiography. *Echocardiography* 2006; 23: 127–132.

38. Karakus G, Kodali V, Inamdar V, et al. Comparative assessment of left atrial appendage by tranesophageal and combined two- and three-dimensional transthoracic echocardiography. *Echocardiography* 2008; 25: 918–924.

39. Kitayama H, Kiuchi K, Endo T, et al. Value of cardiac ultrafast computed tomography for detecting right atrial thrombi in chronic atrial fibrillation. *Am J Cardiol* 1997; 79: 1292–1295.

40. Shapiro MD, Neilan TG, Jassal DS, et al. Multidetector computed tomography for the detection of left atrial appendage thrombus: a comparative study with tranesophageal echocardiography. *J Comput Assist Tomogr* 2007; 31: 905–909.

41. Kim YY, Klein AL, Halliburton SS, et al. Left atrial appendage filling defects identified by multidetector computed tomography in patients undergoing radiofrequency pulmonary vein antral isolation: a comparison with tranesophageal echocardiography. *Am Heart J* 2007; 154: 1199–1205.

42. Hur J, Kim YJ, Nam JE, et al. Thrombus in the left atrial appendage in stroke patients: detection with cardiac CT angiography—a preliminary report. *Radiology* 2008; 249: 81–87.

43. Romero J, Husain SA, Kelesidis I, et al. Detection of left atrial appendage thrombus by cardiac computed tomography in patients with atrial fibrillation: a meta-analysis. *Circ Cardiovasc Imaging* 2013; 6: 185–194.

44. Spagnolo P, Giglio M, Di Marco D, et al. Diagnosis of left atrial appendage thrombus in patients with atrial fibrillation: delayed contrast-enhanced cardiac CT. *Eur Radiol* 2021; 31: 1236–1244.

45. Srichai MB, Barreto M, Lim RP, et al. Prospective-triggered sequential dual-source end-systolic coronary CT angiography for patients with atrial fibrillation: a feasibility study. *J Cardiovasc Comput Tomogr* 2013; 7: 102–109.

46. Ohyama H, Hosomi N, Takahashi T, et al. Comparison of magnetic resonance imaging and tranesophageal echocardiography in detection of thrombus in the left atrial appendage. *Stroke* 2003; 34: 2436–2439.

47. Mohrs OK, Nowak B, Petersen SE, et al. Thrombus detection in the left atrial appendage using contrast-enhanced MRI: a pilot study. *AJR Am J Roentgenol* 2006; 186: 198–205.

48. Rathi VK, Reddy ST, Anreddy S, et al. Contrast-enhanced CMR is equally effective as TEE in the evaluation of left atrial appendage thrombus in patients with atrial fibrillation undergoing pulmonary vein isolation procedure. *Heart Rhythm* 2013; 10: 1021–1027.

49. Kitkungvan D, Nabi F, Ghosn MG, et al. Detection of LA and LAA thrombus by CMR in patients referred for pulmonary vein isolation procedure. *JACC Cardiovasc Imaging* 2016; 9: 809–818.

50. Kim RJ, Wu E, Rafael A, et al. The use of contrast-enhanced magnetic resonance imaging to identify reversible myocardial dysfunction. *N Engl J Med* 2000; 343: 1445–1453.

51. McGann CJ, Kholmovski EG, Oakes RS, et al. New magnetic resonance imaging-based method for defining the extent of left atrial wall injury after the ablation of atrial fibrillation. *J Am Coll Cardiol* 2008; 52: 1263–1271.

52. Oakes RS, Badger TJ, Kholmovski EG, et al. Detection and quantification of left atrial structural remodeling with delayed-enhancement magnetic resonance imaging in patients with atrial fibrillation. *Circulation* 2009; 119: 1758–1767.

53. Akoum N, Daccarett M, McGann C, et al. Atrial fibrosis helps select the appropriate patient and
strategy in catheter ablation of atrial fibrillation: a DE-MRI guided approach. J Cardiovasc Electrophysiol 2011; 22: 16–22.

54. Marrouche NF, Wilber D, Hindricks G, et al. Association of atrial tissue fibrosis identified by delayed enhancement MRI and atrial fibrillation catheter ablation: the DECAAF study. JAMA 2014; 311: 498–506.

55. Akoum N, Fernandez G, Wilson B, et al. Association of atrial fibrosis quantified using LGE-MRI with atrial appendage thrombus and spontaneous contrast on transesophageal echocardiography in patients with atrial fibrillation. J Cardiovasc Electrophysiol 2013; 24: 1104–1109.

56. King JB, Azadani PN, Suksaranjit P, et al. Left Atrial Fibrosis and Risk of Cerebrovascular and Cardiovascular Events in Patients With Atrial Fibrillation. Am Coll Cardiol 2017; 70: 1311–1321.

57. Lip GY, Piotrponikowski P, Andreotti F, et al. Thromboembolism and anti thrombotic therapy for heart failure in sinus rhythm: an executive summary of a joint consensus document from the ESC Heart Failure Association and the ESC Working Group on Thrombosis. Thromb Haemost 2012; 108: 1009–1022.

58. Muhammad Tariq UR and Menon V. Left ventricular thrombus: a fading indication for anti-thrombotic therapy following myocardial infarction in the primary PCI era. Catheterization and Cardiovascular Interventions 2014; 83: S33.

59. Rabbani LE, Waksmonski C, Iqbal SN, et al. Determinants of left ventricular thrombus formation after primary percutaneous coronary intervention for anterior wall myocardial infarction. J Thromb Thrombolysis 2008; 25: 141–145.

60. Weinsaft JW, Kim HW, Crowley AL, et al. LV thrombus detection by routine echocardiography: insights into performance characteristics using delayed enhancement CMR. JACC Cardiovasc Imaging 2011; 4: 702–712.

61. Meurin P, Brandao Carreira V, Dumaine R, et al. Incidence, diagnostic methods, and evolution of left ventricular thrombus in patients with anterior myocardial infarction and low left ventricular ejection fraction: a prospective multicenter study. Am Heart J 2015; 170: 256–262.

62. Sharma ND, McCullough PA, Philbin EF, et al. Left ventricular thrombus and subsequent thromboembolism in patients with severe systolic dysfunction. Chest 2000; 117: 314–320.

63. Mooe T, Teien DE, Karp KH, et al. Dynamics of left ventricular thrombi in patients with acute anterior myocardial infarction treated with thrombolytics. Coron Artery Dis 1995; 6: 703–707.

64. Greaves SC, Zhi G, Lee RT, et al. Incidence and natural history of left ventricular thrombus following anterior wall acute myocardial infarction. Am J Cardiol 1997; 80: 442–448.

65. Grant MD, Mann RD, Kristenson SD, et al. Transthoracic echocardiography: beginner’s guide with emphasis on blind spots as identified with CT and MRI. Radiographics 2021; 41: 1022–1042.

66. Saric M, Armour AC, Arnaout MS, et al. Guidelines for the use of echocardiography in the evaluation of a cardiac source of embolism. J Am Soc Echocardiogr 2016; 29: 1–42.

67. Delewi R, Nijveldt R, Hirsch A, et al. Left ventricular thrombus formation after acute myocardial infarction as assessed by cardiovascular magnetic resonance imaging. Eur J Radiol 2012; 81: 3900–3904.

68. Srichai MB, Junor C, Rodriguez LL, et al. Clinical, imaging, and pathological characteristics of left ventricular thrombus: a comparison of contrast-enhanced magnetic resonance imaging, transthoracic echocardiography, and transesophageal echocardiography with surgical or pathological validation. Am Heart J 2006; 152: 75–84.

69. Weinsaft JW, Kim J, Medicherla CB, et al. Echocardiographic algorithm for post-myocardial infarction LV thrombus: a gatekeeper for thrombus evaluation by delayed enhancement CMR. JACC Cardiovasc Imaging 2016; 9: 505–515.

70. Weinsaft JW, Kim RJ, Ross M, et al. Contrast-enhanced anatomic imaging as compared to contrast-enhanced tissue characterization for detection of left ventricular thrombus. JACC Cardiovasc Imaging 2009; 2: 969–979.

71. Bittencourt MS, Achenbach S, Marwan M, et al. Left ventricular thrombus attenuation characterization in cardiac computed tomography angiography. J Cardiovasc Comput Tomogr 2012; 6: 121–126.

72. Nakao Y, Aono J, Namiguchi K, et al. Usefulness of contrast computed tomography for diagnosing left ventricular thrombus before impella insertion. J Cardiol Cases 2020; 22: 291–293.

73. Ouchi K, Nakamura F, Ikutomi M, et al. Usefulness of contrast computed tomography to detect left ventricular apical thrombus associated
with takotsubo cardiomyopathy. *Heart Vessels* 2016; 31: 822–827.

74. Dall’Armellina E, Karamitsos TD, Neubauer S, et al. CMR for characterization of the myocardium in acute coronary syndromes. *Nat Rev Cardiol* 2010; 7: 624–636.

75. Robinson AA, Jain A, Gentry M, et al. Left ventricular thrombi after STEMI in the primary PCI era: a systematic review and meta-analysis. *Int J Cardiol* 2016; 221: 554–559.

76. Staab W, Bergau L, Schuster A, et al. Detection of intracardiac masses in patients with coronary artery disease using cardiac magnetic resonance imaging: a comparison with transthoracic echocardiography. *Int J Cardiovasc Imaging* 2014; 30: 647–657.

77. Barkhausen J, Hunold P, Eggebrecht H, et al. Detection of intracardiac thrombi on MR imaging. *AJR Am J Roentgenol* 2002; 179: 1539–1544.

78. Roifman I, Connelly KA, Wright GA, et al. Echocardiography vs. Cardiac magnetic resonance imaging for the diagnosis of left ventricular thrombus: a systematic review. *Can J Cardiol* 2015; 31: 785–791.

79. Surder D, Gisler V, Corti R, et al. Thrombus formation in the left ventricle after large myocardial infarction – assessment with cardiac magnetic resonance imaging. *Swiss Med Wkly* 2015; 145: w14122.

80. Cambronero-Cortinas E, Bonanad C, Monneneu JV, et al. Incidence, outcomes, and predictors of ventricular thrombus after reperfused ST-segment-elevation myocardial infarction by using sequential cardiac MR imaging. *Radiology* 2017; 284: 372–380.

81. Caspar T, El Ghannudi S, Ohana M, et al. Magnetic resonance evaluation of cardiac thrombi and masses by T1 and T2 mapping: an observational study. *Int J Cardiovasc Imaging* 2017; 33: 551–559.

82. Baher A, Mowla A, Kodali S, et al. Cardiac MRI improves identification of etiology of acute ischemic stroke. *Cerebrovasc Dis* 2014; 37: 277–284.

83. Takasugi J, Yamagami H, Noguchi T, et al. Detection of left ventricular thrombus by cardiac magnetic resonance in embolic stroke of undetermined source. *Stroke* 2017; 48: 2434–2440.