Radiology: Cardiothoracic Imaging

REVIEW

Mitral Annular Disjunction: Review of an Increasingly Recognized Mitral Valve Entity

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Mitral annular disjunction (MAD) refers to atrial displacement of the hinge point of the mitral valve annulus from the ventricular myocardium. MAD leads to paradoxical expansion of the annulus in systole and may often be associated with mitral valve prolapse (MVP), leaflet degeneration, myocardial and papillary muscle fibrosis, and, potentially, malignant cardiac arrhythmias. Patients with MAD and MVP may present similarly, and MAD is potentially the missing link in explaining why some patients with MVP experience adverse outcomes. Patients with a 5 mm or longer MAD distance have an elevated risk of malignant cardiac arrhythmia compared with those with a shorter MAD distance. Evaluation for MAD is an important component of cardiac imaging, especially in patients with MVP and unexplained cardiac arrhythmias. Cardiac MRI is an important diagnostic tool that aids in recognizing and quantifying MAD, MVP, and fibrosis in the papillary muscle and myocardium, which may predict and help improve outcomes following electrophysiology procedures and mitral valve surgery. This article reviews the history, pathophysiology, controversy, prevalence, clinical implications, and imaging considerations of MAD, focusing on cardiac MRI.

Mitral annular disjunction (MAD) refers to atrial displacement of the hinge point of the mitral valve annulus from the ventricular myocardium (1). Although MAD was first described a few decades ago, our understanding is not comprehensive (2,3). MAD is prospectively seldom recognized without focused evaluation for this entity. Traditional modalities such as echocardiography are more commonly used in managing heart disease than are CT and MRI (4). Various groups have reported differing prevalence rates for MAD using different methods (5). MAD frequently coexists with mitral valve prolapse (MVP). Although MVP has a benign course in 90% or more of patients who have the disease, it is unclear why some develop adverse outcomes. For example, 5%–10% of patients develop chronic severe mitral valve incompetence requiring surgical correction. Also, ventricular arrhythmia–related sudden cardiac death occurs in up to 1% of younger individuals with MVP, with an estimated 0.2%–1.9% annual risk of sudden cardiac death despite no significant valvular incompetence or heart failure (6–9).

For unknown reasons, among the small group of patients with MVP who undergo catheter ablation, approximately one-third develop recurrent ventricular arrhythmias requiring either defibrillator implantation or repeat ablation procedures in the long term (10,11). Similarly, achieving satisfactory outcomes following mitral isthmus ablation in patients with perimitral atrial flutter is challenging (12). In addition to suboptimal patient outcomes, the financial implications of repeat cardiac ablations are not negligible, as one study estimates just more than $35 000 for the median readmission cost in patients with recurrent ventricular arrhythmia (13). Significant complications following ventricular ablations (4.4%), such as cardiac tamponade and death, are higher in patients with structural heart disease than those without (14). Moreover, the preoperative basal left ventricular (LV) annular dynamics in patients with MVP improves when annuloplasty is performed along with valve repair (15). Hence, realizing and addressing anatomic aberrations at the basal LV (the most common site of cardiac arrhythmias) is helpful in improving patient outcomes, as MAD may substantially contribute to adverse outcomes in patients with MVP.

MAD has been increasingly recognized in imaging, literature, and clinical practice in the last decade. However, literature on MAD is generally limited to small cohorts and suffers from selection bias. After identifying MAD at imaging, a clear understanding of clinically significant MAD, as well as its implications and pitfalls, would improve shared decision-making discussions and appropriate risk stratification. This review compiles the history, pathophysiology, controversy, prevalence, and current knowledge regarding the clinical relevance and imaging features of MAD to help cardiac imagers.

Normal Mitral Valve Apparatus

The normal mitral valve apparatus consists of the annulus, two leaflets with three scallops each, chordae tendineae, and papillary muscles (Fig 1) (16). The annulus is a saddle-shaped fibrous structure at the intersection of the left atrium, left ventricle, and mitral valve leaflets. The anterior annulus is continuous with the aortic valve annulus and is part of the fibrous skeleton of the heart (17). The

Abbreviations

HR = hazard ratio, LGE = late gadolinium enhancement, LV = left ventricle, MAD = mitral annular disjunction, MVP = mitral valve prolapse, TAD = tricuspid annular disjunction

Summary

Evaluation for mitral annular disjunction is an important component of cardiac imaging, especially in patients with mitral valve prolapse and unexplained cardiac arrhythmias.

Essentials

- Mitral annular disjunction (MAD) is an increasingly recognized entity of the mitral valve apparatus that frequently coexists with mitral valve prolapse (MVP).
- Patients with a 5 mm or longer MAD distance and late gadolinium enhancement at MRI may have an elevated risk for cardiac arrhythmia compared with patients with a shorter MAD distance.
- The survival figures of patients with MAD with or without coexisting MVP may be similar to those of patients with MVP alone.

Keywords

MR–Dynamic Contrast Enhanced, Cardiac, Mitral Valve, Mitral Annular Disjunction, Mitral Valve Prolapse, Floppy Mitral Valve, Cardiac MRI, Arrhythmia, Sudden Cardiac Death, Barlow Valve

posterior annulus is thin and more mobile. The normal mitral annulus contracts in systole, moving anteriorly and downward, and folds into a deep saddle configuration (18). The anterior leaflet is larger and thicker than the posterior and is contiguous with the fibrous tissue of the aortic valve's noncoronary cusp. The sail-shaped anterior mitral leaflet has lateral (A1), middle (A2), and medial (A3) scallops without defined anatomic boundaries between them. The crescentic posterior leaflet has a large attachment to the annulus and well-defined surface indentations separating it into the superolateral (P1), middle (P2), and inferoseptal (P3) scallops. The posterior leaflet with its annulus is attached to the highly mobile LV free wall.

The single-headed anterolateral and the double-headed posteromedial papillary muscles arise from the apical portions of the LV. Fibrous chordae tendineae originate from the tips of the papillary muscles and insert into the ventricular aspect of the mitral valve leaflets. The delicate and relatively rigid primary chordae tendineae attach to the free edges of the leaflets. The thicker and relatively mobile secondary tendineae attach approximately 1 cm (the "rough zone") away from the edges of the leaflets. The attachments between the papillary muscles, chordae tendineae, and leaflets work harmoniously to tether the leaflets and preserve coaptation during ventricular systole, and to prevent distortion and systolic anterior motion of the leaflets (16).

Mitral Annular Disjunction

History

In 1976, Gilbert et al (19) reported an atypical mitral annulus motion in 24 of 47 patients with echocardiography-proven MVP where the posterior annulus curled downward into the myocardium with minimal anterior motion. The authors found that the annulus was no longer aligned with the LV but conformed to the atrium—a phenomenon known as *annuloventricular decoupling* (20). In 1981, Bharati et al (2) described a case of sudden death by using clinical features, electrocardiography, and histologic analysis to highlight atrial migration of the mitral annulus as the cause. In 1986, Hutchins et al (21) examined 900 adult autopsies and observed abnormal annulus formation in 65 hearts; 23 hearts also had MVP. They described the annulus abnormality by coining a new term, *disjunction*. They found that the patients with MVP (n = 25) were older (68 years ± 3 [SD] vs 60 years ± 2, P < .05) than those with MAD without MVP (n = 42). As most hearts with MVP also had MAD (23 of 25), and the hearts with MAD without MVP were from younger patients, the authors suggested that MAD likely leads to MVP.

Pathophysiology

The outward curling of the posterior annulus increases annulus diameter during systole, myocardial stretch, incidence of poor coaptation, and myxomatous degeneration of the leaflets (1,22). The abnormal tugging on the submitral apparatus results in papillary muscle hypertrophy, myocardial hypertrophy, and eventual fibrosis, which likely serves as an arrhythmogenic substrate (23). Electrophysiologic studies in patients with MVP demonstrating that abnormal fractionated electrograms indicated slowed conduction and ventricular ectopy arising from the papillary muscles, LV outflow tract, and mitral annulus may support this theory (23,24).

Although the posterolateral annulus is frequently implicated in MAD, by using MRI data from 83 patients, Dejgaard et al (25) reported that MAD is most frequently located in the LV anterior wall (28%), inferior wall (26%), or, less commonly, posterolateral wall (9%). MAD median circumferential extent was 150° (range, 30° to 240°), with the extent exclusively along the posterior mitral leaflet.

Controversy

It is currently unknown if MAD is a congenital or an acquired entity. If MAD is congenital, it is unknown if the embryologic attachment of the annulus hinge point in the atrial tissue instead of the ventricular myocardium is abnormal. If it is an acquired entity, it is unclear whether MAD or MVP is the cause, if they are the result of each other, or if they are both within the spectrum of the same disease; however, there are reports of MAD in young patients without mitral valve disease. An MAD distance of 3 mm or less may be a benign finding (21,26). There is no established definition of MAD regarding the extent of annulus involvement and the displacement distance threshold. Hence, it is also unknown whether every MAD is pathologic or if this finding can be within the range of normal variation. It is also unclear if this entity is the same or related to the previously described zone under the mitral valve known as the *subvalvular membrane* (17). Dystrophic calcification is also frequently observed in the mitral annulus (27), and it is unknown if this finding is related to MAD.

The medical community is currently debating whether MAD is an anatomic variation observed in many or a clinically relevant

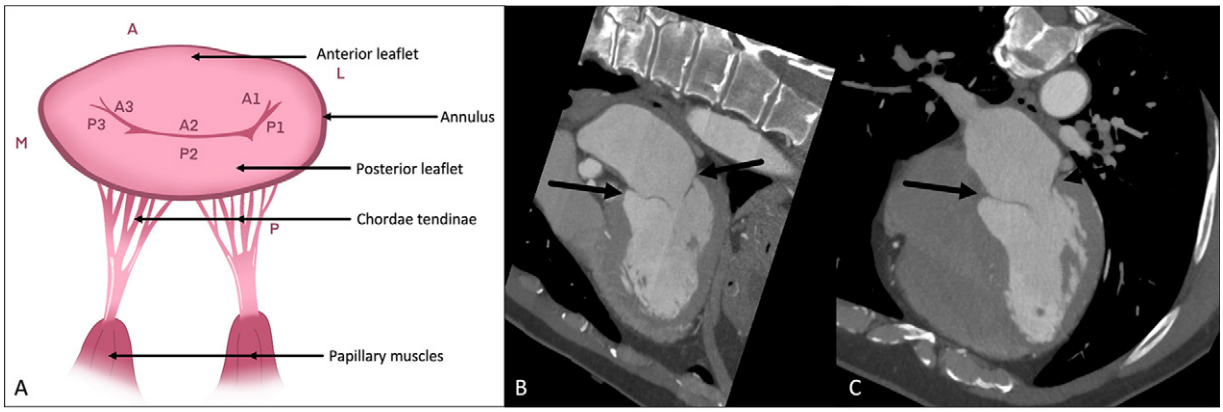


Figure 1: **(A)** A schematic of the normal mitral valve apparatus with annulus, leaflets, chordae tendineae, and papillary muscles. A1–A3: anterior, middle, and medial scallops of the anterior valve leaflet. P1–P3: superolateral, middle, and inferoseptal scallops of the posterior mitral valve leaflet (A = anterior, L = lateral, M = medial). **(B)** Two-chamber and **(C)** four-chamber CT images of the mitral valve leaflet insertion to the top of the left ventricular myocardium denote the normal anatomy of the mitral annulus (arrows in **B** and **C**).

entity observed in a few. Ventricular fibrillation seems correlated with a fraction of patients with MAD; however, our understanding of the causative mechanisms of MAD-related cardiac arrhythmia is primitive (28). Modern CT and MRI techniques have evolved from earlier years, with higher spatial, contrast, and temporal resolution depicting exquisite anatomic details. As a result, we may appreciate fine anatomic details more than before, capturing a large cohort of clinically insignificant MAD. For example, Toh et al (26) found that almost all (96%) of 98 patients with structurally normal hearts had CT-proven MAD (3 mm; range, from 1.5 to 7 mm), predominantly involving P1 and P3 scallops. Similarly, using 1 mm or longer to diagnose MAD at MRI, Zugwitz et al (29) reported that 76% of 2607 participants from the U.K. nationwide Biobank study had at least one MAD site. With a low number of arrhythmias (only six individuals), the authors found no significant association between MAD and arrhythmia. These studies illustrate the high prevalence of insignificant MAD in the population, mainly if a lower distance threshold was used to diagnose MAD. It is essential to appreciate that imaging modalities may not match microscopic histologic tissue details, making it challenging to exhibit MAD's displaced leaflet hinge point accurately. Specific characteristics of MAD, such as a longer MAD distance (5 mm or longer), may be relevant to recognize the clinically significant MAD cohort. Also, because MAD is intertwined with MVP, an unknown number of MAD cases may be annulus remodeling due to MVP-related abnormal mechanics of the valve apparatus. Hence, our understanding of MAD may evolve, similar to how noncompaction cardiomyopathy evolved from being considered fatal cardiomyopathy in earlier publications to a remodeling epiphenomenon that occurs in conjunction with cardiomyopathy.

Prevalence

Various groups have reported differing prevalence for MAD and coexisting MVP using various cohorts, modalities, and thresholds (5). The reported prevalence of MAD in the general population is 7.2%–8.7% and is higher in young women (25,30,31). Based on postmortem studies, MAD is present in 16% to 92% of patients with MVP, although more recent studies report 30% MAD prevalence in patients with MVP (21,30–33), amounting to 1 to 2 million patients among the 3 to 6 million patients with MVP in the United States. However, based on the definitions used, the prevalence of MAD will vary, and the prevalence of clinically significant MAD is likely low and not yet established. These figures and subsequent studies show that MAD and MVP commonly coexist and are closely related (Fig 2).

Clinical Implications

While MAD can be an incidental isolated imaging finding (Fig 3) (30), MAD and MVP coexist in many patients; hence, symptoms, clinical findings, and risks related to MAD may overlap with those of patients with MVP. Patients may present with palpitations, chest pain, syncope, and arrhythmias (Figs 4, 5) (25,31). MAD electrocardiography findings are nonspecific and include biphasic or inverted T waves, ST-segment depression, QT interval prolongation, right bundle branch block, polymorphic ventricular tachycardia, QRS-T wave discordance in the inferior leads, and paroxysmal ventricular contractions. Electroanatomic mapping may show low voltage fractionated complexes in the relatively hypertrophied LV basal myocardium (basal to mid LV lateral wall thickness ratio, 1.5), a finding said to be present in patients with MAD (22). The Table presents the key findings from some of the publications relating ventricular arrhythmia and MAD.

Although the clinical implications of MAD have remained controversial for years, the relation between MAD and ventricular arrhythmia is increasingly recognized in the literature, particularly in patients with a greater extent of MAD and late gadolinium enhancement (LGE) (34) at cardiac MRI. Perazzolo Marra et al (22) compared patients with arrhythmic MVP with (n = 36) and without LGE (n = 16) at cardiac MRI. The LGE-positive group had statistically significant higher MAD distance (4.8 mm vs 1.8 mm) and mitral annulus diameters and greater posterior annulus curling and posterobasal LV relative thickness. Since then, MAD-related arrhythmia has also been reported by

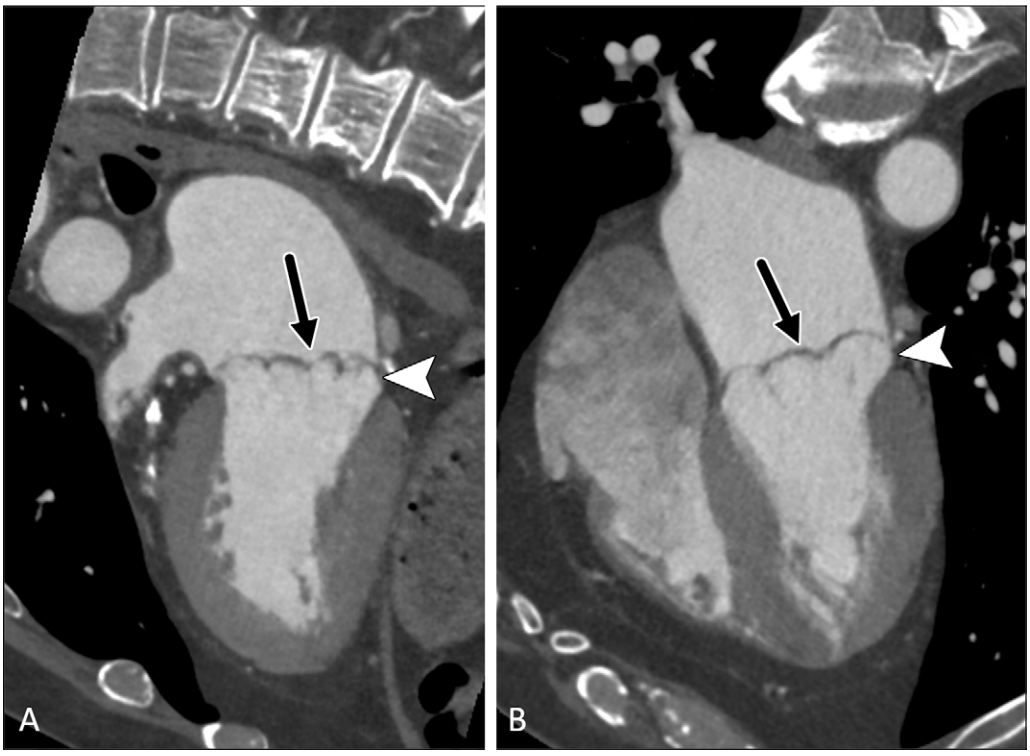


Figure 2: Images in a 73-year-old male patient who presented with chest pain and underwent workup for acute coronary syndrome. Cardiac CT angiograms show incidental mitral valve prolapse with thickening and prolapse of the mitral valve leaflets (black arrow) and 7-mm disjunction of the posterior mitral annulus (white arrowhead), as shown on the end-systolic **(A)** two-chamber and **(B)** four-chamber view images.

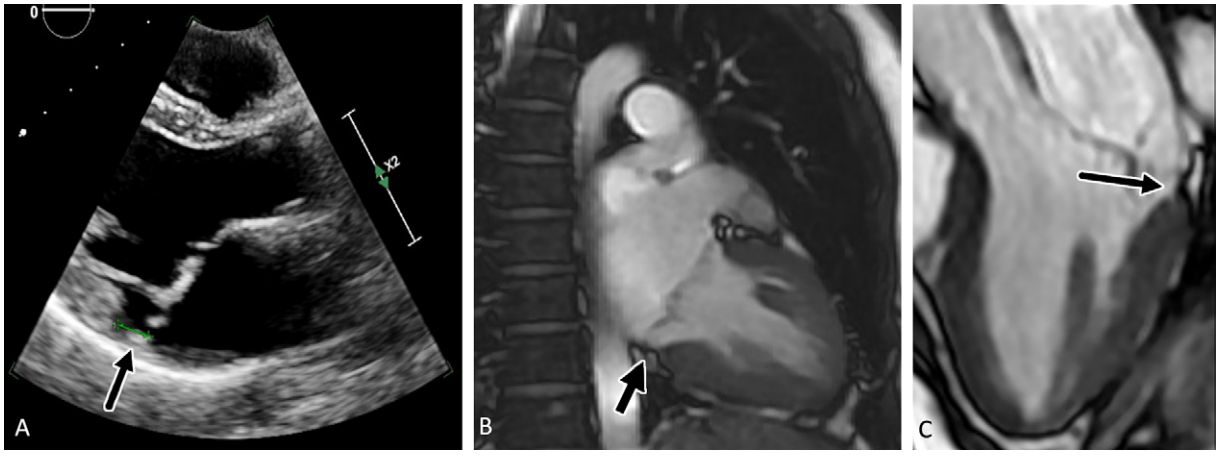


Figure 3: Images in a 24-year-old asymptomatic female patient with mitral valve prolapse diagnosed at 3 years of age. **(A)** Her electrocardiogram showed normal sinus rhythm. A three-chamber view at echocardiography showed a 10-mm gap between the mitral valve hinge point and left ventricular myocardium (black arrow). On the **(B)** two-chamber and **(C)** three-chamber views of cine steady-state free precession cardiac MRI, this gap was confirmed in the end-systolic phase and measured 6 mm (black arrow).

others, with the reasoning that abnormal annular motion and leaflet traction result in increased myocardial stress, degeneration of the valve, and myocardial stretch of the posterior-basal LV and papillary muscles.

A recent study on a large (n = 595) cohort of patients with echocardiographically diagnosed MVP compared cohort characteristics and long-term (10.3 years ± 3.0) survival of patients with (n = 186) and without MAD (n = 409) (31). Patients with MAD were younger, had significantly larger LV systolic diameters, marked leaflet redundancy (odds ratio, 2.9 [95% CI: 1.9, 4.2]), and bileaflet MVP (odds ratio, 5.18 [95% CI: 3.4, 7.9]) in a multivariable analysis compared with those without MAD. The authors found no close link between MAD and flail leaflets or significant mitral valve incompetence. Also, after balancing the cohorts, there was no evidence of a survival difference between patients with and without MAD. However, compared with patients without MAD, patients with MAD had a significantly higher risk for arrhythmia (hazard ratio

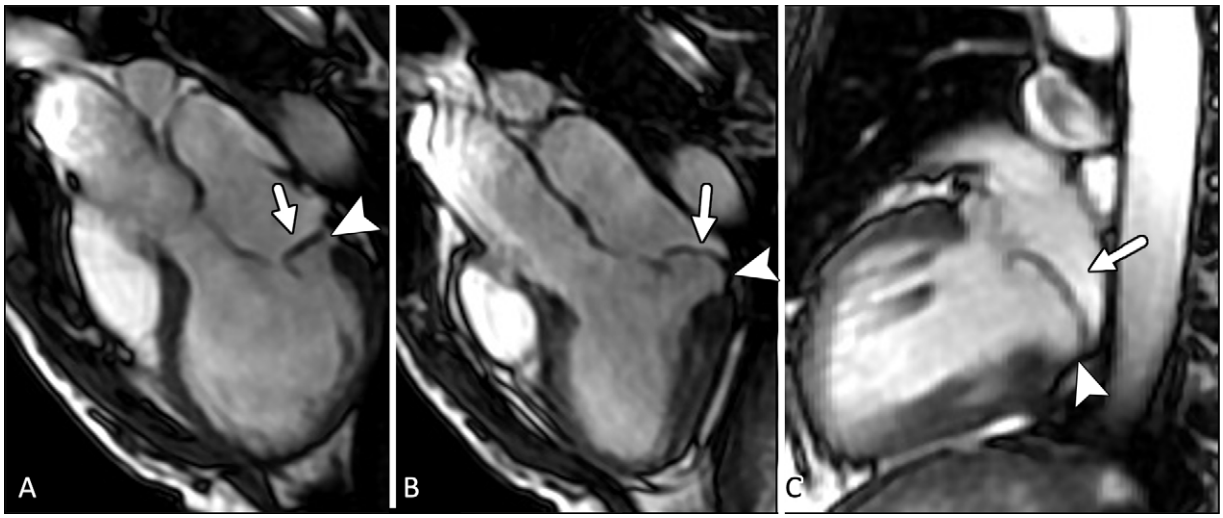


Figure 4: Images in a 43-year-old female patient with mitral valve prolapse who presented with supraventricular tachycardia. Three-chamber **(A)** end-diastolic and **(B)** end-systolic and **(C)** two-chamber end-systolic views from cine steady-state free precession cardiac MRI demonstrate mitral annular disjunction with a distance of 6 mm (white arrowhead). The mitral valve leaflets were thickened and redundant with 15-mm prolapse (white arrow) of the posterior leaflet.

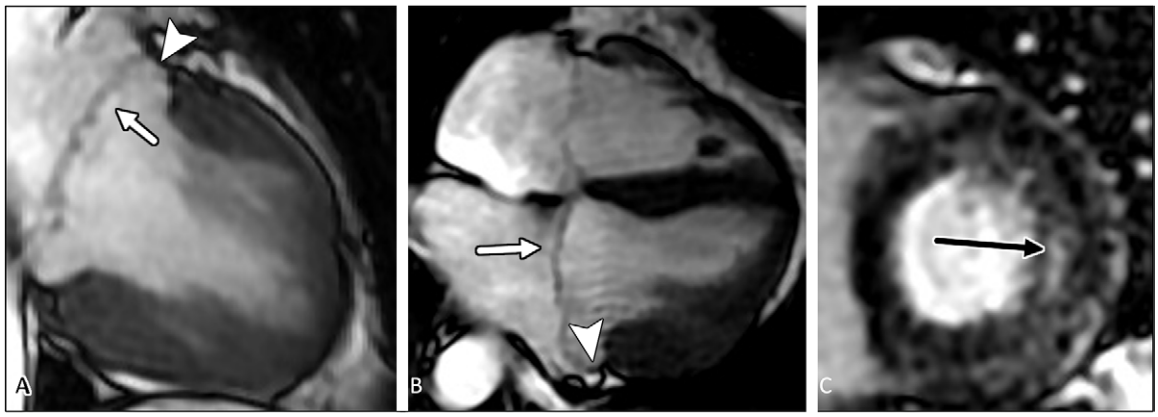


Figure 5: Images in a 40-year-old male patient with near-syncopal episodes, normal sinus rhythm, and T wave inversions at resting electrocardiography. Transthoracic echocardiography showed normal left ventricular function and stable (for 6 years) moderate mitral incompetence, prolapse, and myxomatous valve leaflets. Outpatient Holter monitoring demonstrated infrequent atrial and ventricular ectopy. End-systolic **(A)** two-chamber and **(B)** four-chamber cine steady-state free precession cardiac MRI views helped confirm echocardiography findings of bileaflet prolapse (white arrow) (7 to 10 mm). The images also showed a 7-mm mitral annular disjunction with paradoxical outward curling of the annulus (white arrowhead). **(C)** There was minimal midmyocardial focal late gadolinium enhancement in the inferolateral basal left ventricle, as observed on the short-axis image (black arrow).

[HR], 2.2 [95% CI: 1.5, 2.9]), and risk remained high despite medical management (HR, 2.5 [95% CI: 1.7, 3.8]) but slightly reduced after mitral surgery (HR, 1.5 [95% CI: 0.9, 2.4]). The risk persisted after adjusting for relevant demographic and clinical variables.

Dejgaard et al (25) reviewed a cohort of 116 patients with MAD. They reported 14 patients with severe arrhythmia (10 with aborted cardiac arrests and four with sustained ventricular tachycardia) and 40 patients with an arrhythmia independent of coexisting MVP. They found severe arrhythmias in MAD in younger patients and patients with lower LV ejection fraction, MVP, and papillary muscle fibrosis (25). They also found the posterior wall MAD distance (5 mm) and papillary muscle LGE at cardiac MRI as markers of cardiac arrhythmia on multivariable analysis. Scheirlynck et al (35) reported that 31% of 72 patients with MAD had ventricular arrhythmias. Those who developed arrhythmia also had statistically higher biomarker levels of soluble suppression of tumorigenicity 2, a marker of myocardial stretch, and higher papillary muscle LGE prevalence at cardiac MRI compared with those who did not develop arrhythmias (64% vs 20%).

Van Wijngaarden et al (36) reported that among patients with MVP who had echocardiography-proven MAD (133 of 610, 22%), a cohort of patients with ventricular arrhythmia (26 of 67, 39%) had a longer MAD distance (8 mm vs 7 mm) compared with the nonarrhythmia group (107 of 543, 20%). The proportion of patients with MAD plus MVP was higher in patients with arrhythmia (26 of 67, 39%) than in the nonarrhythmia group (107 of 543, 20%). Similarly, the proportion of patients with dysfunctional annular curling formation plus MVP was higher in those with arrhythmia (42 of 67, 63%) than in the nonarrhythmia group (213 of 543, 39%).

Studies with More than 50 Participants that Linked Cardiac Arrhythmia, MAD, and Cardiac MRI or Echocardiography

Authors and Publication Year	Study Sample	No. of Participants	Other Key Findings
Perazzolo Marra et al 2016 (22)	MVP with arrhythmia	52	Group with LGE (35 of 52 of patients with MVP with arrhythmia) had longer MAD distance (4.8 mm vs 1.8 mm) than the group without LGE; there was a significant correlation (R = 0.61) between MAD distance and LGE percentage
Dejgaard et al 2018 (25)	MAD	116	MAD without and with severe VA; severe VA in younger patients (OR, 0.93 [95% CI: 0.87, 0.97]; P = .002), low LVEF (OR, 0.86 [95% CI: 0.77, 0.96]; P = .008), and MVP (OR, 0.22 [95% CI: 0.06, 0.75]; P = .02) Marker of VA: LGE in anterior papillary muscle (OR, 7.35 [95% CI: 1.15, 47.02]; P = .04)
Scheirlynck et al 2019 (35)	MAD	72	More frequent papillary muscle LGE (64% vs 20%) in patients with VA than patients without VA (P < .001), with an OR of 7.26 (95% CI: 2.3, 22.5) (P = .001)
Essayagh et al 2021 (31)	MVP	595	MAD was linked with VA, younger age, and abnormal mitral valve formation Similar 10-year OS (97% vs 93%) between matched patients with MVP with and without MAD No excess mortality due to MAD (HR, 0.64); also, similar OS between patients with MVP without and with MAD after adjusting for LV size, bileaflet MVP, leaflet redundancy, and mitral regurgitation grade (HR, 1.20; P = .8) Ten-year freedom from VA events was lower (43% vs 66%, P < .0001) with MAD than without MAD, with a strong and independent link between VA and MAD (HR, 2.31; P < .0001)
Van Wijngaarden et al 2021 (36)	MVP without and with VA	610 (543 without VA, 67 with VA)	Compared with the group without VA, the group with VA had a higher proportion of MAD (26 of 67 = 39% vs 107 of 543 = 20%, P < .001) and longer MAD distance (8 mm vs 7 mm, P = .035)
Figliozzi et al 2023 (37)	MVP without significant mitral valve regurgitation or LV dysfunction	474	Higher MAD proportion with bileaflet MVP than without (170 of 321 = 53% vs 55 of 153 = 36%, P < .001) Higher LGE proportion with bileaflet MVP than without (78 of 104 = 75% vs 147 of 370 = 40%, P < .001) Group with LGE had a longer MAD distance than the group without LGE (5.9 mm vs 3.1 mm, P = .001) Compared with the group without LGE, the group with LGE had more adverse events (10 of 104 = 10% vs eight of 370 = 2%, P < .001); also, adverse events were strongly linked with LGE presence (HR, 4.2; P < .006) and extent (HR, 1.2 per 1% increase; P < .006) but not the presence of MAD (P = .89)
Groeneveld et al (53)	Patients with VA vs controls	72	MVP and inferolateral MAD (2 mm or more) were more prevalent in patients with VA than in controls (11% vs 1%, P = .024; 72 patients)

Note.—HR = hazard ratio, LGE = late gadolinium enhancement, LVEF = left ventricle ejection fraction, MAD = mitral annular disjunction, MVP = mitral valve prolapse, OR = odds ratio, OS = overall survival, VA = ventricular arrhythmia.

Investigators from 15 tertiary European centers (118 144 cardiac MRI examinations) reported their findings on patients with MVP without significant mitral regurgitation or LV dysfunction (474 patients; age, 47 years ± 16; 244 women; mean follow-up time, 3.3 years) to improve understanding of the risk profile in MVP (37). They found that LGE (HR, 4.2; P = .006) and the extent of LGE (HR, 1.2 per 1% increase; P = .006) may indicate more adverse events (sustained ventricular tachycardia, sudden cardiac death, and unexplained syncope) than does MAD (P = .89). However, the patients with MAD were significantly younger and experienced more symptoms, ventricular arrhythmia, and bileaflet prolapse than those without MAD. The patients with LGE (n = 104) also had significantly longer MAD (5.9 mm vs 3.1 mm, P = .001) than those without LGE (n = 370).

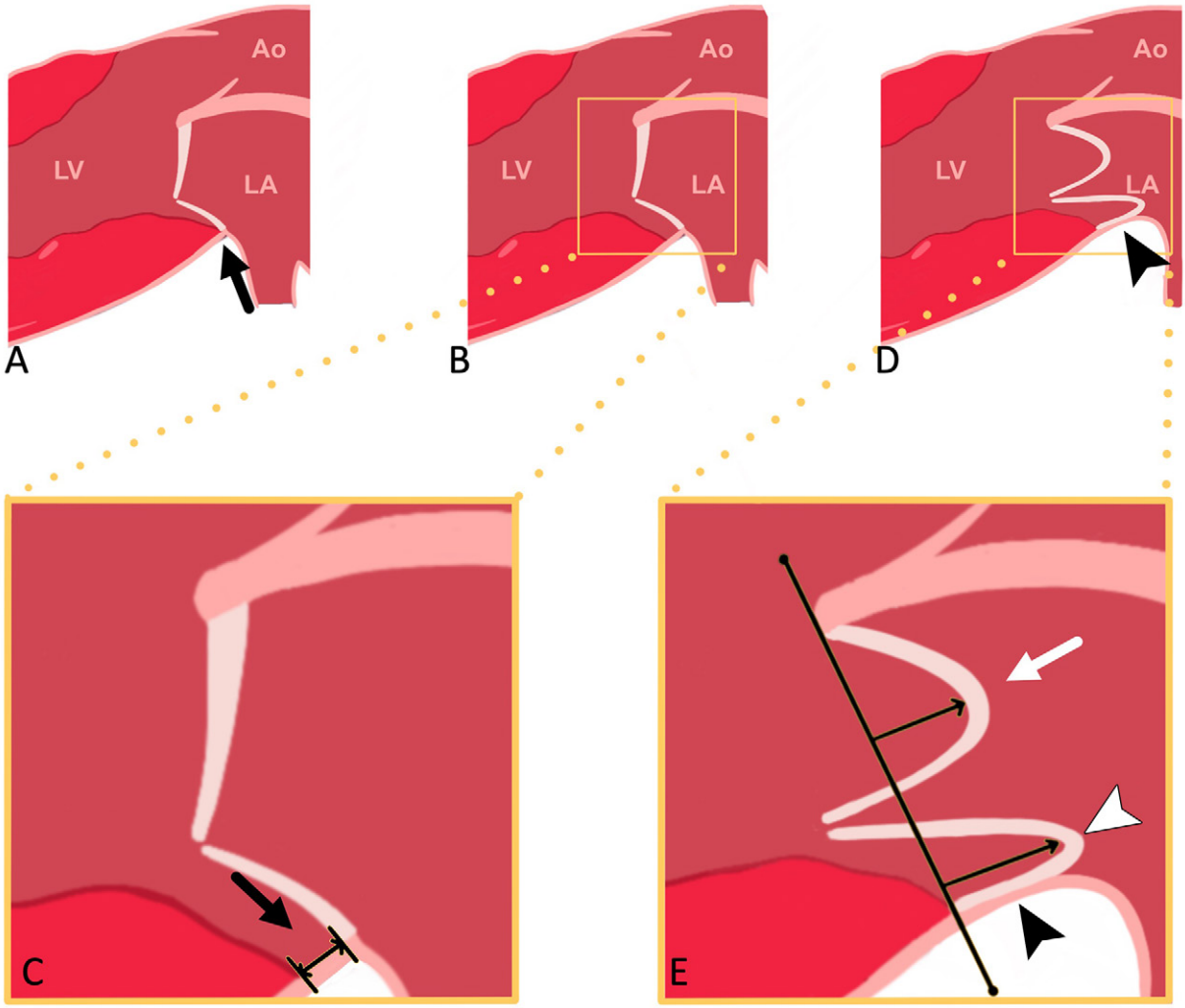


Figure 6: Schematic illustration of the atrioventricular junction during LV systole. **(A)** The leaflet hinge point in the normal position at the top of the basal LV (black arrow). **(B)** Mitral annular disjunction (MAD) with a displaced hinge point to the LA away from the normal position. **(C)** Magnified view of MAD with a caliper measuring MAD distance (black arrow). **(D)** Mitral valve prolapse (MVP) with bileaflet prolapse. **(E)** Magnified view of MVP with measurement of the anterior leaflet (white arrow) and posterior leaflet (white arrowhead) from the basal mitral annulus plane (depicted by a black line connecting the anterior and posterior leaflet). **D** and **E** also illustrate a folded posterior mitral leaflet along the LA wall mimicking the displaced hinge point, also known as *pseudo-MAD* (black arrowhead). Ao = aorta, LA = left atrium, LV = left ventricle.

MAD may also occur with concomitant tricuspid annular disjunction (TAD) (38). Aabel et al (39) reported a 50% incidence of TAD in 84 patients with MAD. Patients with MAD and TAD had a greater circumferential extent and distance of MAD and a higher incidence of MVP than patients without TAD. However, patients with TAD did not have added arrhythmia risk, and TAD was not associated with tricuspid valve incompetence. There are reports of MAD in patients with connective tissue disorders, such as Marfan and Loeys-Dietz syndromes (40,41).

Although we may need to consider the need and the implications of customizing surgical (valve or annulus), transcatheter mitral valve repair, and electrophysiologic procedural techniques in patients with MAD, the outcomes of such modifications have yet to be established (42–44). Hence, the primary focus of managing patients with MAD is coexisting mitral valve diseases and arrhythmia risk rather than MAD, as the benefit-risk profile for specifically addressing MAD is yet unknown, especially in the absence of mitral valve disease or arrhythmia.

Imaging Considerations

Measurements

MAD is irrevocably intertwined with MVP in many. The definition of MVP is a single or bileaflet prolapse at least 2 mm beyond the long-axis annular plane, with or without mitral leaflet thickening (45). Leaflet prolapse with thickening of the leaflets of more than 5 mm is called *classic MVP*. Due to the saddle-shaped formation of the mitral annulus, the three-chamber (parasternal long axis) plane is typically used in echocardiography to diagnose and quantify leaflet prolapse to avoid overdiagnosing MVP (46). The prolapsed leaflet in MVP is measured as the distance between the top of the prolapsed portion of the leaflet during peak systole to the mitral annulus plane, which is at the top of the basal-LV myocardium (Fig 6). In the presence of MAD, the method for measuring the prolapsed leaflet height may be controversial, as the mitral valve annulus plane is displaced, and may be subjective. After ensur-

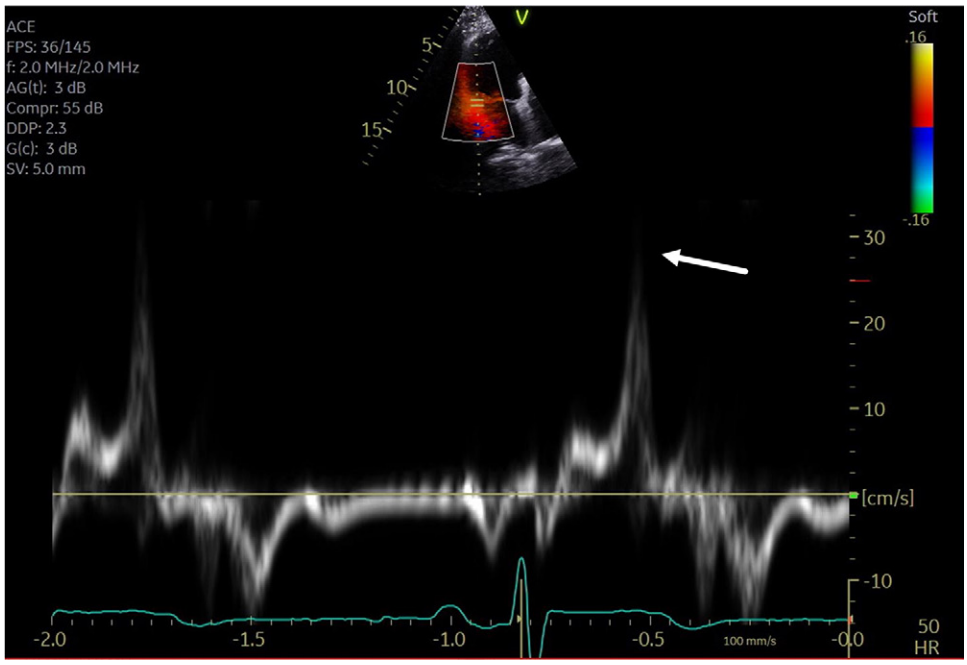


Figure 7: Pickelhaube sign at tissue Doppler imaging. A high-velocity midsystolic spike of the mitral valve annulus (more than 16 cm/sec) resembles a German military helmet with a spike (arrow).

ing MAD is genuinely present by establishing the displaced hinge point, MAD distance can be measured parallel to disjunction as the distance between the hinge point in the atrial wall to the top of the basal-LV myocardium. MAD's anterior and inferior annulus locations may be more common than the inferolateral annulus location. However, the inferolateral location is more associated with MVP and cardiac arrhythmia (29). In the absence of established consensus or guidelines for MAD, we suggest analyzing cine images throughout the cardiac cycle, in long-axis (two-, three-, and four-chamber view) planes, to recognize and confirm MAD. We also recommend using the three-chamber view in systole to measure MAD distance in a standardized manner. Short-axis images also help appreciate the radial extent of MAD; however, this can be challenging, with atrioventricular junctional structures moving in and out of the imaging section. The schematic in Figure 6 (B and C) illustrates measurement methods in MVP and MAD. Because CT images are typically volumetric and have higher spatial resolution than MR images, appreciating the entire extent and measurements may be more accurate.

It is essential to differentiate MAD from pseudo-MAD. The prolapsing mitral valve leaflet can fold during systole and be juxtaposed along the left atrial wall to mimic the displaced hinge point despite the hinge point being still attached to the top of the basal-LV myocardium (pseudo-MAD) (Fig 6D, 6E) (47). On the contrary, the hinge point would be anatomically displaced to the left atrial wall in actual MAD. At the same time, true MAD's thin mitral annulus tissue may collapse over the top of the LV myocardium during diastole, which could either minimize or hide the anatomically displaced hinge point. MAD distance is typically longer in the systolic phase and shorter in the diastolic phase. In the context of no established consensus or guidelines, the risk of overdiagnosing MAD by relying solely on the systolic phase images may be balanced against the underdiagnosis risk of relying only on diastolic images. Evaluating images obtained throughout the cardiac cycle may be necessary to confirm that the mitral valve leaflet-annulus hinge point has, anatomically, indeed displaced away from the top of the basal-LV myocardium to the left atrial wall. Mitral annulus pseudoaneurysm as a complication following mitral valve surgery, infective endocarditis, and myocardial infarction may also mimic MAD (48,49). Hence, it is necessary to correlate with clinical presentation and prior cardiac surgical history.

Transthoracic echocardiography is usually the first modality used in screening for MAD. In an extensive retrospective analysis, Konda et al (30) reported 2 mm as the minimum echocardiographically measurable distance; hence, a smaller MAD distance may not be reliably reproducible. Echocardiographic diagnosis of MAD may be straightforward if the MAD distance is 6 mm or greater (23,50). Specific evaluation for MAD with transesophageal echocardiography may be necessary for young patients with MVP, mitral incompetence, and arrhythmias (50). Studies found no correlation between MAD and the severity of mitral valve incompetence (1,30,31). In tissue Doppler evaluation, a high velocity midsystolic spike of the mitral valve annulus (more than 16 cm/sec) resembles a German military helmet with a spike, called the *Pickelhaube sign* (Fig 7) (51). Transesophageal echocardiography seems to have improved performance compared with transthoracic echocardiography (31,32).

MRI Recommendations

MRI scan parameters must be optimized to appreciate the thin membranous mitral annulus tissue and leaflets. Adapting the recommended imaging protocols by the Society of Cardiovas-

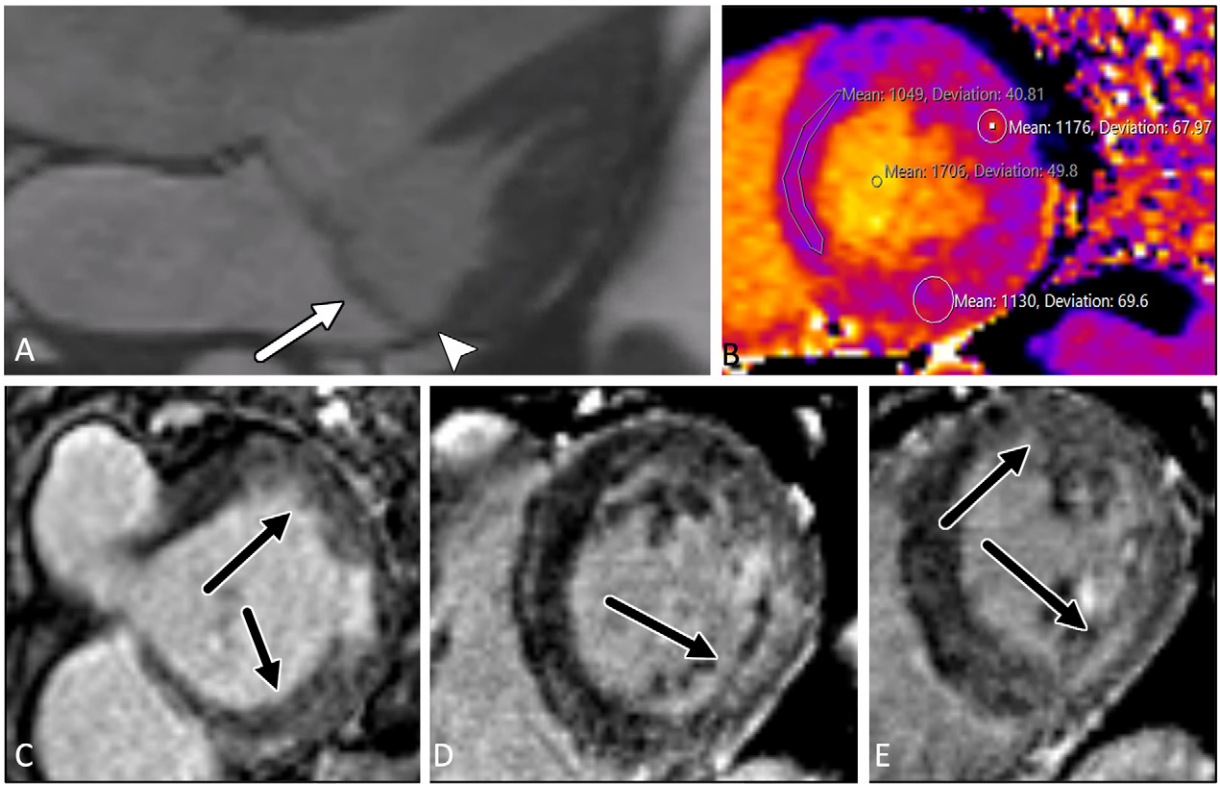


Figure 8: Images in a 55-year-old female patient with frequent episodes of presyncope and syncope diagnosed with systolic dysfunction, high premature ventricular complex (PVC) burden after ablation (20%), nonsustained ventricular tachycardia, and mitral regurgitation. **(A)** As measured on the three-chamber view cardiac MR image, there was mitral valve prolapse (white arrow) and 8 mm of mitral annular disjunction (white arrowhead). **(B)** Precontrast T1 map demonstrates increased native T1 values in the basal inferior (1130 msec) and lateral (1176 msec) walls. **(C-E)** There was extensive delayed gadolinium enhancement in the basal inferolateral and lateral walls and the papillary muscle (black arrows) on delayed postcontrast images. This was partially from prior PVC ablation but may also be due to underlying fibrosis.

cular MRI, we suggest a stack of contiguous long-axis plane (two-, three-, and four-chamber long-axis) bright-blood cine MR images perpendicular to the mitral annulus, with a section thickness of 5 mm without a gap covering the entire annulus, with a temporal resolution of approximately 45 msec or less. Cardiac MRI comprehensively helps evaluate MAD and helps risk stratification (25,32). At cardiac MRI, the reported range of annulus displacement is 1 to 15 mm (25), with a more significant displacement likely associated with malignant arrhythmias and sudden cardiac death (23). The reported range of the extent of MAD involvement at cardiac MRI is 30° to 240° of the mitral annulus (16,25,32), although discrete areas of MAD may be interspersed with normal annular tissue (25). Not surprisingly, one study reported a significant linear correlation (r = 0.85) between the MAD distance with annulus curling and the extent of LGE (22). Additionally, there may be relative hypertrophy of the LV inferior-basal wall compared with the midportion of the LV and reduced left atrial size and volume (5,18,30).

In addition to standard cardiac MRI reporting for patients with MAD, it would be helpful to include the distance of MAD, leaflet prolapse height, and presence of MVP, single or bileaflet prolapse, flail leaflets, paradoxical outward curling of the annulus, basal LV hypertrophy, and LGE of LV myocardium and papillary muscles. However, arrhythmias may occur even in the absence of abnormal LGE. In a retrospective study with 30 patients, Pavon et al (52) demonstrated that increased myocardial extracellular volume in the basal segments, indicating interstitial fibrosis, correlated with MAD distance and risk of cardiac arrest, even in the absence of LGE. Hence, cardiac MRI for LGE and parametric myocardial mapping may also benefit patients with MAD (Figs 8, 9). Figure 10 provides an approach for recognizing MAD correlated with elevated risk of cardiac arrhythmia.

Conclusion

MAD is an increasingly recognized entity associated with MVP and may substantially impact patient management because of its arrhythmogenic potential. However, more work needs to be done in stratifying patients with MAD—specifically, establishing a displacement cutoff value, early identification of patients at risk, and a follow-up strategy to ensure adequate care for those at risk while minimizing false-positive diagnoses and costs. Without understanding the natural history of MAD, it is difficult to disregard this entity as clinically insignificant. Hence, awareness of this diagnosis with its relevant details and implications is helpful, as it may be an incidental imaging finding either isolated or combined with mitral valve disorders or cardiac arrhythmias, particularly in younger patients or those with other systemic diseases.

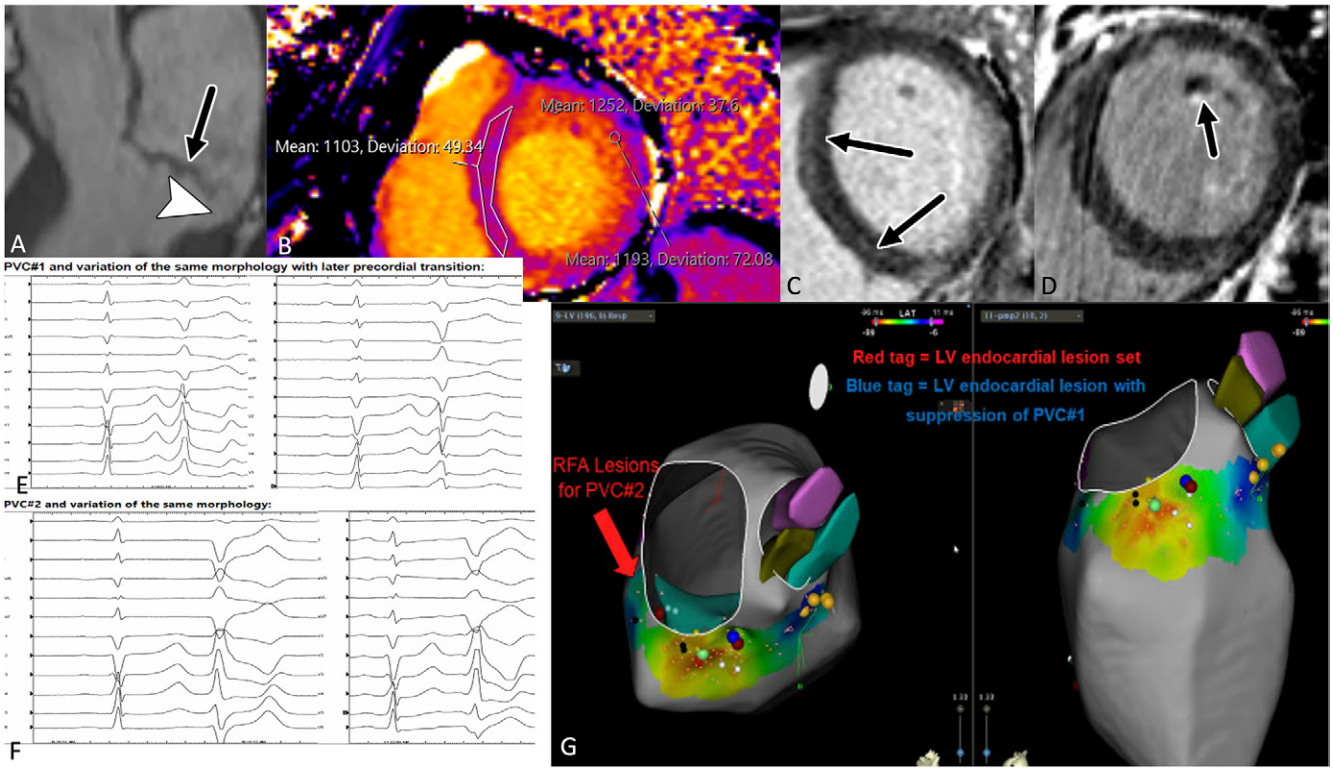
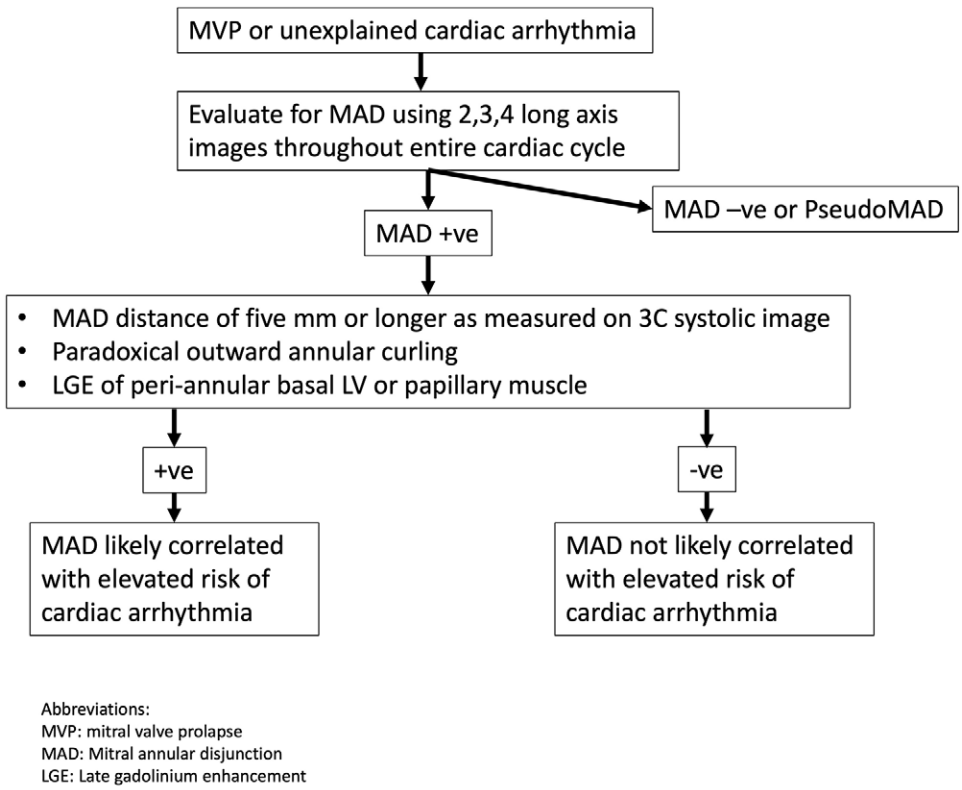


Figure 9: Images in a 60-year-old male patient with long-standing mitral regurgitation, bileaflet prolapse, and low normal left ventricular ejection fraction who recently developed symptomatic palpitations with 10% premature ventricular complex (PVC) burden and frequent bigeminy. **(A)** Three-chamber cine steady-state free precession cardiac MRI view demonstrates 6–8-mm bileaflet prolapse (black arrow) with 9-mm mitral annular disjunction (white arrowhead). **(B)** The T1 map at the basal section demonstrates diffuse high T1 values ranging between 1103 msec and 1252 msec. **(C, D)** Short-axis postcontrast cardiac MRI views demonstrate basal midmyocardial (black arrows in **C**) and papillary muscle (black arrow in **D**) late gadolinium enhancement. At electrophysiologic-guided endocardial mapping during ablation of frequent PVC, there was abnormal voltage mapping throughout the basal LV. PVC localized to the basal inferolateral wall and posterior papillary muscle as shown on **(E, F)** voltage maps and **(G)** electroanatomic images. LV = left ventricle, RFA = radiofrequency ablation.

Figure 10: Flowchart shows the approach for recognizing MAD correlated with elevated risk of cardiac arrhythmia. LV = left ventricle, –ve = negative, +ve = positive, 3C = three-chamber.



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