Correlation between Cardiac MRI and Voltage Mapping in Evaluating Atrial Fibrosis

Radiology: Cardiothoracic Imaging

ORIGINAL RESEARCH

Correlation between Cardiac MRI and Voltage Mapping in Evaluating Atrial Fibrosis: A Systematic Review

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Purpose: To provide an overview of existing literature on the association between late gadolinium enhancement (LGE) cardiac MRI and low voltage areas (LVA) obtained with electroanatomic mapping (EAM) or histopathology when assessing atrial fibrosis.

Materials and Methods: A systematic literature search was conducted in the PubMed, Embase, and Cochrane Library databases to identify all studies published until June 7, 2022, comparing LGE cardiac MRI to LVA EAM and/or histopathology for evaluation of atrial fibrosis. The study protocol was registered at PROSPERO (registration no. CRD42022338243). Two reviewers independently evaluated the studies for inclusion. Risk of bias and applicability for each included study were assessed using Quality Assessment of Diagnostic Accuracy Studies–2 (QUADAS-2) criteria. Data regarding demographics, electrophysiology, LGE cardiac MRI, and study outcomes were extracted.

Results: The search yielded 1048 total results, of which 22 studies were included. Nineteen of the 22 included studies reported a significant correlation between high signal intensity at LGE cardiac MRI and LVA EAM or histopathology. However, there was great heterogeneity between included studies regarding study design, patient samples, cardiac MRI performance and postprocessing, and EAM performance.

Conclusion: Current literature suggests a correlation between LGE cardiac MRI and LVA EAM or histopathology when evaluating atrial fibrosis but high heterogeneity between studies, demonstrating the need for uniform choices regarding cardiac MRI and EAM acquisition in future studies.

Supplemental material is available for this article.

Atrial remodeling is associated with cardiac dysfunction, increased morbidity, and mortality (1). It is characterized by structural, electrophysiologic, and mechanical alterations of the atrial myocardial tissue (2). Structural atrial remodeling is characterized by fibrosis and dilatation. Histopathologic validation is considered the reference standard for assessing atrial fibrosis, but acquiring human cardiac tissue is often impossible. Assessment of low voltage areas (LVA) with electroanatomic mapping (EAM) is accepted as a surrogate parameter (3). However, EAM is performed during invasive electrophysiologic (EP) studies and cannot be used as a routine diagnostic tool. Alternatively, late gadolinium enhancement (LGE) cardiac MRI can be used to noninvasively assess areas with increased extracellular matrix, the hallmark of atrial fibrosis. Previous studies showed that the degree of atrial fibrosis estimated with LGE cardiac MRI among patients with atrial fibrillation (AF) who undergo ablation was independently associated with arrhythmia recurrence (4–8) and stroke risk (9,10). Study results on the accuracy of using LGE cardiac MRI to identify gaps in ablation lines and to guide repeated ablation procedures are conflicting (11–16). A recent randomized controlled trial, the Delayed-Enhancement MRI Determinant of Successful Radiofrequency Catheter Ablation of Atrial Fibrillation (ie, DECAAF) II trial, showed that targeting areas of LGE for ablation in addition to pulmonary vein isolation was only superior in patients in whom less than 20% of the total left atrium (LA) was fibrotic (17).

When LGE cardiac MRI is used as the index test to identify atrial fibrosis, it should be noted that hyperenhancement at LGE cardiac MRI is not equivalent to fibrosis. It is merely a reflection of tissue characteristics (shortening of T1 relaxation time) resulting from focal contrast material accumulation and washout properties. LGE areas reflect focally increased extracellular space, which is a hallmark of replacement fibrosis, as well as necrosis, inflammation, and edema (18). It is yet impossible to differentiate between LGE caused by replacement fibrosis, iatrogenic scar, physiologic extracellular matrix, or interference with

Abbreviations

AF = atrial fibrillation, EAM = electroanatomic mapping, EP = electrophysiologic, LA = left atrium, LGE = late gadolinium enhancement, LVA = low voltage areas, PRISMA-DTA = Preferred Reporting Items for Systematic Review and Meta-Analysis of Diagnostic Test Accuracy Studies, QUADAS-2 = Quality Assessment of Diagnostic Accuracy Studies–2, SI = signal intensity, SR = sinus rhythm, 3D = three-dimensional

Summary

Current studies suggest a correlation between high signal intensity at late gadolinium enhancement cardiac MRI and low voltage areas at electroanatomic mapping when assessing atrial fibrosis.

Key Points

- In a systematic review of 22 studies (567 patients) assessing atrial fibrosis, 19 found a significant correlation between high signal intensity at late gadolinium enhancement cardiac MRI and low voltage areas at electroanatomic mapping.
- The Quality Assessment of Diagnostic Accuracy Studies–2 assessment showed concerns for included studies regarding the risk of bias and applicability in all domains.
- There was large heterogeneity between included studies, hampering the interpretation and extrapolation of study results; thus, uniform choices at cardiac MRI and voltage mapping performance, postprocessing, and alignment are crucial.

Keywords

Cardiac, MR Imaging, Left Atrium

adjacent hyperenhanced structures, such as epicardial fat. This is more important when imaging the atria compared with the ventricles, as the thin atrial walls require high resolution while maintaining sufficient signal-to-noise ratio and are more prone to partial volume effects. Studies combining high-resolution three-dimensional (3D) LGE cardiac MRI and high-quality LVA EAM with homogeneous research strategies are necessary to define the complementary role of both techniques and define thresholds for LGE cardiac MRI validated to LVA EAM. Of importance, LVA EAM is not the reference standard for atrial fibrosis, merely the best surrogate. Cross-validation between diagnostic tests will create bias as both methods may lack the sensitivity to detect early stages of the disease. This systematic review summarizes the available data on the association between LGE cardiac MRI and LVA obtained with EAM or histopathology for the assessment of atrial fibrosis to evaluate their diagnostic value and provide practical considerations for future clinical and scientific applications.

Materials and Methods

This systematic review was exempt from review by our institutional review board and was performed in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis of Diagnostic Test Accuracy Studies (PRISMA-DTA) criteria. The study protocol was registered in the PROSPERO online database of systematic reviews (registration no. CRD42022338243).

Literature Search

A comprehensive literature search was performed in the PubMed, Embase, and Cochrane Library electronic databases to identify all studies published until June 7, 2022. The following search terms were used with their respective synonyms: "atrial fibrosis" (ie, target condition), "late gadolinium enhancement magnetic resonance imaging" (ie, index test), and "electro-anatomic mapping or voltage mapping" (ie, reference standard). The extensive search string is presented in Appendix E1 (supplement).

Eligibility Criteria

Inclusion criteria were clinical studies in which: *(a)* an EP study was performed, including bipolar voltage measurement; *(b)* LGE cardiac MRI was performed prior to the EP study, with the rationale that in clinical practice, the EP study is directly followed by the ablation procedure; hence, LGE cardiac MRI after ablation will also include postablation scarring and affect the results; and *(c)* the correlation between LGE cardiac MRI and histopathology or bipolar voltage mapping was evaluated. Exclusion criteria were as follows: *(a)* studies for which no English full-text article was available, *(b)* case reports, and *(c)* different determinants, for example, cardiac MRI with T1 mapping instead of LGE. Two readers (G.P.B., with 13 years of experience as a physician specializing in cardiology; H.M.J.M.N., with 6 years of experience as a physician specializing in radiology research) independently performed the search and assessed the studies for eligibility. The reference lists of all potential eligible studies were screened for additional relevant studies. Disagreement on study inclusion between the two readers was solved by consensus.

Data Extraction and Quality Assessment

A predefined data extraction form was used to record details from the included studies as stated in Appendix E1 (supplement). The methodological quality of each included study was assessed using the Quality Assessment of Diagnostic Accuracy Studies–2 (QUADAS-2) (19). This checklist assesses the risk of bias and the clinical applicability of studies based on different domains. The rating criteria for risk of bias and study-specific signaling questions are provided in Appendix E2 (supplement). Studies using LGE cardiac MRI as the reference standard were considered as having a high risk of bias (–2, ie, downgraded two steps), and studies with voltage mapping as the reference standard were also downrated (–1, ie, downgraded one step) in this domain, as histopathology is the reference standard to assess the target condition. Both data extraction and quality assessment were performed independently by two readers (G.P.B. and H.M.J.M.N., see above). The corresponding authors of all included studies were contacted to request additional diagnostic indexes (sensitivity and specificity) that could not be retrieved from the publication. Any disagreement between the two readers was solved by consensus using a third independent reader (C.M., with 13 years of experience as a physician and researcher in radiology). The heterogeneity in patient samples, cardiac MRI, and EP parameters observed between the included studies precluded us from merging data in a meta-analysis.

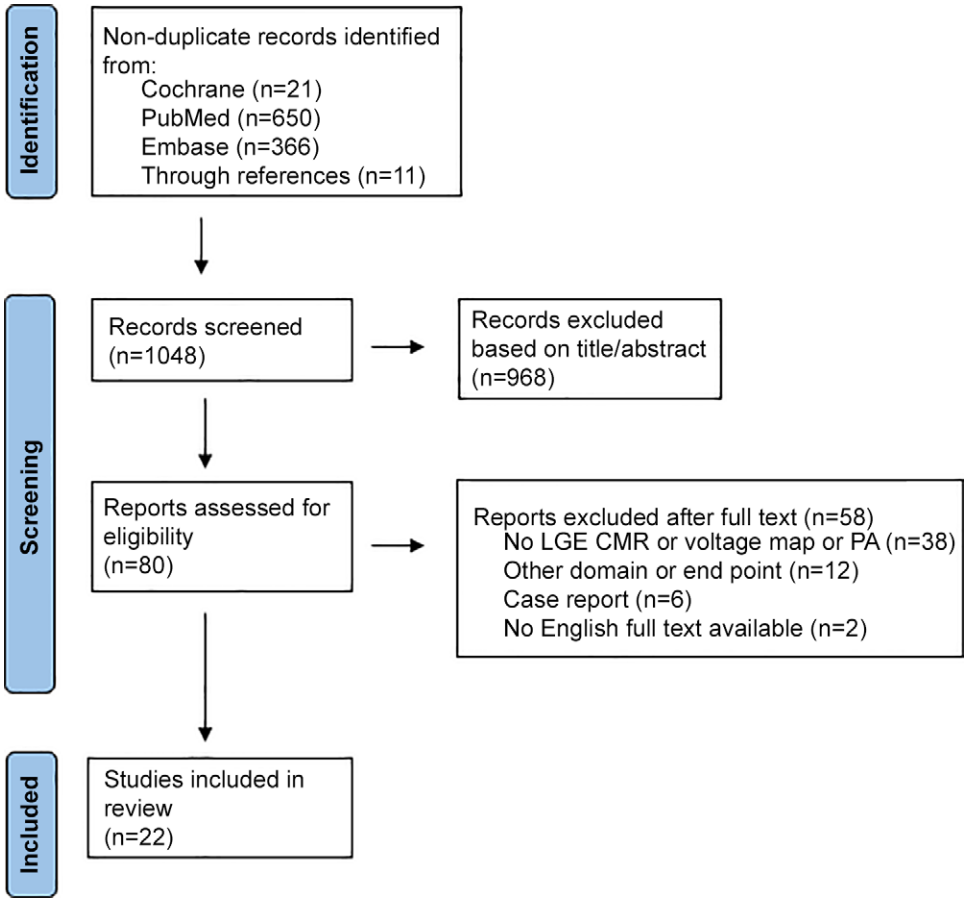

Figure 1: PRISMA flowchart of identification of studies. LGE = late gadolinium enhancement, PA = histopathology, PRISMA = Preferred Reporting Items for Systematic Review and Meta-Analysis.

Results

Literature Search

In the primary literature search, 1048 nonduplicate citations were identified from the electronic databases and checked for cross-references. Based on title and abstract, 968 studies were excluded from further analysis. Of the remaining 80 studies, 58 studies were excluded as they did not meet the eligibility criteria. Therefore, a total of 22 studies were included in this systematic review (7,8,11,12,15,16,20–35). Figure 1 shows the PRISMA flowchart illustrating the identification process.

Quality Assessment

Results of the quality assessment of the included studies are presented in Figures 2 and 3. The QUADAS-2 assessment showed concerns regarding risk of bias in all domains, but most importantly in the following areas: *(a)* patient selection, due to the lack of information on patient enrollment, high drop-out rate, or long interval of inclusion; *(b)* index test and reference test, due to lack of prespecified thresholds or blinding; and *(c)* flow and timing, due to high patient exclusion at the time of cardiac MRI, EAM, or both.

The QUADAS-2 assessment also showed concerns for applicability in all domains, but most importantly in the following domains: *(a)* patient selection, due to heterogeneity regarding ablation history; *(b)* index test, due to a subjective method of cardiac MRI performance and thresholding; and *(c)* reference test, due to the lack of histopathologic proof of atrial fibrosis in all but one study (30). Because EAM is currently considered the best surrogate marker for fibrosis, the five studies using LGE cardiac MRI as reference standard instead of EAM were considered an additional concern for applicability (25,26,28,31,33).

Patient Characteristics

Study sample–related parameters are described in Table 1. A total of 567 patients were included in these studies. Study sample sizes ranged from 10 to 75 patients (median, 19).The mean age of the patients was 61 years ± 3 (SD), and by estimation, 414 of 567 (73%) patients were men. The study population was rather heterogeneous with regard to previous ablation history. Ten studies (7,20,21,23,25,29–32,35) included only patients who had not undergone previous ablation, seven studies (8,22,24,26–28,33) included both patients who had undergone and those who had not undergone previous ablation, and five studies (11,12,15,16,34) included only patients who had undergone previous ablation. In most studies, AF type was mixed (7,11,12,15,16,20–22,24,26–28,30,32–34). One study included only patients with paroxysmal AF (8), and five studies included only patients with persistent AF (23,25,29,31,35).

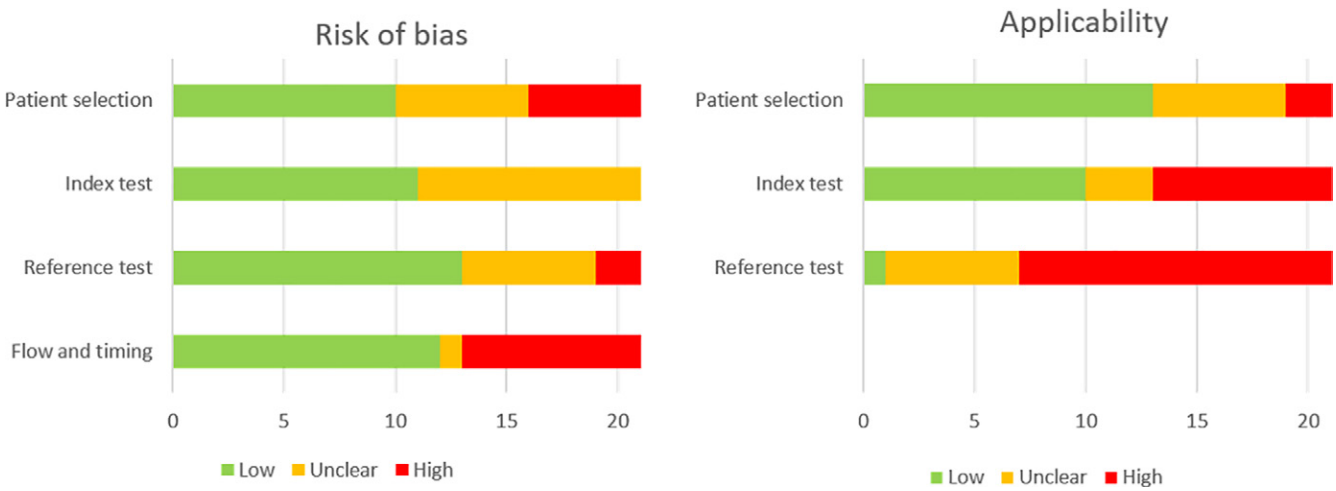

Figure 2: Graphical display of different domains of the QUADAS-2 checklist for all included studies (*n* = 22). The x-axis indicates the number of studies, and the y-axis indicates the domain. QUADAS-2 = Quality Assessment of Diagnostic Accuracy Studies–2.

Authors (year)	Risk of bias PATIENT SELECTION	Applicability PATIENT SELECTION	Risk of bias INDEX TEST	Applicability INDEX TEST	Risk of bias REFERENCE STANDARD	Applicability REFERENCE STANDARD	Risk of bias FLOW AND TIMING
Oakes et al. (2009)	high	low	unclear	high	unclear	high	high
Badger et al. (2010)	high	low	low	high	low	high	high
Spragg et al. (2012)	unclear	low	unclear	high	low	high	low
Malcolme-Lawes et al. (2013)	high	unclear	low	low	low	high	high
Jadidi et al. (2013)	low	unclear	low	low	low	high	low
Bisbal et al. (2014)	low	low	low	unclear	low	unclear	low
Casagranda et al. (2014)	low	unclear	unclear	high	unclear	high	unclear
Kapa et al. (2014)	low	high	unclear	high	high	high	high
Khurram et al. (2014)	low	unclear	low	low	low	high	low
McGann et al. (2014)	high	low	unclear	unclear	low	low	low
Harrison et al. (2015)	unclear	low	low	low	low	high	low
Hwang et al. (2015)	high	unclear	unclear	high	high	high	high
Sramko et al. (2015)	low	low	low	high	low	high	high
Benito et al. (2017)	unclear	low	unclear	low	unclear	high	high
Zghaib et al. (2018)	low	high	unclear	low	unclear	unclear	low
Chen et al. (2019)	low	low	unclear	high	low	unclear	low
Lee et al. (2019)	unclear	low	low	low	unclear	high	low
Qureshi et al. (2019)	high	unclear	low	low	low	high	high
Kuo et al. (2020)	unclear	high	unclear	low	high	unclear	low
Althoff et al. (2021)	low	low	low	unclear	unclear	unclear	low
Caixal et al. (2021)	unclear	low	unclear	low	low	high	high
Eichenlaub et al. (2022)	low	low	low	high	low	unclear	low

Figure 3: Tabular display of the QUADAS-2 results (*n* = 22). QUADAS-2 = Quality Assessment of Diagnostic Accuracy Studies–2.

Table 1: Patient Characteristics of Included Studies

Method of Correlation	Year	First Author	Sample Size Analyzed*	AF Type	Prior Ablation N (%)	Age (y)†	Men N (%)	Reference Test	Time between Cardiac MRI and EAM
LA as a whole	2009	Oakes (7)	54 (118)	Mixed	0 (0)	64 ± 12	NA (64)	EAM	Before
	2010	Badger (11)	13 (144)	Mixed	13 (100)	63 ± 13	NA (71)	EAM	NA
	2015	Sramko (32)	56 (95)	Mixed	0 (0)	59 ± 8	NA (71)	EAM	<1 week
	2022	Eichenlaub (35)	37 (41)	Persistent	0 (0)	66 ± 9	NA (84)	EAM	<1 day
LA divided in regions with and without LGE	2012	Spragg (16)	10 (10)	Mixed	10 (100)	56	NA	EAM	5 days ± 3
	2013	Jadidi (25)	18 (18)	Persistent	0 (0)	63 ± 7	16 (89)	MRI	1–2 days
	2014	Bisbal (12)	15 (15)	Mixed	15 (100)	57 ± 8	12 (80)	EAM	NA
	2014	Casagrande (22)	32 (37)	Mixed	12 (32)	61	29 (78)	EAM	1 week
	2014	Kapa (26)	12 (20)	Mixed	6 (50)	61 ± 9	6 (60)	MRI	NA
	2015	Hwang (24)	33 (42)	Mixed	6 (18)	58 ± 10	32 (84)	EAM	Before
	2019	Chen (23)	16 (16)	Persistent	0 (0)	62 ± 12	13 (81)	EAM	2 days
	2019	Qureshi (31)	14 (20)	Persistent	0 (0)	62 ± 11	11 (55)	MRI	Before
	2021	Althoff (34)	18 (22)	Mixed	18 (100)	57 ± 8	17 (77)	EAM	Median 1.5 days
Point-by-point correlation	2013	Malcolme-Lawes (8)	21 (50)	Paroxysmal	11 (52)	60 ± 13	NA (31)	EAM	Before
	2014	Khurram (27)	75 (75)	Mixed	32 (43)	62 ± 8	56 (75)	EAM	Before
	2015	Harrison (15)	20 (20)	Mixed	20 (100)	59 ± 7	17 (85)	EAM	2–3 weeks
	2017	Benito (20)	15 (30)	Mixed	0 (0)	58 ± 10	NA (87)	EAM	<2 weeks
	2018	Zghaib (33)	26 (26)	Mixed	17 (65)	63 ± 8	19 (73)	MRI	median 1 day
	2019	Lee (29)	20 (20)	Persistent	0 (0)	64	NA	EAM	median 57 days
	2020	Kuo (28)	40 (40)	Mixed	24 (60)	63 ± 9	30 (75)	MRI	12 days
	2021	Caixal (21)	16 (88)	Mixed	0 (0)	63 ± 7	5 (29)	EAM	<2 weeks
PA	2014	McGann (30)	10 (457)	Mixed	0 (0)	64 ± 12	NA (64)	PA	Before

Note.—Except where otherwise noted, data are numbers, with percentages in parentheses. AF = atrial fibrillation, EAM = electroanatomic mapping, LA = left atrium, LGE = late gadolinium enhancement, PA = histopathology, NA = not available.
*Data in parentheses are total numbers of participants (including patients who were not used for analysis with LGE and EAM).
†Data are means ± SDs. Some included studies did not provide the SD for the mean age.

Cardiac MRI

LGE cardiac MRI sequence parameters are described in Table 2. Reconstructed voxel sizes ranged from 0.63 × 0.63 × 1.25 mm (highest spatial resolution) to 1.25 × 1.25 × 2.5 mm (lowest spatial resolution). Six studies used a 3-T imager (12,20,21,24,34,35), and all other studies used a 1.5-T imager. McGann et al (30) used both 1.5-T and 3-T imagers. In eight studies, patients were imaged while in sinus rhythm (SR) (8,12,15,21,26,33–35). In five studies, the percentage of patients in SR varied from 66% to 90% (7,22,27,30,32), and heart rhythm during imaging was not reported in the remaining nine studies (11,16,20,23–25,28,29,31). 3D LGE cardiac MRI was performed 10–25 minutes after administering a gadolinium-based contrast agent with equivalent weight-based doses, except for in two studies (8,31) that used a fixed contrast material dose per patient regardless of their body weight. Signal intensity (SI) of enhanced atrial tissue was normalized to the blood pool in most studies published from 2017 onward (78%; seven of nine), in contrast to earlier studies (23%; three of 13). Seven studies (8,15,20,21,27,28,33) used the SI as a continuous parameter for correlation with bipolar voltage. The remaining 15 studies used a cutoff value to define atrial fibrosis, with values varying between studies from greater than 1 SD to greater than 4 SDs above the mean SI of atrial tissue. A tendency toward the use of greater than 3 or 4 SDs was noted, as used in the initial publication by Oakes et al (7). In two studies, the reader could change the threshold by 1 SD higher or lower when deemed appropriate for that specific case (7,32). The two most recent studies used a certain normalized SI threshold, expressed as the image intensity ratio, for fibrosis.

Electrophysiology

EP-related parameters are described in Table 3. The number of voltage points acquired in each study ranged from a mean of 90 (16) to 2566 points (34) per LA. Two recent studies acquired voltage maps with a high number of voltage points but excluded 90% of these points on the basis of ana-

Table 2: Cardiac MRI–related Parameters of Included Studies

Method of Correlation	Year	First Author	Vendor and Strength	SR (%)	Contrast Dose (mmol/kg of body weight)	Acquired Resolution (mm)	TI (msec)	TR (msec)	TE (msec)	Flip Angle (°)	Normalized to BP	Cutoff Value(s) for Fibrosis
LA as a whole	2009	Oakes (7)	Siemens 1.5 T	90	0.1	1.25 × 1.25 × 2.5	230–320	6.1	2.4	22	No	>2 or >3 or >4 SDs*
	2010	Badger (11)	Siemens 1.5 T	NA	0.1	1.25 × 1.25 × 2.5	270–310	5.5	2.3	NA	No	>3 SD
	2015	Sramko (32)	Siemens 1.5 T	66	0.2	1.6 × 1.6 × 3.0	fixed, 270	4.8	1.5	10	No	>2, >3, and >4 SDs and FWHM and expert opinion†
	2022	Eichenlaub (35)	Siemens 3 T	100	0.1	1.25 × 1.25 × 2.5	NA	3.1	1.4	14	Yes (IIR)	>0.74, >0.97, and >1.20 and Utah method†
LA divided in regions with and without LGE	2012	Spragg (16)	Siemens 1.5 T	NA	0.2	1.0 × 1.0 × 1.2	280–300	2.5	0.97	25	No	Visual
	2013	Jadidi (25)	Siemens 1.5 T	NA	0.2	0.63 × 0.63 × 2.5‡	260–320	5.4	2.3	22	No	>4 SDs
	2014	Bisbal (12)	Siemens 3 T	100	0.2	1.25 × 1.25 × 2.5	280–380	2.3	1.4	11	No	Scar > 60% of max SI
	2014	Casagrande (22)	Siemens 1.5 T	70	0.1	1.2 × 1.2 × 1.5	>310	6.3	2.3	22	No	Visual
	2014	Kapa (26)	Siemens 1.5 T	100	0.2	1.3 × 1.3 × 1.5	250–350	700	1.7	NA	No	>2 SDs
	2015	Hwang (24)	Philips 3 T	NA	0.2	1.5 × 1.5 × 1.5	230–270	4.7	1.4	25	No	>2, >3, >4, >5, and >6 SDs and FWHM†
	2019	Chen (23)	Siemens 1.5 T	NA	0.2	1.25 × 1.25 × 2.5	260–320	5.4	2.3	22	No	>4 SDs
	2019	Qureshi (31)	Philips 1.5 T	NA	20 mL§	1.5 × 1.5 × 4.0	NA	3.1	1.0	NA	Yes (NLA)	>2 SDs
	2021	Althoff (34)	Siemens 3 T	100	0.2	1.25 × 1.25 × 2.5	280–380	2.3	1.4	11	Yes (IIR)	>1.2

(Table 2 *continues*)

tomic location and electrical characteristics, resulting in a mean of 123 and 253 points per LA for analysis, respectively (21,28). Earlier studies used the ablation catheter, consisting of four poles with a diameter of 3.5 mm and interelectrode spacing of 2-5-2 mm, to acquire bipolar voltage maps. Most studies from 2017 onward used high-density bipolar mapping catheters. Bipolar voltage was measured during SR in 11 studies (8,12,15,20,21,24,26,27,29,33,35), during AF in three studies (23,25,32), and with a mixed rhythm in three studies (7,11,28). In three studies, the rhythm was not specified (16,22,34). Qureshi et al (31) performed voltage mapping during both SR and AF in each patient. Ten

Table 2 (*continued*): Cardiac MRI–related Parameters of Included Studies

Method of Correlation	Year	First Author	Vendor and Strength	SR (%)	Contrast Dose (mmol/kg of body weight)	Acquired Resolution (mm)	TI (msec)	TR (msec)	TE (msec)	Flip Angle (°)	Normalized to BP	Cutoff Value(s) for Fibrosis
Point-by-point correlation	2013	Malcolme-Lawes (8)	Philips 1.5 T	100	20 mL[§]	1.5 × 1.5 × 4.0	NA	3.1	1.0	NA	Yes (NLA)	No[‖]
	2014	Khurram (27)	Siemens 1.5 T	88	0.2	1.3 × 1.3 × 2.0	240–290	3.8	1.52	10	Yes (IIR)	No[‖]
	2015	Harrison (15)	Philips 1.5 T	100	0.2	1.3 × 1.3 × 4.0	NA	6.2	3.0	25	Yes (NLA)	No[‖]
	2017	Benito (20)	Siemens 3 T	NA	0.2	1.25 × 1.25 × 2.5	280–380	2.3	1.4	11	Yes (IIR)	No[‖]
	2018	Zghaib (33)	Siemens 1.5 T	100	0.2	1.3 × 1.3 × 2.0	240–290	3.8	1.52	10	Yes (IIR)	No[‖]
	2019	Lee (29)	Siemens 1.5 T	NA	0.1	1.25 × 1.25 × 2.5	340–360	NA	NA	NA	Yes (NLA)	>1 SD and >2 SD and FWHM[†]
	2020	Kuo (28)	Siemens 1.5 T	NA	0.2	1.37 × 1.37 × 1.5	310–350	700–870	1.3–1.6	NA	No	No[‖]
	2021	Caixal (21)	Siemens 3 T	100	0.2	1.25 × 1.25 × 2.5	280–380	2.3	1.4	11	Yes (IIR)	No[‖]
PA	2014	McGann (30)	Siemens 1.5 T or 3 T	67	0.1	1.25 × 1.25 × 2.5	NA	3.1	1.4	14	No	>2 or >3 or >4 SD

Note.—BP = blood pool, FWHM = full-width at half-maximum method, IIR = image intensity ratio (SI voxel/mean SI of LA BP), LA = left atrium, LGE = late gadolinium enhancement, NA = not available, NLA = normalized LA ([SI voxel – mean SI BP]/SD BP), PA = histopathology, SI = signal intensity, SR = sinus rhythm, TE = echo time, TI = inversion time, TR = repetition time.
*Reader could change the threshold by 1 SD higher or lower when deemed appropriate for that specific case.
[†]Study analyzed multiple cutoff values for fibrosis.
[‡]Reconstructed resolution.
[§]Study used a fix dose of contrast material per patient regardless of their body weight.
[‖]Absolute values used.

studies used bipolar voltage as a continuous parameter for correlation with cardiac MRI findings (8,12,15,20,21,25–28,33). Eleven studies used a cutoff value to categorize the data, with lower than 0.5 mV the most common cutoff value for fibrotic tissue and lower than 0.1 mV for dense scarring (7,11,16,22–24,29,31,32,34,35).

Method of Correlation and Effect Size

Study results are shown in Table 4. Most included studies found a significant correlation between SI acquired using LGE cardiac MRI and bipolar voltage acquired using EAM (7,8,11,12,15,16,20–22,24,25,27–30,33,34). Chen et al (23), Sramko et al (32), and Eichenlaub et al (35) found no significant correlation. Qureshi et al (31) found a significant correlation when voltage mapping was acquired during AF, but not during SR. Kuo et al (28) only found a significant correlation in patients with previous ablation, and Kapa et al (26) did not report an effect size.

Three methods to study the correlation between LGE cardiac MRI and EAM were used in the included studies. Four studies gathered information about global extensiveness of disease by comparing the amount (or percentage) of the LA with fibrosis at both diagnostic modalities (7,11,32,35). Nine studies gathered information on rough spatial correlation by dividing the LA into regions with and without LGE and investigating the EP parameters of these regions (12,16,22–26,31,34). In some of these studies, only the mean millivolts of the voltage points allocated to these regions were compared (12,16,25). Eight studies gathered information about spatial correlation by point-by-point matching each cardiac MRI pixel to the closest EAM point (8,15,20,21,27–29,33). The accepted radius between "matched" points mostly ranged between less than 2 mm and 3 mm,

Table 3: Electrophysiology-related Parameters of Included Studies

Method of Correlation	Year	First Author	Rhythm during EAM	Mapping Catheter and No. of Poles/Interelectrode Spacing	Voltage Points (Mean ± SD)*	Cutoff Values Related to Fibrosis (mV)
LA as a whole	2009	Oakes (7)	Mixed	NTC: 4/3.5 mm	≥100	<0.1 | 0.1–0.5 | 0.5–1 | >1†
	2010	Badger (11)	Mixed	BW: 10/3 mm	≥100	<0.1 | 0.1–0.5 | 0.5–1 | >1†
	2015	Sramko (32)	AF	NTC: 4/3.5 mm	219 ± 49	<0.5 and <0.2
	2022	Eichenlaub (35)	SR	Pent and Lasso: 20/1 mm	2129 ± 484	<0.5
LA divided in regions with and without LGE	2012	Spragg (16)	NA	NTC: 4/3.5 mm	90 ± 24	<0.5
	2013	Jadidi (25)	AF	AFII: 20/1 mm	514 ± 77	No‡
	2014	Bisbal (12)	SR	Lasso: 20/1 mm	808	No‡
	2014	Casagrande (22)	NA	NA	≥200	<0.5 and < 0.05
	2014	Kapa (26)	SR	NTC: 4/3.5 mm	141 ± 12	No‡
	2015	Hwang (24)	SR	NTC: 4/3.5 mm	NA	<0.5
	2019	Chen (23)	AF	AFII: 20/1 mm	1000	<0.5
	2019	Qureshi (31)	AF and SR	AFII: 20/1 mm	AF 660 ± 28, SR 557 ± 326	AF <0.35, SR <1.8
	2021	Althoff (34)	NA	Pent and Lasso: 20/1 mm	2566	<0.5
Point-by-point correlation	2013	Malcolme-Lawes (8)	SR	Lasso and AFII: 20/1 mm	200	No‡
	2014	Khurram (27)	SR	NTC: 4/3.5 mm	100	No‡
	2015	Harrison (15)	SR	NTC: 4/3.5 mm	338 ± 210	No‡
	2017	Benito (20)	SR	Lasso: 20/1 mm	124 ± 81	No‡
	2018	Zghaib (33)	SR	Lasso: 20/1 mm	734	No‡
	2019	Lee (29)	SR	NA	NA	<0.5
	2020	Kuo (28)	Mixed	Pent and Lasso: 20/1 mm	123	No‡
	2021	Caixal (21)	SR	Lasso: 20/1 mm	253 ± 139	No‡

Note.—AF = atrial fibrillation, AFII = double-spiral Afocus II, BW = Biosense Webster circular mapping catheter, EAM = electroanatomic mapping, LA = left atrium, LGE = late gadolinium enhancement, NA = not available, NTC = Navistar-ThermoCool, Pent = PentAray, SR = sinus rhythm.

*Some studies did not provide the SD for the mean voltage points.

†Study included different ranges for different degrees of fibrosis, with greater than 1 mV considered healthy tissue, less than 0.1 mV considered fibrotic scar, and between 0.5 mV and 0.1 mV considered low voltage tissue.

‡Absolute values were used.

although Kuo et al (28) accepted a radius of 10 mm. Harrison et al (15) determined the correlation using a radius of both 2.5 mm and 5 mm. One study used histopathology as the reference standard (30). They obtained LA tissue in patients with surgical AF, and the surgeon marked the biopsy location to align it with postablation 3D LGE cardiac MRI (30).

Discussion

Current existing literature, presented in this systematic review, suggests a correlation between high SI at LGE cardiac MRI and LVA at EAM when assessing the atria. There is large heterogeneity between studies regarding study design, patient population, and cardiac MR image and LVA acquisition and postprocessing.

High-quality cardiac MR image acquisition is crucial for an accurate noninvasive assessment of atrial fibrosis. Due to the thin atrial wall, a sufficiently high spatial resolution is required while maintaining a reasonable signal-to-noise ratio. In some studies, the voxel size exceeds the estimated atrial wall thickness (2–4 mm) (36), introducing partial volume effects that may lead to misinterpretations (8,15,31,32). One should also be aware of MRI artifacts caused by the respiratory navigator restore pulse, resulting in higher SI of the tissue around the navigator (such as the neighboring atrial wall, blood pool, and right-sided pulmonary vein).

Normalization of LGE to the blood pool is an important step in minimizing interpatient variation, as it corrects for patient-specific pharmacokinetics of the contrast agent that influence the obtained SI (eg, heart rate, renal function, LV function). After 2015, all studies included in this review normalized their LGE signal intensities to the blood pool (image intensity ratio or normalized LA), except Chen et al (23) and Kuo et al (28).

The threshold to discriminate between normal and fibrotic tissue varies greatly between studies, with a tendency toward greater than 3 or 4 SDs above the mean SI of the atrial wall. Of note, seven studies (8,22,24,26–28,33) combined the information of patients with and without previous ablation. However,

Table 4: Results from Included Studies

Method of Correlation	Year	First Author	Cardiac MRI–EAM Correlation Found*	Results					
				Correlation Coefficient *(r)*	Sensitivity (%)	Specificity (%)	Significance	Reference Test	Radius for Alignment (mm)
LA as a whole	2009	Oakes (7)	Yes	0.78	NA	NA	$P < .05$	EAM	NA
	2010	Badger (11)	Yes	0.57	NA	NA	NA	EAM	NA
	2015	Sramko (32)	<0.5 mV: no	−0.11	NA	NA	$P = .40$	EAM	NA
			<0.2 mV: no	−0.16	NA	NA	$P = .20$		
	2022	Eichenlaub (35)	Utah method: no	NA	NA	NA	$P = .06$	EAM	NA
			IIR 0.74: no	NA	NA	NA	$P = .34$		
			IIR 0.97: no	NA	NA	NA	$P = .75$		
			IIR 1.2: no	NA	NA	NA	$P = .66$		
LA divided in regions with and without LGE	2012	Spragg (16)	Yes	NA	84	68	$P < .001$	EAM	NA
	2013	Jadidi (25)	D vs N: yes	NA	NA	NA	$P < .0001$	MRI	NA
			D vs P: yes	NA	NA	NA	$P < .0001$		
			P vs N: yes	NA	NA	NA	$P = .94$		
	2014	Bisbal (12)	Yes	NA	NA	NA	$P < .001$	EAM	NA
	2014	Casagrande (22)	Yes	NA	66	87	NA	EAM	NA
	2014	Kapa (26)	NA	NA	NA	NA	NA	MRI	NA
	2015	Hwang (24)	FWHM: yes	NA	86	96	NA	EAM	NA
			6 SDs: yes	NA	82	96	NA		
	2019	Chen (23)	No	NA	42	46	NA	EAM	NA
	2019	Qureshi (31)	AF: yes	NA	77	79	AUC: 0.82	MRI	NA
			SR: no	NA	63	67	AUC: 0.70		
	2021	Althoff (34)	Yes	NA	68	92	NA	EAM	NA
Point-by-point correlation	2013	Malcolme-Lawes (8)	2 vs 3 SDs: yes	NA	NA	NA	$P = .002$	EAM	<2
			3 vs 4 SDs: yes	NA	NA	NA	$P < .001$		
			4 vs 5 SDs: yes	NA	NA	NA	$P = .048$		
			>5 SDs: no	NA	NA	NA	$P > .05$		
	2014	Khurram (27)	Yes	−2.44	NA	NA	$P < .001$	EAM	<1.5
	2015	Harrison (15)	2.5 mm: yes	−0.18	NA	NA	95% CI: −0.26, −0.10	EAM	<2.5 and <5
			5 mm: yes	−0.19	NA	NA	95% CI: −0.27, −0.11		
	2017	Benito (20)	Yes	−0.2	NA	NA	$P < .001$	EAM	<2
	2018	Zghaib (33)	Yes	−0.85	NA	NA	$P < .0001$	MRI	NA
	2019	Lee (29)	Yes	NA	41	99	NA	EAM	<3
	2020	Kuo (28)	Redo: yes	−0.049	NA	NA	$P < .001$	MRI	<10
			Naive: no	−0.004	NA	NA	$P = .70$		
	2021	Caixal (21)	Yes	−0.39	NA	NA	$P < .001$	EAM	NA
PA	2014	McGann (30)	Yes	NA	100	100	NA	PA	NA

Note.—AF = atrial fibrillation, AUC = area under the receiver operating characteristic curve, D = dense LGE region, EAM = electroanatomic mapping, FWHM = full-width at half-maximum method, IIR = image intensity ratio, LA = left atrium, LGE = late gadolinium enhancement, N = non-LGE region, NA = not available, P = patchy LGE region, PA = histopathology, Redo = patient underwent previous ablation, SR = sinus rhythm.

*Different studies used different parameters to check for correlation, or found correlation among certain patient groups (eg, patients who had undergone prior ablation vs those who did not).

replacement fibrosis resulting from natural atrial remodeling most likely differs from iatrogenic transmural ablation scar and might necessitate separate cutoff values.

EAM quality is primarily defined by the number of voltage mapping points. Technical aspects that influence the measured bipolar voltage are tissue contact, wave propagation, atrial rhythm, and heart rate frequency (37). With the introduction of high-density mapping catheters, recent studies are of superior quality with 500 to greater than 2000 voltage points per LA (23,31,33–35), as compared with 100–200 points in other studies (7,8,11,16,20–22,26–28,32). Interestingly, Qureshi et al (31) performed voltage mapping both during SR and AF in each patient and found that bipolar voltage was significantly lower during AF compared with SR and that bipolar voltage measured during AF had a better correlation with LGE cardiac MRI than during SR. Most studies used a threshold of 0.5 mV to distinguish normal myocardium from atrial fibrosis, and often a threshold of 0.15 mV was used for dense or iatrogenic scar.

The only studies that found no significant correlation between LGE cardiac MRI and bipolar voltage at EAM or histopathology were Chen et al (23), Sramko et al (32), and Eichenlaub et al (35). Of note, Sramko et al (32) compared the "total percentage of LA with LGE" with "the total percentage of LA with low voltage." Chen et al (23) compared "non-LGE regions" with "LGE regions," but also included "patchy regions" in the LGE group. Because the patchy regions consist of voxels with and without hyperenhancement, this may have influenced the results.

The chosen method of alignment and correlation between LGE cardiac MRI and EAM is of great importance. The first method (extensiveness of disease) reflects properties of the LA as a whole; consequently, conclusions on spatial correlation cannot be drawn. However, the extent of disease of the entire LA can be useful for preprocedural planning and patient risk stratification. The second method (rough spatial correlation) provides more robust measurements due to lower sensitivity for focal differences caused by artifacts, but it is not useful for focal tissue characterization. The third method (point-by-point correlation) can be used to establish cutoff values for LGE cardiac MRI and to detect ablation gaps, provided that the cardiac MRI and EAM are of high quality and alignment is accurate. Although the radius between aligned points seems important, Harrison et al (15) tested a radius of 2.5 mm and 5 mm in each patient and found no evidence of a difference.

Based on the systematic review of the current literature, the following aspects of quantifying atrial fibrosis should be considered for future studies. First, 3D LGE cardiac MRI should be performed during SR, with sufficiently high spatial resolution, and normalization to the blood pool is imminent. Second, LGE cardiac MRI cutoff values should be defined per individual center after internal validation of normal values (analog to current practice for T1 mapping). However, there is some evidence that previously found image intensity ratio cutoff values can be used in different machines and centers with good reproducibility (38). Third, voltage mapping should be used as the reference standard, acquiring a high number of voltage points (preferably >1000 points). Last, a correlation method that matches the research objective should be chosen. When determining cutoff values or ablation gaps, a point-by-point comparison is desired. When determining the extensiveness of disease to aid preprocedural planning or as a prognostic marker, quantifying atrial fibrosis per region or of the LA as a whole is preferred.

Our study had some limitations. First, although EAM is considered the best surrogate for LA fibrosis, histopathology is the reference standard; hence, any study not using this as a reference standard induces bias. Second, although not an inclusion criterion for this systematic review, all studies included a patient sample with AF. This results in a lack of information from patients with different clinical backgrounds (eg, valvular disease, congenital heart disease). Finally, the included studies did not routinely report the atrial parameters (eg, LA volume, LA diameter, diastolic function). This induces bias because these parameters are associated with atrial remodeling and extent of LA fibrosis.

In conclusion, the existing literature demonstrates a correlation between high SI at LGE cardiac MRI and LVA at EAM when evaluating atrial fibrosis. However, the clinical and technical methods between the included studies varied substantially, hampering the interpretation and extrapolation of study results. To understand and maximize the potential of LGE cardiac MRI as a noninvasive diagnostic tool for the evaluation of atrial fibrosis, uniform choices at both cardiac MRI and EAM, as well as matching the method of correlation with the clinical or research objective, are crucial.

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References

1. Triposkiadis F, Pieske B, Butler J, et al. Global left atrial failure in heart failure. Eur J Heart Fail 2016;18(11):1307–1320.
2. Goette A, Kalman JM, Aguinaga L, et al. EHRA/HRS/APHRS/SOLAECE expert consensus on atrial cardiomyopathies: definition, characterization, and clinical implication. Europace 2016;18(10):1455–1490.
3. Boldt A, Wetzel U, Lauschke J, et al. Fibrosis in left atrial tissue of patients with atrial fibrillation with and without underlying mitral valve disease. Heart 2004;90(4):400–405.
4. 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(1):16–22.

5. Chelu MG, King JB, Kholmovski EG, et al. Atrial fibrosis by late gadolinium enhancement magnetic resonance imaging and catheter ablation of atrial fibrillation: 5-year follow-up data. J Am Heart Assoc 2018;7(23):e006313.
6. 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(5):498–506.
7. 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(13):1758–1767.
8. Malcolme-Lawes LC, Juli C, Karim R, et al. Automated analysis of atrial late gadolinium enhancement imaging that correlates with endocardial voltage and clinical outcomes: a 2-center study. Heart Rhythm 2013;10(8):1184–1191.
9. Daccarett M, Badger TJ, Akoum N, et al. Association of left atrial fibrosis detected by delayed-enhancement magnetic resonance imaging and the risk of stroke in patients with atrial fibrillation. J Am Coll Cardiol 2011;57(7):831–838.
10. Bisbal F, Baranchuk A, Braunwald E, Bayés de Luna A, Bayés-Genís A. Atrial failure as a clinical entity: JACC Review Topic of the Week. J Am Coll Cardiol 2020;75(2):222–232.
11. Badger TJ, Daccarett M, Akoum NW, et al. Evaluation of left atrial lesions after initial and repeat atrial fibrillation ablation: lessons learned from delayed-enhancement MRI in repeat ablation procedures. Circ Arrhythm Electrophysiol 2010;3(3):249–259.
12. Bisbal F, Guiu E, Cabanas-Grandío P, et al. CMR-guided approach to localize and ablate gaps in repeat AF ablation procedure. JACC Cardiovasc Imaging 2014;7(7):653–663.
13. Mishima T, Miyamoto K, Morita Y, et al. Feasibility of late gadolinium enhancement magnetic resonance imaging to detect ablation lesion gaps in patients undergoing cryoballoon ablation of paroxysmal atrial fibrillation. J Arrhythm 2019;35(2):190–196.
14. Peters DC, Wylie JV, Hauser TH, et al. Detection of pulmonary vein and left atrial scar after catheter ablation with three-dimensional navigator-gated delayed enhancement MR imaging: initial experience. Radiology 2007;243(3):690–695.
15. Harrison JL, Sohns C, Linton NW, et al. Repeat left atrial catheter ablation: cardiac magnetic resonance prediction of endocardial voltage and gaps in ablation lesion sets. Circ Arrhythm Electrophysiol 2015;8(2):270–278.
16. Spragg DD, Khurram I, Zimmerman SL, et al. Initial experience with magnetic resonance imaging of atrial scar and co-registration with electroanatomic voltage mapping during atrial fibrillation: success and limitations. Heart Rhythm 2012;9(12):2003–2009.
17. Marrouche NF. Fibrosis ablation shows promise in atrial fibrillation with low grade fibrotic myopathy. DECAAF II trial presented in a Hot Line Session at ESC Congress 28-08-2021. https://www.escardio.org/The-ESC/Press-Office/Press-releases/Fibrosis-ablation-shows-promise-in-atrial-fibrillation-with-low-grade-fibrotic-myopathy. Updated August 28, 2021. Accessed June 7, 2022.
18. Kim RJ, Chen EL, Lima JA, Judd RM. Myocardial Gd-DTPA kinetics determine MRI contrast enhancement and reflect the extent and severity of myocardial injury after acute reperfused infarction. Circulation 1996;94(12):3318–3326.
19. Whiting PF, Rutjes AW, Westwood ME, et al. QUADAS-2: a revised tool for the quality assessment of diagnostic accuracy studies. Ann Intern Med 2011;155(8):529–536.
20. Benito EM, Carlosena-Remirez A, Guasch E, et al. Left atrial fibrosis quantification by late gadolinium-enhanced magnetic resonance: a new method to standardize the thresholds for reproducibility. Europace 2017;19(8):1272–1279.
21. Caixal G, Alarcón F, Althoff TF, et al. Accuracy of left atrial fibrosis detection with cardiac magnetic resonance: correlation of late gadolinium enhancement with endocardial voltage and conduction velocity. Europace 2021;23(3):380–388.
22. Casagranda G, dal Piaz EC, Ravanelli D, et al. Identification of left atrial fibrosis with a late-enhancement MR sequence (LE-MR): preliminary results. Radiol Med (Torino) 2014;119(8):595–600.
23. Chen J, Arentz T, Cochet H, et al. Extent and spatial distribution of left atrial arrhythmogenic sites, late gadolinium enhancement at magnetic resonance imaging, and low-voltage areas in patients with persistent atrial fibrillation: comparison of imaging vs. electrical parameters of fibrosis and arrhythmogenesis. Europace 2019;21(10):1484–1493.
24. Hwang SH, Oh YW, Lee DI, Shim J, Park SW, Kim YH. Evaluation of quantification methods for left arial late gadolinium enhancement based on different references in patients with atrial fibrillation. Int J Cardiovasc Imaging 2015;31(Suppl 1):91–101.
25. Jadidi AS, Cochet H, Shah AJ, et al. Inverse relationship between fractionated electrograms and atrial fibrosis in persistent atrial fibrillation: combined magnetic resonance imaging and high-density mapping. J Am Coll Cardiol 2013;62(9):802–812.
26. Kapa S, Desjardins B, Callans DJ, Marchlinski FE, Dixit S. Contact electroanatomic mapping derived voltage criteria for characterizing left atrial scar in patients undergoing ablation for atrial fibrillation. J Cardiovasc Electrophysiol 2014;25(10):1044–1052.
27. Khurram IM, Beinart R, Zipunnikov V, et al. Magnetic resonance image intensity ratio, a normalized measure to enable interpatient comparability of left atrial fibrosis. Heart Rhythm 2014;11(1):85–92.
28. Kuo L, Zado E, Frankel D, et al. Association of left atrial high-resolution late gadolinium enhancement on cardiac magnetic resonance with electrogram abnormalities beyond voltage in patients with atrial fibrillation. Circ Arrhythm Electrophysiol 2020;13(2):e007586.
29. Lee J, Thornhill RE, Nery P, et al. Left atrial imaging and registration of fibrosis with conduction voltages using LGE-MRI and electroanatomical mapping. Comput Biol Med 2019;111:103341.
30. McGann C, Akoum N, Patel A, et al. Atrial fibrillation ablation outcome is predicted by left atrial remodeling on MRI. Circ Arrhythm Electrophysiol 2014;7(1):23–30.
31. Qureshi NA, Kim SJ, Cantwell CD, et al. Voltage during atrial fibrillation is superior to voltage during sinus rhythm in localizing areas of delayed enhancement on magnetic resonance imaging: An assessment of the posterior left atrium in patients with persistent atrial fibrillation. Heart Rhythm 2019;16(9):1357–1367.
32. Sramko M, Peichl P, Wichterle D, et al. Clinical value of assessment of left atrial late gadolinium enhancement in patients undergoing ablation of atrial fibrillation. Int J Cardiol 2015;179:351–357.
33. Zghaib T, Keramati A, Chrispin J, et al. Multimodal examination of atrial fibrillation substrate: correlation of left atrial bipolar voltage using multielectrode fast automated mapping, point-by-point mapping, and magnetic resonance image intensity ratio. JACC Clin Electrophysiol 2018;4(1):59–68.
34. Althoff TF, Garre P, Caixal G, et al. Late gadolinium enhancement-MRI determines definite lesion formation most accurately at 3 months post ablation compared to later time points. Pacing Clin Electrophysiol 2022;45(1):72–82.
35. Eichenlaub M, Mueller-Edenborn B, Minners J, et al. Comparison of various late gadolinium enhancement magnetic resonance imaging methods with high-definition voltage and activation mapping for detection of atrial cardiomyopathy. Europace 2022;24(7):1102–1111.
36. Whitaker J, Rajani R, Chubb H, et al. The role of myocardial wall thickness in atrial arrhythmogenesis. Europace 2016;18(12):1758–1772.
37. Wong GR, Nalliah CJ, Lee G, et al. Dynamic atrial substrate during high-density mapping of paroxysmal and persistent AF: implications for substrate ablation. JACC Clin Electrophysiol 2019;5(11):1265–1277.
38. Bertelsen L, Alarcón F, Andreasen L, et al. Verification of threshold for image intensity ratio analyses of late gadolinium enhancement magnetic resonance imaging of left atrial fibrosis in 1.5T scans. Int J Cardiovasc Imaging 2020;36(3):513–520.