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Cardiac Magnetic Resonance Imaging for the Diagnosis of Infective Endocarditis in the COVID-19 Era

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Abstract: In the COVID-19 pandemic, to minimize aerosol-generating procedures, cardiac magnetic resonance imaging (CMR) was utilized at our institution as an alternative to transesophageal echocardiography (TEE) for diagnosing infective endocarditis (IE). This retrospective study evaluated the clinical utility of CMR for detecting IE among 14 patients growing typical microorganisms on blood cultures or meeting modified Duke Criteria. Seven cases were treated for IE. In 2 cases, CMR results were notable for possible leaflet vegetations and were clinically meaningful in guiding antibiotic therapy, obtaining further imaging, and/or pursuing surgical intervention. In 2 cases, vegetations were missed on CMR but detected on TEE. In 3 cases, CMR was non-diagnostic, but patients were treated empirically. There was no difference in antibiotic duration or outcomes over 1 year. CMR demonstrated mixed results in diagnosing valvular vegetations and guiding clinical decision-making. Further prospective

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controlled trials of CMR Vs TEE are warranted. (Curr Probl Cardiol 2022;48:101396.)

Introduction

Infective endocarditis (IE) is a complex multi-faceted disease involving any surface of the endocardium; particularly, native valves, chordae tendineae, congenital anomalies, prosthetic valves, and intracardiac devices.[1] Additionally, depending on the clinical scenario and laterality of involvement, IE is associated with various intracardiac and extracardiac complications, including but not limited to valvular insufficiency, heart failure, paravalvular extension, atrioventricular conduction disturbance, myocarditis, pericarditis, septic pulmonary or systemic embolization, metastatic abscess, mycotic aneurysm, glomerulonephritis, and systemic immune reaction.[1-4] The diagnosis of IE is based upon a combination of clinical, microbiological, and echocardiographic findings as specified in the modified Duke criteria.[5,6] Given the significant morbidity and mortality of IE, prompt diagnosis and risk stratification are critical, as a delay in definitive management predisposes patients to further complications and portends worse outcomes.[3] However, the diagnosis of IE remains challenging as patients present with a wide spectrum of clinical manifestations from asymptomatic, chronic illness with low-grade fever and non-specific symptoms, systemic complications due to septic embolization, or acute rapidly progressive septic and cardiogenic shock.[7]

For patients undergoing diagnostic workup of suspected IE, imaging plays a critical role, and echocardiography is the first-line imaging modality. The goals of echocardiographic evaluation include assessing the anatomy of the valvular structures, identifying and characterizing the presence of vegetations, defining any resultant impairment in valvular function, assessing for paravalvular extension or abscesses, identifying involvement of prosthetic valves, examining indwelling catheters, assessing intracardiac devices such as a left ventricular assist device, and for patients with a cardiac implantable electronic device (CIED) such as a permanent pacemaker or implantable cardioverter-defibrillator (ICD), visualizing the leads if possible.[8] While transthoracic echocardiography (TTE) and transesophageal echocardiography (TEE) often serve complimentary roles, TEE as compared to TTE is a superior modality of imaging due to its enhanced spatial resolution resulting in higher sensitivity for identifying and characterizing

valvular vegetations and paravalvular extension, particularly in the setting of prosthetic valves.[7,9] Three-dimensional (3D) TEE also allows for improved identification of valvular vegetation vs abscess, leaflet perforation, prosthetic paravalvular leak, prosthetic valve dehiscence, and vegetation size and localization.[10] However, when there remains diagnostic uncertainty following TEE, particularly in the setting of prosthetic valves, paravalvular extension, and intracardiac devices, the modern diagnostic approach involves the utilization of multi-modality imaging techniques such as leukocyte scintigraphy, ^{18}F-fluorodeoxyglucose positron emission tomography / computed tomography (^{18}FDG-PET/CT), multi-detector computed tomography (MDCT), and cardiac magnetic resonance imaging (CMR).[8,11] Recent advancements in radiotracers, multi-detector scanners, iterative reconstruction algorithms, magnet field strength, and artificial intelligence models have allowed multi-modality imaging to help improve diagnostic accuracy and inform management decisions.[8]

Particularly, CMR is a unique imaging modality that utilizes non-ionizing radiation to provide both anatomic and functional data in exquisite detail. Specifically, CMR allows for excellent visualization and quantitative assessment of valvular regurgitation/stenosis, ventricular volumes, ventricular systolic function, valvular vegetations, paravalvular extension, pericarditis, and myocarditis.[12,13] However, CMR is limited by the requirement of gadolinium contrast, preventing its use in advanced renal insufficiency (estimated glomerular filtration rate less than 30 mL/min) due to concern for the rare complication of nephrogenic systemic fibrosis, imaging artifacts secondary to mechanical prosthetic valves, incompatible CIEDs, ferromagnetic metallic implants, lengthy acquisition times, cost, and availability.[13] Although CMR is now well accepted for identifying myopericardial complications and increasingly utilized for the quantitative assessment of valvular function, the exact role of CMR in the evidence-based diagnostic pathway of IE currently remains unclear due to a paucity of studies.[7,14]

Additionally, while the gold standard for the diagnosis of IE, TEE is an aerosol-generating procedure (AGP) due to the traversal of a transesophageal probe through the aerodigestive tract, thus posing a potential SARS-CoV-2 transmission risk to healthcare personnel.[15,16] From the outset of the COVID-19 pandemic, CMR was utilized at our institution as an alternative to TEE in patients growing typical microorganisms on blood cultures or meeting modified Duke criteria for IE. We evaluate the clinical utility of CMR in diagnosing patients with IE.

Methods

Patient Population

This retrospective single-center observational study consisted of 14 patients growing typical microorganisms (eg, Staphylococci, Streptococci, and Enterococci) on blood cultures or meeting modified Duke criteria for IE who underwent CMR for the diagnostic evaluation of IE during the initial phase of the COVID-19 pandemic from March 14, 2020, to February 14, 2021, at ProMedica Toledo Hospital.

Imaging Protocol

Multi-planar multi-sequence gated CMR was performed with steady state free precession imaging and pre- and post-contrast delayed myocardial enhancement views obtained prior to and following the administration of intravenous gadolinium contrast. Additionally, contrast velocity flow imaging of the valves was performed to evaluate valvular function.

Data Retrieval

A total of 119 patients who underwent CMR from March 14, 2020, to February 14, 2021, were retrieved. Through manual chart review, 14 patients who demonstrated growth of typical microorganisms on blood cultures as noted above or met modified Duke criteria for IE were included in the analysis. Baseline demographic data, clinical course data, and imaging findings were retrieved manually from the electronic medical record and collated into a shared database for further analysis.

Statistical Analysis

Continuous variables have been expressed as the mean $\pm$ 1 standard deviation, and statistical significance was calculated using the Student's t-test. Categorical variables have been expressed as absolute numbers or percentages, and statistical significance was calculated using the Chi-squared test. A statistically significant difference between variables required a P-value ≤ 0.05. All statistical analysis was performed using Microsoft Excel 2010.

Approval

This retrospective observational study was approved as an expedited review by the Institutional Review Board (IRB) at the University of Toledo and ProMedica Toledo Hospital.

Results

Patient Characteristics

The study consisted of 14 patients with baseline demographic information as specified in Table 1. The population was notable for 9 males (64%), ages ranging from 36 to 88 years old with an average age of 58 ± 15 years. Regarding risk factors: 1 patient (7%) had a history of IE; 2 patients (14%) had a history of intravenous drug use (IVDU); 3 patients (21%) had a history of heart failure (HF); 1 patient (7%) had a prosthetic

TABLE 1. Baseline characteristics

Total	14
Min age (years)	36
Max age (years)	88
Median age (years)	55
Average age (years)	58 ± 15
Male	9 (64%)
History of infective endocarditis	1 (7%)
History of intravenous drug use	2 (14%)
History of heart failure	3 (21%)
Prosthetic valve	1 (7%)
Intracardiac device	0 (0%)
Indwelling catheter	0 (0%)
Dialysis dependent	0 (0%)
COVID-19 positive via PCR	1 (7%)
Modified Duke criteria met	3 (21%)
Positive blood cultures	14 (100%)
Methicillin-susceptible Staphylococcus aureus	7 (50%)
Methicillin-resistant Staphylococcus aureus	1 (7%)
Coagulase-negative Staphylococci (Staphylococcus lugdunensis)	1 (7%)
Enterococcus faecalis	4 (29%)
Enterococcus avium	1 (7%)
Streptococcus constellatus (a subgroup of viridans streptococci)	1 (7%)
Klebsiella oxytoca	1 (7%)
Citrobacter youngae	1 (7%)
Candida glabrata	1 (7%)

Abbreviations: COVID-19, coronavirus disease 2019, PCR, polymerase chain reaction.
All values are reported as n (%) unless otherwise specified.

valve; 0 patients (0%) had an intracardiac device, an indwelling catheter, or required dialysis.

Microbiological Data

All patients had positive blood cultures (MSSA 50%, MRSA 7%, Coagulase-negative staphylococci 7%, Enterococcus faecalis 29%, Enterococcus avium 7%, Viridans streptococci 7%, Klebsiella oxytoca 7%, Citrobacter youngae 7%, Candida glabrata 7%). Modified Duke criteria were confirmed in 3 cases (21%), possibly met in 9 cases (64%), and rejected in 2 cases (14%). One patient (7%) tested positive for COVID-19 via PCR. Further details regarding cultures, imaging findings, modified Duke criteria, final diagnosis, and management on a per-case basis are outlined in Table 2.

Clinical Performance of CMR

In total, 7 of 14 cases (50%) were treated for confirmed or presumed IE as outlined in Table 3. In 2 of the 7 cases, CMR was notable for possible leaflet vegetation and was clinically meaningful in guiding antibiotic therapy, obtaining further imaging, and in 1 case eventually pursuing a surgical intervention. In another 2 of the 7 cases, leaflet vegetation were missed on CMR but detected on TEE. In the remaining 3 of the 7 cases, CMR results were unremarkable or obscured by artifact, but the patients were treated for IE based on either meeting definite modified Duke criteria in 1 case or empirically based on high clinical suspicion in 2 cases.

Furthermore, 6 of 14 cases (43%) were notable for delayed myocardial enhancement, most suggestive of an inflammatory or infectious fibrotic process, but these findings were deemed nonspecific and did not guide medical decision-making. In 3 of the 6 cases, patients were treated specifically for IE based on alternative findings. In the remaining 3 of the 6 cases, patients were not diagnosed with IE, but had concomitant indications for prolonged antibiotics.

Concomitant Indications for Prolonged Antibiotics

There was no significant difference in the duration of antibiotics for patients with CMR findings positive or equivocal Vs negative for IE (6.0 Vs 5.8 weeks, $P = 0.59$). However, in 9 patients (64%) there were 13 separate indications for prolonged courses of antibiotics as outlined in Table 2. The indications included 7 cases (50%) of spinal involvement (eg, vertebral osteomyelitis, diskitis, paraspinal or epidural phlegmon/

TABLE 2. Diagnostic findings, treatment regimens, and clinical outcomes

Patient #	Blood culture speciation and sensitivities	CMR results	TTE results	TEE results	Modified Duke criteria	Diagnosis & concominant indications for prolonged antibiotics	Treatment regimen	Treated specifically for IE	Repeat blood culture results	IE readmission	Death
1	Enterococcus faecalis (ampicillin-susceptible)	No evidence of IE	No evidence of IE	Not performed	Possible	Enterococcus faecalis bacteremia, pyelonephritis secondary to obstructing ureteral calculi	Ureteral stenting, amoxicillin / clavulanic acid x 4 wk (patient refused ampicillin IV x 4 wk)	No	Negative	No	No
2	Methicillin-resistant Staphylococcus aureus	No evidence of IE	No evidence of IE	Not performed	Rejected	MRSA bacteremia, left breast necrotizing fasciitis, and widely disseminated skin and soft tissue infection with multiple abscesses	I&D, vancomycin IV x 2 wk −> linezolid PO x 2 wk (due to vancomycin reaction)	No	Negative	No	No
3	Methicillin-susceptible Coagulase-negative Staphylococci (Staphylococcus lugdunensis)	Patchy subepicardial and mid-myocardial enhancement - most suggestive of inflammatory or infectious process; mild thickening of the anterior and posterior mitral valve leaflets	No evidence of IE	Small anterior mitral leaflet vegetation with moderate mitral regurgitation	Possible	Staphylococcus lugdunensis bacteremia, native mitral valve endocarditis, and lumbar vertebral osteomyelitis / diskitis with associated phlegmon	Cefazolin IV x 6 wk −> followed by chronic suppresive therapy with cephalexin	Yes	-	No	No
4	Methicillin-susceptible Staphylococcus aureus	No evidence of IE	No evidence of IE	Not performed	Possible	MSSA bacteremia, left 4th finger cellulitis and septic arthritis of the proximal interphalangeal joint, vertebral osteomyelitis / diskitis, psoas muscle abscess	Daptomycin IV x 6 wk (switched from cefazolin IV for logistics)	No	-	No	No

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TABLE 2. (*continued*)

Patient #	Blood culture speciation and sensitivities	CMR results	TTE results	TEE results	Modified Duke criteria	Diagnosis & concominant indications for prolonged antibiotics	Treatment regimen	Treated specifically for IE	Repeat blood culture results	IE readmission	Death
5	Methicillin-susceptible Staphylococcus aureus	No evidence of IE	No evidence of IE	Not performed	Definite	MSSA bacteremia and endocarditis with septic pulmonary emboli	Daptomycin IV x 6 wk (switched from cefazolin IV for logistics)	Yes	-	No	No
6	Methicillin-susceptible Staphylococcus aureus	Mild non-specific patchy delayed enhancement of the mid myocardium - represent a non-specific fibrotic process possibly from inflammatory or infectious processes	No evidence of IE	Not performed	Possible	MSSA bacteremia, vertebral osteomyelitis / diskitis, throacic paraspinal abscesses, lumbar epidural abscess, psoas muscless abscess, left ankle hardware infection in the setting of a remote left distal fibular metaphysis fracture s/p fixation, right shoulder sub-deltoid bursa and shoulder region abscess, septic bursitis of left olecranon	Nafcillin IV x 6 wk −> cefazolin IV x 2 wks	No	Negative	No	No
7	Methicillin-susceptible Staphylococcus aureus	No evidence of IE	No evidence of IE	Not performed	Possible	MSSA bacteremia and right 2nd toe osteomyelitis	Debridement and amputation of right second toe, cefazolin IV x 3 wk −> cefalexin PO x 3 wk	No	-	No	No

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TABLE 2. (*continued*)

Patient #	Blood culture speciation and sensitivities	CMR results	TTE results	TEE results	Modified Duke criteria	Diagnosis & concominant indications for prolonged antibiotics	Treatment regimen	Treated specifically for IE	Repeat blood culture results	IE readmission	Death
8	Streptococcus constellatus (a subgroup of viridans streptococci)	Asymmetric focal thickening of the non-coronary aortic valve leaflet which could represent early calcifications and/or possible early vegetation	No evidence of IE	Not performed	Possible	Strep constellatus bacteremia with presumed endocarditis complicated by mycotic aneurysm with intraparenchymal hemorrhage, septic pulmonary emboli, septic splenic emboli, and presence of ventricular septal defect	Ceftriaxone IV x 6 wk	Yes	-	No	No
9	Methicillin-susceptible Staphylococcus aureus	Delayed myocardial enhancement involving the basal septum the myocardium and basal lateral wall which is non-specific and could relate to an inflammatory or infectious fibrotic process	No evidence of IE	Not performed	Rejected	MSSA bacteremia, vertebral osteomyelitis / diskitis, and epidural phlegmon vs abscess	Nafcillin IV x 6 wk	No	-	No	No
10	Enterococcus faecalis (ampicillin-resistant), Enterococcus avium (ampicillin-susceptible), Klebsiella oxytoca (ampicillin-resistant, cefazolin-resistant), Citrobacter youngae (cephalosporin-resistant), Candida glabrata (micafungin-susceptible, fluconazole-intermediate)	Possible mild delayed myocardial enhancement of the mid myocardium of the proximal septum and inferior lateral wall which is non-specific and could represent inflammatory process or non-ischemic fibrosis	No evidence of IE	Not performed	Possible	Central line related polymicrobial bacteremia/fungemia, diskitis, bilateral septic emboli, possible endocarditis	Imipenem IV x 6 wk & micafungin IV x 6 wk	Yes	Negative	No	No

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TABLE 2. (*continued*)

Patient #	Blood culture speciation and sensitivities	CMR results	TTE results	TEE results	Modified Duke criteria	Diagnosis & concominant indications for prolonged antibiotics	Treatment regimen	Treated specifically for IE	Repeat blood culture results	IE readmission	Death
11	Methicillin-susceptible Staphylococcus aureus	Possible delayed myocardial enhancement in a non-ischemic distribution involving the proximal lateral and mid myocardium of the septum which could relate to inflammatory or infectious fibrotic process	No evidence of IE	Not performed	Possible	MSSA bacteremia with septic arthritis of left hip, right shoulder / glenohumeral joint / acromioclavicular joint	Cefazolin IV x 6 wk	No	-	No	No
12	Enterococcus faecalis (ampicillin-susceptible)	No evidence of IE, but prosthetic aortic valve partly obscured by magnetic susceptibility artifact	No evidence of IE	Not performed	Possible	Recurrent Enterococcus faecalis bacteremia, initially likely secondary to catheter associated urinary tract infection, later complicated by presumed prosthetic aortic valve endocarditis and confirmed epidural lumbar abscess	Vancomycin IV, ceftriaxone IV, and gentamicin IV x 6 wk	Yes	Negative	No	No

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TABLE 2. (*continued*)

Patient #	Blood culture speciation and sensitivities	CMR results	TTE results	TEE results	Modified Duke criteria	Diagnosis & concominant indications for prolonged antibiotics	Treatment regimen	Treated specifically for IE	Repeat blood culture results	IE readmission	Death
13	Methicillin-susceptible Staphylococcus aureus	Moderate aortic regurgitation with thickening Vs nodule of the right coronary valve leaflet measuring 0.6 × 1.1 cm which could represent a nodule or vegetation, patchy delayed myocardial enhancement suggestive of a non-ischemic inflammatory or infiltrative process	Dilated aortic root with moderate to severe aortic regurgitation; no valvular vegetations visualized	Aortic valve demostrates severe eccentric regurgitation with aortic diastolic flow reversal, and the right coronary cusp appears partially torn with an echogenic structure consistent with vegetation	Definite	MSSA bacteremia and native aortic valve endocarditis	Surgical aortic valve replacement, cefazolin IV x 6 wk	Yes	-	No	No

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TABLE 2. (*continued*)

Patient #	Blood culture speciation and sensitivities	CMR results	TTE results	TEE results	Modified Duke criteria	Diagnosis & concominant indications for prolonged antibiotics	Treatment regimen	Treated specifically for IE	Repeat blood culture results	IE readmission	Death
14	Enterococcus faecalis (ampicillin-susceptible)	No evidence of IE	Severe aortic regurgitation, small echogenicity on the left ventricular side of the aortic valve suspicious for vegetation, and moderate mitral regurgitation	Large, mobile vegetation on the aortic valve well over a cm in length, severe, wide-open aortic regurgitation with an eccentric jet, moderate to severe mitral regurgitation, mitral valve is diffusely thickened, and more focal thickening along P3 where a tiny vegetation is possible	Definite	Enterococcus faecalis bacteremia with native aortic valve endocarditis	Surgical aortic valve replacement and mitral valve repair, ceftriaxone IV & ampicillin IV x 6 wk	Yes	-	No	No

Abbreviations: CMR, cardiac magnetic resonance imaging, I&D, incision and drainage, IE, infective endocarditis, IV, intravenous, MRSA, methicillin-resistant Staphylococcus aureus, MSSA, methicillin-susceptible Staphylococcus aureus, PO, oral, s/p, status post, TEE, transesophageal echocardiography, TTE, transthoracic echocardiography.

TABLE 3. CMR performance among patients treated for confirmed or presumed IE

Patient #	CMR findings	TTE findings	TEE findings	Modified Duke Criteria	Diagnosis of IE	Concomitant indication for prolonged antibiotics	CMR result clinically useful in guiding antibiotic therapy	Comments
3	Equivocal (mild thickening of the anterior and posterior mitral valve leaflets	Negative	Positive (small anterior mitral valve leaflet vegetation, moderate mitral regurgitation)	Possible	Confirmed	Yes	No	CMR was not diagnostic. IE was diagnosed only by TEE. Additionally, treated with a prolonged antibiotic course for vertebral osteomyelitis / diskitis
5	Negative	Negative	Not performed	Definite	Confirmed	No	No	CMR was negative, but IE was diagnosed by modified Duke criteria (blood cultures, intravenous drug use, fever, and septic pulmonary emboli).
8	Positive (asymmetric focal thickening of aortic valve leaflet - early calcification Vs vegetation)	Negative	Not performed	Possible	Presumed	No	Yes	CMR was the only advanced imaging study performed and was abnormal, though not definitively diagnostic. There was already high clinical suspicion for IE given numerous embolic phenomena (mycotic aneurysm, septic pulmonary emboli, and septic splenic emboli) in the setting of a ventricular septal defect. Thus, treated empirically for IE.

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TABLE 3. (*continued*)

Patient #	CMR findings	TTE findings	TEE findings	Modified Duke Criteria	Diagnosis of IE	Concomitant indication for prolonged antibiotics	CMR result clinically useful in guiding antibiotic therapy	Comments
10	Negative (nonspecific delayed myocardial enhancement)	Negative	Not performed	Possible	Presumed	Yes	No	Despite negative CMR, treated empirically for IE given bilateral septic pulmonary emboli in the setting of central line related polymicrobial bacteremia / fungemia. Additionally, treated with a prolonged antibiotic course for diskitis.
12	Negative (prosthetic aortic valve partly obscured by magnetic susceptibility artifact)	Negative	Not performed	Possible	Presumed	Yes	No	CMR demonstrated low diagnostic utility due to artifact from prosthetic valve. Regardless, treated empirically for prosthetic valve endocarditis given recurrent Enterococcus bacteremia. Additionally, treated with a prolonged antibiotic course for epidural lumbar abscess.
13	Positive (moderate aortic regurgitation with lesion of right coronary aortic valve leaflet which could represent a nodule Vs vegetation)	Positive (moderate to severe aortic regurgitation, though no valvular vegetations visualized)	Positive (severe aortic regurgitation, right coronary cusp partially torn with an echogenic structure consistent with vegetation)	Definite	Confirmed	No	Yes	TTE demonstrated significant valvulopathy. While CMR was notable for a lesion, it was not definitively diagnostic. A TEE was completed for further characterization and clearly demonstrated both a valvular vegetation and the resultant valvular insufficiency. Subsequently underwent surgical aortic valve replacement.

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TABLE 3. (*continued*)

Patient #	CMR findings	TTE findings	TEE findings	Modified Duke Criteria	Diagnosis of IE	Concomitant indication for prolonged antibiotics	CMR result clinically useful in guiding antibiotic therapy	Comments
14	Negative	Positive (severe aortic regurgitation, small echogenicity on the left ventricular side of the aortic valve suspicious for vegetation, and moderate mitral regurgitation)	Positive (large, mobile vegetation on the aortic valve, severe, wide-open aortic regurgitation with an eccentric jet, moderate to severe mitral regurgitation, mitral valve diffusely thickened, and more focal thickening along P3 where a tiny vegetation is possible)	Definite	Confirmed	No	No	IE clearly identified on TTE & TEE. IE missed on CMR, but the study was actually performed for purposes of a viability study to determine need for concomitant single vessel coronary artery bypass grafting during open heart surgery. Subsequently underwent surgical aortic valve replacement and mitral valve repair.

Abbreviations: CMR, cardiac magnetic resonance imaging, IE, infective endocarditis, TEE, transesophageal echocardiography, TTE, transthoracic echocardiography.

abscess), 1 case (7%) of orthopedic hardware-related osteomyelitis, 1 case (7%) of septic arthritis, 2 cases (14%) of complicated skin and soft tissue infection, and 2 cases (14%) of psoas muscle abscesses.

Clinical Outcomes

Two cases (14%) underwent surgical valve replacement in addition to antibiotic therapy, of which only 1 of 2 cases had a vegetation visualized on CMR (Fig 1) as compared to 2 of 2 cases on TEE. Of the 5 cases (36%) that completed repeat blood cultures after antibiotic therapy, 100% remained negative. No readmissions for IE or deaths were reported among the entire study population over a follow-up period of 1 year.

Discussion

Context

To the best of our knowledge, this is the third study ever conducted examining the real-world application of CMR as the primary imaging modality following TTE for the diagnosis of IE. Previously, Dursun et al. studied 16 patients with a preliminary diagnosis of IE and found 14 valvular vegetations in 11 patients on CMR; additionally, they noted delayed contrast enhancement attributable to extension of inflammation in numerous locations.[17] They concluded that features of IE can be readily

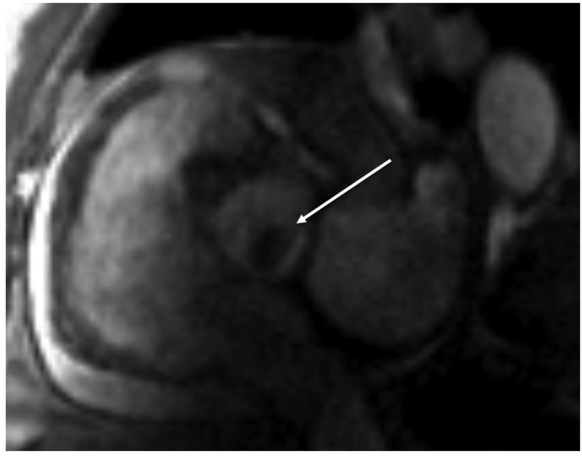

FIG 1. Vegetation of the right coronary valve leaflet measuring 0.6 × 1.1 cm associated with severe aortic insufficiency.

detected by CMR, via visualization of either valvular vegetations or delayed enhancement representing endothelial inflammation of the cardiovascular structures, and thus CMR could contribute to the diagnosis and management of IE. In contrast, Zatorska et al. studied 20 patients, and noted vegetation visualization was rather limited by the low spatial resolution of CMR, though they noted significant advantages in diagnosing perivalvular complications, assessing the degree of valvular insufficiency and resultant hemodynamic consequences, and evaluating the degree of myocardial inflammation.[18]

Value of Findings

In our study, both the diagnostic accuracy and clinical utility of CMR for IE appear questionable. CMR detected valvular vegetations in 2 cases but also missed valvular vegetations in 2 cases; in comparison, when TEE was performed in 3 of these 4 cases, valvular vegetations were detected in all 3 cases. Additionally, in 1 case with a prosthetic aortic valve, magnetic susceptibility artifact reduced the diagnostic utility of the study. Moreover, 3 cases were treated empirically for IE regardless of CMR findings, based on clinical suspicion alone. Finally, 6 cases were notable for delayed myocardial enhancement, but these results were deemed non-specific and did not guide medical decision-making. Taken together, these findings cast doubt on CMR as a viable diagnostic modality for IE at this time.

Pros and Cons of CMR

In theory, CMR confers many advantages in the diagnosis of IE. In addition to being a non-invasive modality utilizing non-ionizing radiation, there are multiple techniques available to gather a diverse array of clinical information.[13,19] Spin echo accurately defines cardiovascular anatomy, without the limitations of acoustic windows or attenuation artifacts due to body habitus associated with echocardiography and nuclear imaging respectively. Balanced steady-state free precession cine quantifies ventricular cavity size and function, valvular function, and defines intracardiac masses. Phase contrast velocity mapping quantifies the severity of valvular regurgitation and stenosis. These quantitative measures are highly accurate, precise, and reproducible across studies as no geometric assumptions are required.[13] Late gadolinium enhancement (LGE) patterns can help characterize myocarditis, and delayed hyperenhancement can help identify and characterize pericarditis.

However, CMR is a rapidly evolving area of imaging. It requires deep local expertise and technical staff to appropriately protocolize and execute studies correctly. Electrocardiographic gating and breath holding or respiratory gating are required to achieve optimal temporal and spatial resolution.[19] Magnetic susceptibility artifact from mechanical prosthetic valves and CIEDs can drastically affect diagnostic utility. Additionally, there are numerous considerations when contemplating a study including cardiac rhythm, renal function, CIED compatibility, ferromagnetic metallic implants, duration, cost, and availability of the modality.

Limitations

This study has several limitations. From a design perspective, the primary reason CMR was utilized was to prevent aerosol generation and thus protect healthcare workers. However, this risk must be balanced against the risk of transporting a critically ill or high-risk patient through the hospital to the MRI scanner, exposure risk to multiple personnel including nurses and technicians, contamination of the MRI room requiring full disinfection, and long acquisition times for MRI.[15,16] From a technical perspective, only 3 cases underwent TEE, thus limiting direct CMR Vs TEE comparisons, particularly given TEE is the current gold standard. Additionally, the interpretation and management of delayed myocardial enhancement was unclear, thus confusing the clinical picture. Furthermore, regardless of the presence of IE, many patients had concurrent indications for prolonged antibiotic therapy, thus confounding the clinical picture. Finally, given such diverse clinical scenarios (eg, type of organism, native Vs prosthetic valve involvement, and underlying patient risk factors), small sample size, and low event rate of valvular vegetations, comparing long-term outcomes is difficult.

Further Directions

The clinical scope of CMR continues to expand as capabilities increase and limitations are addressed. For spatial resolution, magnetic field strength is a critical factor with respect to image quality, signal-to-noise ratio, contrast-to-noise ratio, and acquisition time; newer magnet technologies allow significantly higher field strengths than the conventional 1.5 Tesla magnets, with many clinical laboratories utilizing 3 Tesla magnets, and research laboratories studying ultrahigh field strengths up to 9 Tesla with promising results and new challanges.[20-23] For temporal resolution, the recent development of 4-dimensional (4D) flow CMR enables

comprehensive assessment of blood flow via simultaneous velocity encoding that is resolved in all 3 dimensions of space and the dimension of time over multiple phases in the cardiac cycle.[24] Recently this 4D flow CMR was utilized in conjunction with 3D TEE to characterize and intervene in a significant mitral paravalvular leak following a bio-prosthetic mitral valve replacement for IE.[25] For limitations related to electrocardiographic and respiratory gating as well as acquisition time, novel developments in post-processing promise to allow free-breathing, non-electrocardiographic techniques for obtaining sequences faster while preserving spatial and temporal quality.[26-28] For limitations related to CIEDs, recent studies demonstrate that CMR in non-MRI-conditional systems, including those with hybrid configurations, is feasible and safe without clinically meaningful device parameter changes or adverse events.[29,30] Though, abandoned leads remain a challenge.[31-34] Recent advances in wideband LGE protocols, for both segmented and single-shot sequences, have demonstrated efficacy in accurately reducing device-related artifact, particularly with transvenous ICDs and cardiac resynchronization therapy devices.[35-37]

Conclusions

CMR may provide a viable alternative to TEE in settings where AGPs should be minimized, such as the COVID-19 pandemic. However, the role of CMR requires further clarification. In our study, CMR demonstrated mixed results in diagnosing valvular vegetations and guiding clinical decision making; additionally, a portion of patients were treated empirically for IE based on clinical suspicion alone, suggesting a lack of confidence in CMR as a valid diagnostic modality. Further prospective studies are needed to evaluate the performance of CMR relative to TEE for the diagnosis and management of IE. As CMR is a rapidly evolving technology, future developments may address current diagnostic limitations, particularly regarding temporal and spatial resolution.

Author Contributions

Sapan Bhuta: data collection/curation, formal analysis, writing - original draft, writing - review & editing. Neha J. Patel: data collection/curation, writing - review & editing. Jacob A. Ciricillo: data collection/curation. Michael N. Haddad: data collection/curation. Waleed Khokher: writing - review & editing. Mohammed Mhanna: writing - review & editing. Mitra Patel: writing - review & editing. Cameron Burmeister: writing

- review & editing. Hazem Malas: writing - review & editing. Joel A. Kammeyer: Conceptualization, writing - review & editing, Supervision.

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