ESC European Society of Cardiology

European Heart Journal - Cardiovascular Imaging (2021) **00**, 1–8
https://doi.org/10.1093/ehjci/jeab230

ORIGINAL PAPER

Myocarditis following COVID-19 vaccination: magnetic resonance imaging study

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Received 27 July 2021; editorial decision 18 October 2021; accepted 20 October 2021

Aims To describe the cardiac magnetic resonance (CMR) imaging findings of patients who developed myocarditis following messenger RNA (mRNA) coronavirus disease 2019 (COVID-19) vaccination.

Methods and results The present study retrospectively evaluated patients with clinically adjudicated myocarditis within 42 days of the first Pfizer-BNT162b2 mRNA COVID-19 vaccination, between 20 December 2020 and 24 May 2021 who underwent CMR. A total of 15 out 54 patients (28%) with myocarditis underwent a CMR and were included, 100% males, median age of 32 years (interquartile range = 22.5–40). Most patients presented with chest pain (87%) and had an abnormal electrocardiogram (79%). The severity of the disease was mild in 67% and intermediate in 33%. All patients survived and one patient was readmitted during the study period. CMR was performed at a median of 65 days (range 3–130 days) following diagnosis. Median ejection fraction was 58% (range 51–74%) global- and regional wall motion abnormalities were present in one and three patients, respectively. Native T1 was available in 13/15 patients (2/3 in 3 T and 11/12 in the 1.5 T), with increased values among 6/13. Late gadolinium enhancement (LGE) was found among 13/15 patients with a median of 2% (range 0–15%) with inferolateral wall being the most common location (8/13). The patterns of the LGE were: mid-wall in six patients; epicardial in five patients; and mid-wall and epicardial in two patients.

Conclusions Among patients who were diagnosed with post-vaccination clinical myocarditis, CMR imaging findings are mild and consistent with 'classical myocarditis'. The short-term clinical course and outcomes were favourable.

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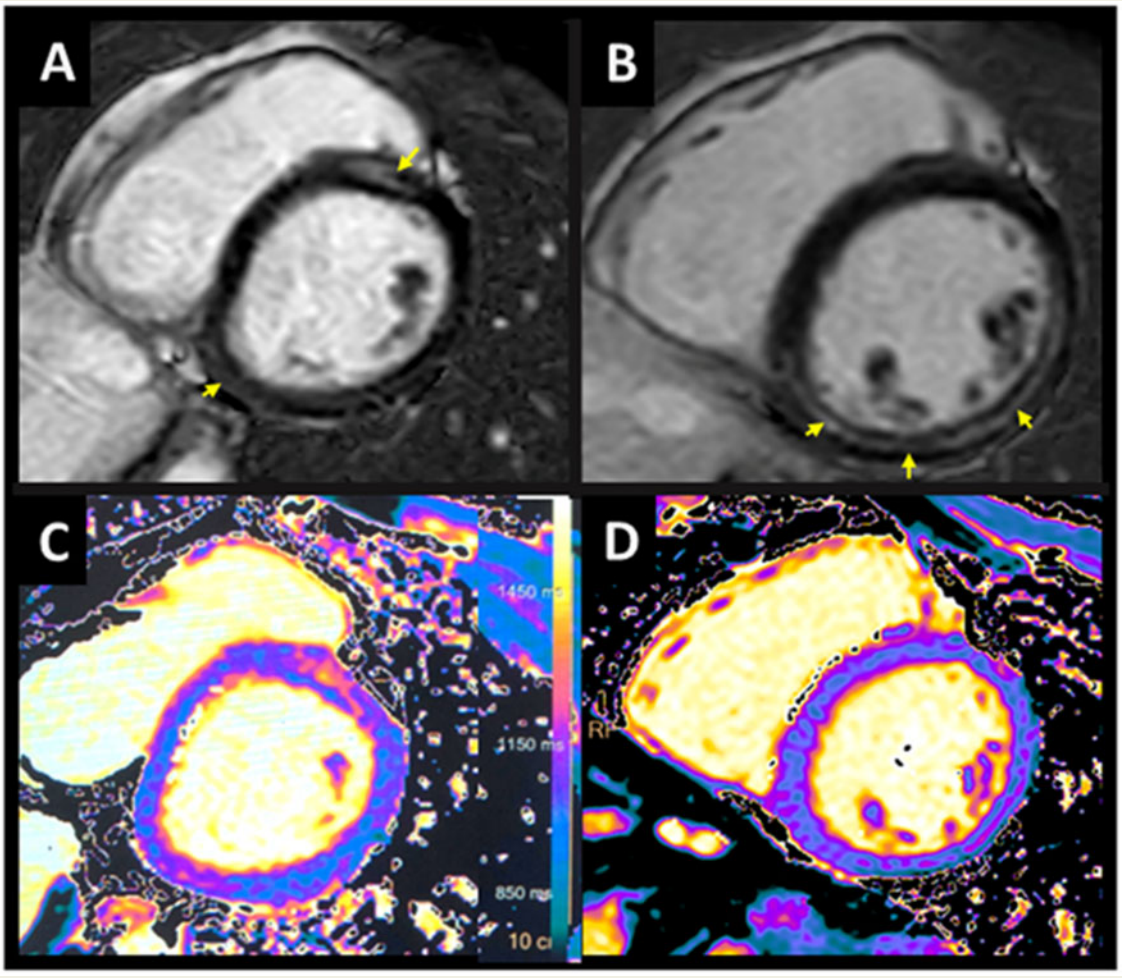
Graphical Abstract



Keywords myocarditis • COVID-19 vaccination • cardiac magnetic resonance

Introduction

Myocarditis has been reported following coronavirus disease 2019 (COVID-19) infection but not clearly recognized as a possible adverse event of the Pfizer-BNT162b2 messenger RNA (mRNA) COVID-19 vaccination.[1] Recently, a likely association between myocarditis or pericarditis and COVID-19 vaccination among young people has been reported by the Centers for Disease Control and Prevention (CDC)[2] as well as by the Israeli Ministry of Health.[3] A number of case reports and small series described myocarditis in temporal association with the mRNA-based COVID-19 vaccination.[4–6] To date, there has been very limited data of cardiovascular magnetic resonance (CMR) imaging findings in patients presenting with myocarditis following COVID-19 vaccination.[4–6]

In the present study, we evaluated: (i) CMR imaging findings, (ii) clinical presentation and short-term clinical outcomes in a group of patients with probable myocarditis at early onset following immunization with the Pfizer-BNT162b2 mRNA COVID-19 vaccines.

Methods

Study population

Our sample frame included all members of Clalit Health Services (CHS), the largest health maintenance organization in the Israeli National Healthcare System (covering a population of 4.7 million patients, 52% of the Israeli population) who received at least one dose of the Pfizer-BNT162b2 mRNA COVID-19 vaccination between 20 December 2020 and 24 May 2021. Patients with myocarditis within up-to 42 days from vaccination were identified through the CHS database, which has been elaborately described previously,[7] using ICD-9 coding. Thereafter, each suspected case was independently reviewed by two cardiologists through careful evaluation of the patient's electronic medical record which

Table 1 Baseline characteristics, clinical findings, and outcomes of the study cohort

Variable	Statistic	Number of cases
Demographics		
Age: years, median (IQR)	32 (22.5–40)	15
Sex: male (%)	100%	15
Time from first vaccine to diagnosis[a] (days), median (IQR)	26 (17–28.5)	15
Time from first vaccine to diagnosis[b] (days), median (IQR)	8 (6–11)	5
Time from second vaccine to diagnosis (days), median (IQR)	3.5 (3–5.75)	10
Comorbidity and risk factors (%)		
Diabetes mellitus	0%	15
Hypertension	20%	15
Dyslipidaemia	7%	15
Atrial fibrillation	0%	15
Coronary artery disease	0%	15
Previous myocarditis	0%	15
Previous pericarditis	7%	15
Known LV dysfunction	0%	15
Baseline medications (%)		
Aspirin	0%	15
P2Y12 inhibitors	0%	15
Beta blockers	7%	15
ACE I/ARBs	13%	15
Presenting symptoms and signs		
Chest pain (%)	87%	15
Palpitations (%)	0%	15
Dyspnoea (%)	0%	15
Fever (%)	13%	15
Symptoms of viral infection (%)	13%	15
ECG findings		
Normal (%)	21%	14
ST elevation (%)	50%	14
T-wave changes (%)	14%	14
Atrial fibrillation (%)	5.1%	14
Non-sustained ventricular tachycardia (%)	5.1%	14
Laboratory values		
Troponin T (ng/L), median (IQR)	958 (196–2659)	13
Creatine kinase (mg/dL), median (IQR)	574 (160–1300)	9
C-reactive protein (mg/dL), median (IQR)	5.2 (1.2–19.6)	12
Haemoglobin, median (IQR)	13.8 (13–15.3)	12
White blood cells (K/micl), median (IQR)	9.1 (7.5–12)	12
	0.8 (0.7–0.82)	12
Creatinine (mg/dL), median (IQR)		
EF upon presentation (%), median (IQR)	55 (50–58.5)	10
Coronary CTA	42%	12
Coronary angiography	8%	12
Biopsy	7%	15
Clinical course during index hospitalization and outcomes		
Need for inotropes/vasopressors (%)	0%	15
Need for mechanical circulatory support (%)	0%	15
Arrhythmias (%)	0%	14
Disease severity: mild	67%	15
Disease severity: intermediate	33%	15
Disease severity: severe	0%	14
Death	0%	15
Readmission	6%	15

ACE I, angiotensin-converting enzyme inhibitor; ARB, angiotensin receptor blocker; CTA, computed tomography angiography; ECG, electrocardiogram; EF, ejection fraction; LV, left ventricle; IQR, interquartile range.
[a]Among all patients.
[b]Among patients in whom myocarditis was diagnosed after the first vaccine.

includes all admission and discharge summaries, results of laboratory and imaging tests, and outpatient and primary clinic visits summaries. Every cardiologist separately adjudicated the diagnosis of vaccine-associated myocarditis according to the CDC case definition criteria for probable myocarditis.[8] In case of disagreement, the case was reviewed by a third cardiologist who settled the dispute. Myocarditis was classified as fulminant or non-fulminant according to the definition of the American Heart Association.[9] As part of the adjudication process, active COVID-19 infection was ruled out either by PCR or serological testing (all patients admitted to Israeli hospitals, regardless of the admission diagnosis underwent COVID-19 screening, so this was available in all cases included in our study). Non-fulminant myocarditis cases were further classified as mild or intermediate disease according to the definition by Sinagra *et al.*[10] This definition classifies as intermediate-risk patients with persistent left ventricular dysfunction, regional wall motion abnormalities, persistent electrocardiogram (ECG) abnormalities, presence of late gadolinium enhancement (LGE) on CMR, or frequent non-sustained ventricular arrhythmias.

The present study included patients with clinically diagnosed and adjudicated myocarditis who underwent CMR, either during hospitalization or after discharge.

This study was approved by the CHS institutional review board and performed consistently with the Helsinki declaration. Exemption from informed consent was granted.

CMR imaging

CMR imaging was performed using either 1.5-T scanner (Ingenia; Philips Medical System) or 3-T scanner (Magnetom Vida; Siemens Healthineers), implementing standardized imaging protocols. CMR protocol included multiplanar cine imaging for acquisition of cardiac function, volumes, and

Table 2 CMR findings of the study patients

No.	Age (years)	Sex	From first vaccine to diagnosis (days)	From second vaccine to diagnosis (days)	Time between diagnosis and MRI (days)	LVEF (%)	Wall motion abnormality	LVEDV/ BSA	LVESV/ BSA	LV mass (gr)	LV mass/ BSA	T1 map global (ms)	T2 map global	Global ECV	LGE (%)	LGE localization	LGE pattern	LGE in pericard	Pericardial effusion	Diameter of effusion (mm)[a]
1	41	M	25	4	103	70	None	58.2	17.7	90	48.8	1009	48.7	25	1	Inferolateral (basal)	Mid-wall	N	Circular	3
2	24	M	26	3	100	51	Global	114	56	63.5	37.6	950	50.2	24	2	Inferolateral (basal)	Mid-wall and epicardial	N	Circular	2
3[b]	17	M	23	3	4	58	None	78	33	62	37.4	1270			9	Inferolateral, anterolateral, (basal to apical)	Epicardial	N	Circular	3.5
4[b]	37	M	40		8	67	None	67.2	22.5	104.4	50.2	1235			3	Inferolateral (basal, mid)	Epicardial	Y	Circular	6.8
5[b]	39	M	27	5	3	52	Regional	51.3	24.9	56.5	33.7				15	Inferoseptal, anteroseptal (basal), inferolateral, anterolateral (basal) Inferolateral (med), septum, lateral (apical)	Mid-wall and epicardial	N	N	
6	53	M	6		130	59	None	62.2	25.7	89.4	48.2	1022	50.8	24.5	0	None	NA	Y	Local	
7	19	M	30	6	37	56	Regional	82.1	36.2	77.7	45.2	1100	49.5	28.1	12	Inferior (apical-basal) Inferolateral (mid, basal), anterior (basal, mid) septum, lateral (apical)	Mid-wall	Y	N	
8	28	M	49	27	112	58	None	75.9	32.1	97.6	52.4	1070	52.8	29	4	Inferolateral, anterolateral (basal)	Mid-wall	N	N	
9	21	M	11		65	63	None	55.6	20.7	104	57	1066	49.5	22.3	0	None	NA	N	N	
10	17	M	23	2	15	62	None	81.1	30.8	92.9	48.1	1023	51.9	32.7	5		Epicardial	N	Circular	6

Continued

Table 2 *Continued*

No.	Age (years)	Sex	From first vaccine to diagnosis (days)	From second vaccine to diagnosis (days)	Time between diagnosis and MRI (days)	LVEF (%)	Wall motion abnormality	LVEDV/ BSA	LVESV/ BSA	LV mass (gr)	LV mass/ BSA	T1 map global (ms)	T2 map global	Global ECV	LGE (%)	LGE localization	LGE pattern	LGE in pericard	Pericardial effusion	Diameter of effusion (mm)[a]
																Inferior, inferolateral (basal), inferior, inferoseptal, inferolateral (mid)				
11	36	M	6		57	62	None	69.4	26.2	75	41.9	1072	49.9	26.6	1	Lateral (apical)	Mid-wall	Y	Circular	3
12	27	M	26	3	102	58	None	69.8	48	91.5	48	1007	47.5	27.3	2	Inferolateral (basal)	Epicardial	N	N	
13	42	M	8		47	74	None	59.4	15.5	104	52	1057	49.8	34	2	Inferolateral (apical, basal), anterolateral (basal)	Epicardial	N	Y	3
14	76	M	35	14	103	55	Regional	78.5	35	112	55				2	Inferolateral (basal)	Mid-wall	N	N	
15	32	M	26	3	80	58	None	61.6	25.8	80	42	989		27.5	1	Inferior (basal), inferolateral (basal)	Mid-wall	N	N	

BSA, body surface are; LGE, late gadolinium enhancement; LV, left ventricular; LVEDV, left ventricular end-diastolic volume; LVESV, left ventricular end-systolic volume; M, male; N, no; Y, yes.
[a]Diameter of pericardial effusion was measured at end-systolic frame.
[b]Patients no. 3–5: MRI was performed at 3-T scanner, while the rest at 1.5-T scanner.

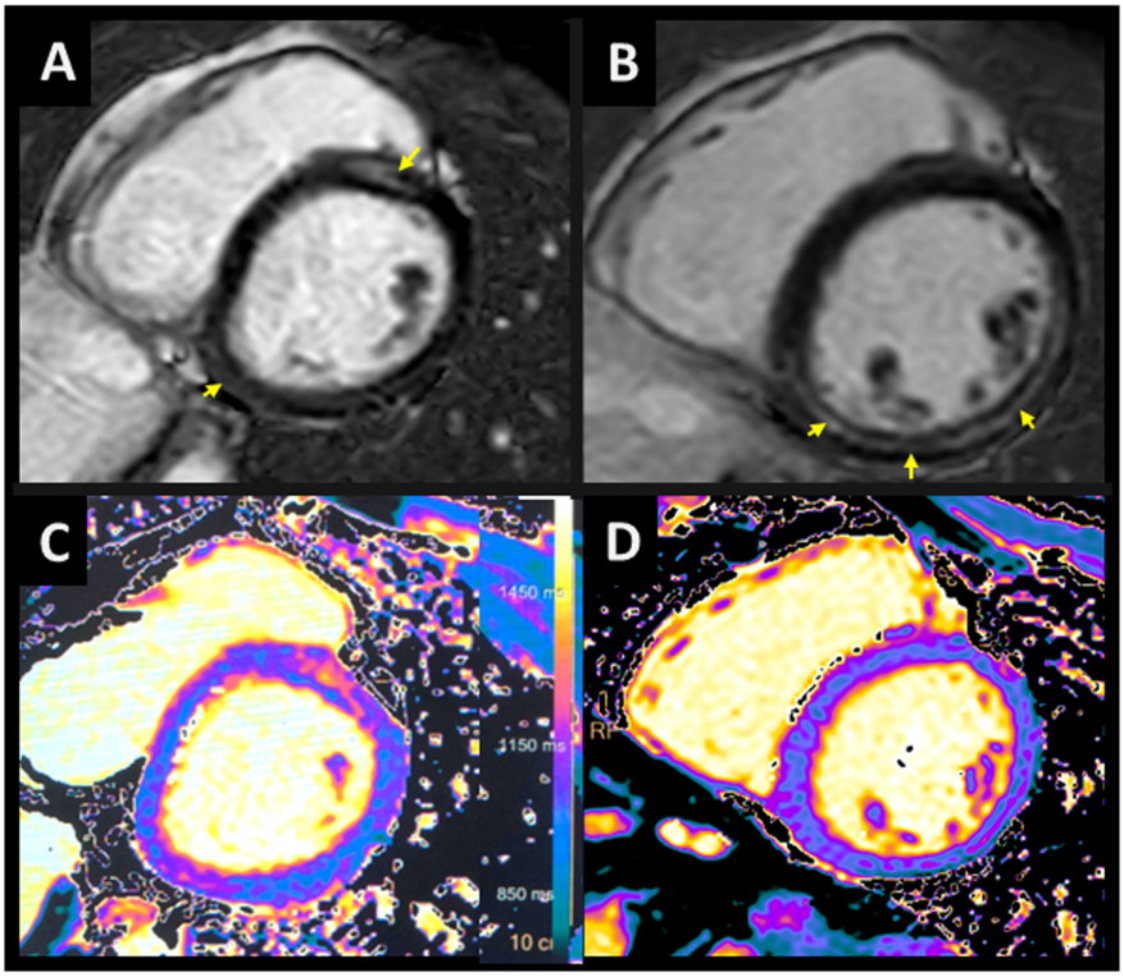


Figure 1 Representative example of cardiac magnetic resonance imaging in patient number 7 demonstrating late gadolinium enhancement involving the mid-wall of the basal antero-septal and inferior segments (*A*), and of the mid-ventricular inferior and infero-lateral segments (*B*). A corresponding myocardial injury in native T1 mapping is presented (*C* and *D*).

mass, and LGE imaging for scar imaging. At 1.5-T scanner balanced steady state free precession, single breath-hold modified inversion recovery Look-Locker (MOLLI) was used for T1 mapping and a navigator gated black blood prepared gradient spin-echo sequence was used for T2 mapping. At 3-T scanner, myocardial T1 mapping was performed using MOLLI sequence and T2 mapping using Myomaps. Native T1 and T2 mapping, and postcontrast T1 mapping were acquired in a three short-axis slices (apical, mid-ventricular, and basal).

For data analysis, the complete dataset was transmitted to a dedicated CMR workstation (Philips Intellispace Portal, version 11.0). Cardiac volumes, function, and mass were measured using automated contour detection with manual correction if required. Myocardial T1 and T2 relaxation times were measured for the complete mid-ventricular slice using motion-corrected images consistent with a previous report by Puntmann *et al.*[12] To avoid overestimation of T1 value due to partial volume effect,[13] the apical slices were not analysed. In addition, there are no differences in T1 value between basal and mid-ventricular slices[13] and in some cases, the basal slice may contain part of left ventricular outflow tract. For the assessment of T1, T2 relaxation times, and LGE endo- and epicardial contours of the left ventricle were traced, while excluding epicardial fat, pericardium, and blood from analysis. For 1.5-T scanner, abnormal native T1 and T2 values were defined as greater than 1060 ms and greater than 57 ms; respectively[11] and for 3-T scanner abnormal native T1 values were defined as greater than 1105 ms.[12] LGE was defined as an image intensity level ≥2 SDs above the mean of the remote myocardium. The amount of LGE was expressed as percentage of left ventricular myocardial mass and the extracellular volume (ECV) was calculated based on pre- and postcontrast T1 images. Pericardial LGE was considered present when enhancement involved both pericardial layers, irrespective of the presence of pericardial effusion. The diameter of pericardial effusion was measured at end-systolic frame.

Statistical analysis

The current study applied descriptive statistical methodology. Baseline characteristics of the patients are presented as counts (%) for categorical variables and median (interquartile range) or mean (±standard deviation) for continuous variables, as appropriate.

Results

Throughout the study period, 2 566 825 CHS members received at least one dose of the BNT162b2 mRNA COVID-19 vaccine, of which 2 404 581 (94%) had received both doses. Initially, 159 potential myocarditis cases were identified within 42 days of vaccination. A total of 54 patients met the clinical diagnosis of myocarditis following the adjudication process as abovementioned. Of these, CMR was performed in 15 patients (28%) who are included in this study. A total of 10 (67%) patients were diagnosed with myocarditis after the second vaccine [3.5 (3–5.75) days (median (interquartile range, IQR)] and 5 (33%) after the first vaccine [8 (6–11) days (median (IQR))]. In the former group (10 patients with myocarditis after the second vaccine), the time from the first vaccine and the diagnosis was [26 (25.25–29.25) days (median (IQR)].

Clinical characteristics

All the included 15 patients were males with a median age of 32 years (IQR = 22.5–40). The baseline characteristics of the study cohort are presented in *Table 1*. The rates of comorbidity and cardiovascular risk factors in the study cohort were very low, with most of the patients being otherwise healthy prior to the index event (i.e. myocarditis), without significant prior medical therapy. The most common presenting symptom was chest pain (87% of patients), while only 13% presented with fever or other symptoms clinically associated with viral infection. Abnormal electrocardiographic findings were recorded among 79% of the evaluated patients, with the most prevalent abnormality being ST-segment elevation. The median value of the peak Troponin level was 958 ng/L (IQR = 196–2659) and for creatine kinase 574 mg/dL (IQR = 574–1300). The median C-reactive protein was 5.2 mg/dL (IQR = 1.2–19.6). The median ejection fraction, as evaluated by echocardiography upon presentation, was 55% (IQR = 50–58.5). Obstructive coronary artery disease was excluded among six patients, who were older with relatively high prevalence of cardiovascular risk factors, in five patients using computed tomography coronary angiography and in one patient using invasive coronary angiography. Only one patient underwent a myocardial biopsy which showed interstitial infiltration of mostly lymphocytes as well as eosinophils and few neutrophils infiltration consistent with myocarditis. The severity of the disease was defined as mild in 67% and intermediate in 33% (no severe or fulminant cases) based on the previously mentioned classification, no patient required inotropes or mechanical circulatory support. All patients survived during the study period and only one patient was readmitted following the myocarditis event.

CMR imaging findings

Patients underwent CMR imaging after a median of 65 (range 3–130 days) days following the diagnosis of myocarditis. The main findings of the CMR and the representative images are presented in *Table 2* and *Figure 1*. The median left ventricular ejection fraction was within normal range 58% (range 51–74%), global- and regional wall motion abnormalities present in one and three patients; respectively. Native T1 was available in 13/15 patients (2/3 in 3-Tesla scanner and 11/12 in 1.5-Tesla scanner), with increased values among 6/13 patients. T2 values were within normal range, and ECV was increased among 4/11 patients. LGE was present among 13/15 patients with a median LGE% of 2% (range 0–15%) with inferolateral wall being the most common location (8/13). The patterns of the LGE were as following: (i) mid-wall in six patients; (ii) epicardial in five patients; and (iii) mid-wall and epicardial in two patients. LGE in the pericardium was present in 4/15 patients with pericardial effusion present in 7/15 patients, circular in 6/7 and local in 1/7 patients. The diameter of pericardial effusion was 3 mm (range 2–6.8 mm).

Discussion

We report herein in-depth CMR imaging findings, clinical presentation and short-term clinical outcomes of a case series of 15 patients with a clinical diagnosis of myocarditis following the Pfizer-BNT162b2 mRNA COVID-19 vaccination and meeting the CDC definition of probable myocarditis. To our knowledge, this is the largest report to date with a comprehensive clinical evaluation and systemic CMR imaging evaluation of this potential adverse reaction of mRNA-based COVID-19 vaccine. All patients were male and had a relatively short-term interval between vaccination, mostly second vaccine dose, and symptom onset. The consistent pattern of clinical presentation, rapid recovery from acute myocarditis, and excellent short-term clinical outcomes characterized the presented case series.

CMR imaging findings in our case series suggest that myocarditis following COVID-19 vaccination is overall mild, consistent with myocarditis secondary to other aetiologies, and similar to those described in smaller CMR case series evaluating possible association between mRNA driven COVID-19 vaccine and myocarditis.[4–6] Notably, CMR imaging findings were mild in most patients: left ventricular ejection fraction was normal or very mildly reduced, the parametric mapping showed normal or a mildly elevated T1 relaxation time, and the delayed phase sensitive images showed relatively small extent of LGE in most patients. Interestingly, the findings are also similar to the CMR findings described by Puntmann *et al.*[12] in a cohort of unselected patients who recently recovered from COVID-19, which could imply some common aetiological pathways.

Despite the fact that myocardial biopsy was performed in only one patient, the notable consistent clinical presentation and the pattern of clinical course suggests hypersensitivity myocarditis as reported in vaccine-associated myocarditis.[14,15] In addition, the close temporal relation between a clinical presentation and vaccination, usually after a second dose, is a typical feature of reported cases of vaccine-associated myocarditis and suggests an immune-mediated mechanism.[16] Myocarditis following receipt of other vaccines is rare and is recognized as causally linked only with smallpox immunization.[17] Notably, in contrast to passive case-finding, Engler *et al.*[14] reported a significantly higher myocarditis and pericarditis after smallpox vaccination in active prospective follow-up of participant receiving vaccination. Therefore, larger prospective follow-up studies using CMR imaging of participant receiving COVID-19 vaccination is warranted.

Limitations

CMR was performed after a median of 65 days following the diagnosis of myocarditis and therefore the T2 relaxation values were within normal range. Thus, the CMR imaging findings are not consistent with the updated Lake Louise criteria for the early diagnosis of

myocarditis[18]; however, our case series included patients with a clinical diagnosis of probable myocarditis based on CDC case definition but not based on Lake Louise criteria. Furthermore, our study includes 15 patients in whom CMR was performed, out of 54 patients with clinically diagnosed vaccine-associated myocarditis. Although the distribution of clinical severity did not differ between patients who underwent and those that did not undergo a CMR, selection bias could not be ruled out.

Conclusions

We presented a case series of patients with myocarditis temporally associated with the Pfizer-BNT162b2 mRNA COVID-19 vaccine. CMR imaging findings, clinical characteristics, and short-term clinical outcomes suggest a favourable clinical course. These findings should be taken into account in the preventive management of COVID-19 pandemic geared towards large scale population immunization programmes.

Conflict of interest: none declared.

Data availability

The data that support the findings of this study are available from the Rabin Medical Center and Clalit Health Services, but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of the Rabin Medical Center and Clalit Health Services.

References

1. Agricola E, Beneduce A, Esposito A, Ingallina G, Palumbo D, Palmisano A *et al.* Heart and lung multimodality imaging in COVID-19. *JACC Cardiovasc Imaging* 2020;**13**:1792–808.
2. Centers for Disease Control and Prevention. Selected adverse events reported after COVID-19 vaccination. 2021. https://www.cdc.gov/coronavirus/2019-ncov/vaccines/safety/adverse-events.html (10 July 2021, date last accessed).
3. Surveillance of Myocarditis (Inflammation of the Heart Muscle) Cases Between December 2020 and May 2021 (Including) | Ministry of Health [Internet]. https://www.gov.il/en/departments/news/01062021-03 (13 June 2021, date last accessed).
4. Montgomery J, Ryan M, Engler R, Hoffman D, McClenathan B, Collins L *et al.* Myocarditis following immunization with mRNA COVID-19 vaccines in members of the US Military. *JAMA Cardiol* 2021; **6**:e212833.
5. Shaw KE, Cavalcante JL, Han BK, Gössl M. Possible association between COVID-19 vaccine and myocarditis: clinical and CMR findings. *JACC Cardiovasc Imaging* 2021;**14**:1856–61.
6. Rosner CM, Genovese L, Tehrani BN, Atkins M, Bakhshi H, Chaudhri S *et al.* Myocarditis temporally associated with COVID-19 vaccination. *Circulation* 2021; **144**:502–5.
7. Dagan N, Barda N, Kepten E, Miron O, Perchik S, Katz MA *et al.* BNT162b2 mRNA Covid-19 vaccine in a nationwide mass vaccination setting. *N Engl J Med* 2021;**384**:1412–23.
8. Centers for Disease Control and Prevention (cdc.gov). MMWR Weekly Report, May 30, 2003. https://www.cdc.gov/media/mmwrnews/2003/n030530.htm (12 July 2021, date last accessed).
9. Kociol RD, Cooper LT, Fang JC, Moslehi JJ, Pang PS, Sabe MA *et al.*; American Heart Association Heart Failure and Transplantation Committee of the Council on Clinical Cardiology. Recognition and initial management of fulminant myocarditis: a scientific statement from the American Heart Association. *Circulation* 2020;**141**:e69–92.
10. Sinagra G, Anzini M, Pereira NL, Bussani R, Finocchiaro G, Bartunek J *et al.* Myocarditis in clinical practice. *Mayo Clin Proc* 2016; **91**:1256–66.
11. Bohnen S, Radunski UK, Lund GK, Ojeda F, Looft Y, Senel M *et al.* Tissue characterization by T1 and T2 mapping cardiovascular magnetic resonance imaging to monitor myocardial inflammation in healing myocarditis. *Eur Heart J Cardiovasc Imaging* 2017;**18**:744–51.
12. Puntmann VO, Carerj LM, Wieters I, Fahim M, Arendt C, Hoffmann J *et al.* Outcomes of cardiovascular magnetic resonance imaging in patients recently recovered from coronavirus disease 2019 (COVID-19). *JAMA Cardiol* 2020;**5**:1265–73.
13. Puntmann VO, Valbuena S, Hinojar R, Petersen SE, Greenwood JP, Kramer CM *et al.*; SCMR Clinical Trial Writing Group. Society for Cardiovascular Magnetic Resonance (SCMR) expert consensus for CMR imaging endpoints in clinical research: part I—analytical validation and clinical qualification. *J Cardiovasc Magn Reson* 2018;**20**:67.
14. Engler RJ, Nelson MR, Collins LC, Spooner C, Hemann BA, Gibbs BT *et al.* A prospective study of the incidence of myocarditis/pericarditis and new onset cardiac symptoms following smallpox and influenza vaccination. *PLoS One* 2015;**10**:e0118283.
15. Tschöpe C, Ammirati E, Bozkurt B, Caforio ALP, Cooper LT, Felix SB *et al.* Myocarditis and inflammatory cardiomyopathy: current evidence and future directions. *Nat Rev Cardiol* 2021;**18**:169–93.
16. Stone CA Jr, Rukasin CRF, Beachkofsky TM, Phillips EJ. Immune-mediated adverse reactions to vaccines. *Br J Clin Pharmacol* 2019;**85**:2694–706.
17. Dudley MZ, Halsey NA, Omer SB, Orenstein WA, O'Leary ST, Limaye RJ *et al.* The state of vaccine safety science: systematic reviews of the evidence. *Lancet Infect Dis* 2020;**20**:e80–9.
18. Ferreira VM, Schulz-Menger J, Holmvang G, Kramer CM, Carbone I, Sechtem U *et al.* Cardiovascular magnetic resonance in nonischemic myocardial inflammation: expert recommendations. *J Am Coll Cardiol* 2018; **72**:3158–76.