Atrial septal defects (ASDs) are associated with atrial arrhythmias, but the arrhythmia substrate in these patients is poorly defined. We hypothesized that bi-atrial fibrosis is present and that right atrial fibrosis is associated with atrial arrhythmias in ASD patients. We aimed to evaluate the extent of bi-atrial fibrosis in ASD patients and to investigate the relationships between bi-atrial fibrosis, atrial arrhythmias, shunt fraction, and age.

Patients with uncorrected secundum ASDs (n = 36; 50.4 ± 13.6 years) underwent cardiac magnetic resonance imaging with atrial late gadolinium enhancement. Comparison was made to non-congenital heart disease patients (n = 36; 60.3 ± 10.5 years) with paroxysmal atrial fibrillation (AF). Cardiac magnetic resonance parameters associated with atrial arrhythmias were identified and the relationship between bi-atrial structure, age, and shunt fraction studied. Bi-atrial fibrosis burden was greater in ASD patients than paroxysmal AF patients (20.7 ± 14% vs. 10.1 ± 8.6% and 14.8 ± 8.5% vs. 8.6 ± 6.1% for right and left atria respectively, P = 0.001 for both). In ASD patients, right atrial fibrosis burden was greater in those with than without atrial arrhythmias (33.4 ± 18.7% vs. 16.8 ± 10.3%, P = 0.034). On receiver operating characteristic analysis, a right atrial fibrosis burden of 32% had a 92% specificity and 71% sensitivity for predicting the presence of atrial arrhythmias. Neither age nor shunt fraction was associated with bi-atrial fibrosis burden.

Bi-atrial fibrosis burden is greater in ASD patients than non-congenital heart disease patients with paroxysmal AF. Right atrial fibrosis is associated with the presence of atrial arrhythmias in ASD patients. These findings highlight the importance of right atrial fibrosis to atrial arrhythmogenesis in ASD patients.

Keywords: atrial septal defect • right atrium • atrial arrhythmias • cardiac MRI • late gadolinium enhancement
development of conduction velocity heterogeneity, conduction block, and increased vulnerability to the development and maintenance of AF.\textsuperscript{1,4}

Atrial late gadolinium enhancement cardiac magnetic resonance (CMR) imaging has been used to quantify atrial fibrosis in non-congenital heart disease AF patients where the presence and extent of fibrosis are associated both with disease severity and recurrence of arrhythmia following AF ablation.\textsuperscript{9,10} Localized atrial fibrosis has been demonstrated on histological examination of left and right atrial appendage and free wall tissue sampled at surgical closure in one study of ASD patients.\textsuperscript{11} However, no studies have evaluated the presence of pan-atrial fibrosis, the relative burden of right and left atrial fibrosis, or the relationship between atrial fibrosis and arrhythmogenesis in this cohort.

We hypothesized that CMR-defined bi-atrial fibrosis is detectable in ASD patients and may be comparable in extent to that of non-congenital heart disease patients with paroxysmal AF. Given the preferential exposure of the right atrium to the haemodynamic consequences of the ASD from birth, we further hypothesized that (i) right atrial fibrosis may be of particular importance for arrhythmogenesis in ASD patients and (ii) progressive right atrial structural remodelling may be related to patient age and/or shunt size (Qp:Qs).

Methods

This prospective cohort study conformed to the principles outlined in the Declaration of Helsinki. Ethical approval was granted by the Health Research Authority (17/LO/1218). Informed written consent was obtained prior to study participation. Consecutive adult patients >18 years with an uncorrected secundum ASD being considered for ASD closure were recruited to the ASD group. The comparison group consisted of adult patients with paroxysmal AF being considered for first-time AF ablation. Patients with significant co-existing structural heart disease including significant left ventricular hypertrophy, hypertrophic cardiomyopathy, and severe valvular disease were excluded. All patients underwent CMR imaging with dedicated bi-atrial late gadolinium enhancement sequences together with assessment of atrial area and volume. The presence of prior documented atrial arrhythmia on 12-lead ECG or 24-h continuous ambulatory monitoring was used to classify ASD patients into those with and without known atrial arrhythmias.

Imaging protocol

All patients underwent CMR imaging on a 1.5 T scanner (Magnetom Area, Siemens Healthineers, Erlangen, Germany) using a previously described protocol.\textsuperscript{12} Short-axis imaging was performed through the atria using a standard bSSFP technique (slice thickness 8 mm, 50 phases). A respiratory navigated (acceptance window ±2.5 mm), ECG triggered, 3D whole heart magnetic resonance angiogram (MRA) was performed 90 seconds after infusion of 0.2 mmol/kg gadobutrol (Gadovist, Bayer Healthcare Pharmaceuticals, Berlin, Germany) with coverage to include both atria in axial orientation. For patients in sinus rhythm, scan acquisition was timed to atrial diastole, immediately prior to the opening of the mitral valve, with a duration of less than 150 ms to minimize atrial wall motion artefact. For patients scanned in atrial fibrillation, scan acquisition was similarly timed to the period following atrial filling immediately prior to mitral valve opening with the same constraint placed on acquisition duration (<150 ms). Twenty minutes after contrast administration, late gadolinium enhancement imaging was performed using an ECG-triggered, respiratory navigated, 3D whole heart, inversion recovery spoiled gradient echo sequence in axial orientation (T1 spatial resolution 1.3 mm × 1.3 mm × 4 mm reconstructed to 1.3 mm × 1.3 mm × 2 mm, TR 4 ms, TE 2 ms, flip angle 20\textdegree), phase encoding direction; anterior–posterior, frequency encoding direction; right–left, parallel imaging; GRAPPA\textsuperscript{15} factor 2. A preceding single slice multi-phase inversion time mapping sequence (Look-Locker approach)\textsuperscript{16} was used to determine the correct inversion time to achieve adequate nulling of ventricular myocardium. In ASD patients, phase contrast imaging was performed in planes orthogonal to the aorta and main pulmonary artery to allow aortic and pulmonary flow calculation.

Image processing

Right and left atrial fibrosis maps were created using CEMRG (cermgapp.com) according to previously published methods.\textsuperscript{12,16} Semi-automatic segmentations of the atrial blood pool were performed to create bi-atrial surface shells. In ASD patients, the right and left atria were segmented as one and clipped through the plane of the defect whereas separate segmentations of the right and left atria were created in non-congenital heart disease paroxysmal AF patients owing to the presence of the intact atrial septum. The pulmonary veins and left atrial appendage were removed from the left atrial shell and the inferior vena cava, superior vena cava, and right atrial appendage removed from the right atrial shell using clipping tools in CEMRG and Paraview (www.paraview.org) (Figure 1). Total atrial fibrosis burden was expressed as the percentage of the shell above a threshold of 1.2 times the mean signal intensity of the blood pool (IIR 1.2).\textsuperscript{17} Bi-atrial area and volume were measured using the CVI42 imaging analysis platform (CVI42, v5.1.1, Circle Cardiovascular Imaging, Calgary, ON, Canada). Right and left atrial areas were measured on four-chamber cine acquisitions at end atrial diastole. Right and left atrial volumes were calculated from cross-sectional slices generated from short-axis imaging through the atria. The shunt fraction (Qp:Qs) was calculated from phase contrast imaging of aortic and main pulmonary artery blood flow using CVI42 (Figure 1) in ASD patients.

Statistical analysis

Data analysis was performed using SPSS Statistics (IBM, Version 24) and Prism (GraphPad Software, Version 7). Normality of data was assessed using the Shapiro–Wilks test. Normally distributed continuous variables were expressed as mean ± standard deviation. Comparison of means between groups was performed using independent samples t-test for normally distributed data and Mann–Whitney U test for non-normally distributed data. Associations between continuous variables were assessed using Pearson’s correlation co-efficient for normally distributed data and Spearman’s correlation co-efficient for non-normally distributed data. An R-value of 0.0–0.39 indicated a weak relationship, a value of 0.4–0.59 a moderate relationship, and one of >0.6 a strong relationship.\textsuperscript{18} Receiver operating characteristic (ROC) analysis was used to determine fibrosis thresholds associated with atrial arrhythmia. Throughout, P < 0.05 was considered statistically significant. Since there is no prior data available on atrial LGE-CMR imaging in ASD patients a power calculation was not performed. Instead, consecutive patients were approached for participation from June 2017 to June 2019 and sample sizes of 36 patients per group were achieved.

Results

Baseline demographics

Thirty-six ASD patients (15 male, 21 female) and 36 non-congenital heart disease patients with paroxysmal AF (22 male, 14 female) were
recruited (Table 1). The mean age was 50.4 ± 13.6 years in the ASD group vs. 60.3 ± 10.5 years in the paroxysmal AF group. The maximum defect size was 2.1 ± 0.7 cm and mean Qp:Qs was 2.2 ± 0.8. One ASD patient had a history of pulmonary hypertension. Eight ASD patients had a history of documented atrial arrhythmias. Four patients had persistent AF, two had paroxysmal AF and two had atrial flutter. Three patients in the ASD group and three patients in the AF group were scanned in AF with a controlled ventricular rate. All other patients were scanned in sinus rhythm.

### Table 1  Baseline demographics of the study groups

|                | ASD group | AF group | P-value |
|----------------|-----------|----------|---------|
| Age            | 50.4 ± 13.6 | 60.3 ± 10.5 | 0.001   |
| Male sex (n, %)| 15 (41.7)  | 22 (61.1) | 0.099   |
| Hypertension (n, %) | 7 (19.4)  | 11 (30.6) | 0.276   |
| Diabetes (n, %) | 3 (8.3)    | 3 (8.3)   | 1.000   |
| Stroke/TIA (n, %)| 2 (5.6)   | 1 (2.8)   | 0.555   |
| CCF (n, %)      | 0 (0)      | 0 (0)     |         |
| CAD (n, %)      | 1 (2.8)    | 7 (19.4)  | 0.024   |
| CHA2DS2-VASc (mean) | 1.1       | 1.5       | 0.421   |

AF, atrial fibrillation; ASD, atrial septal defect; CAD, coronary artery disease; CCF, congestive cardiac failure; CHA2DS2-VASc score, C, congestive cardiac failure, H, hypertension, A, age, D, diabetes mellitus, S, stroke or transient ischaemic attack, V, vascular disease, Sc, sex, TIA, transient ischaemic attack.

### Atrial area and volume

Atrial anatomical parameters are summarized in Table 2. Right atrial area and volume were both significantly greater in ASD patients than non-congenital heart disease AF patients (P < 0.001 for both), but there was no significant difference in left atrial area or volume between the study groups (P = 0.228 and P = 0.397, respectively) (Figure 2).

### Atrial fibrosis

Atrial fibrosis maps were excluded from analysis in the case of poor image quality or if prior ablation had been performed on the ipsilateral side (one left atrial map in the ASD group and two right atrial maps in the paroxysmal AF group). Thirty-four right atrial and 33 left atrial fibrosis maps in the ASD group and 33 right atrial and 35 left atrial fibrosis maps in the paroxysmal AF group were therefore available for analysis. Representative late enhancement images and fibrosis maps are shown in Figure 3.

Bi-atrial fibrosis burden was significantly greater in ASD patients than paroxysmal AF patients (right atrium, 20.7 ± 14% vs. 10.1 ± 8.6%; left atrium, 14.8 ± 8.5% vs. 8.6 ± 6.1%, P = 0.001 for both) (Figure 2, Table 2). In the ASD group, the mean fibrosis burden was greater in the right atrium than the left atrium although this difference did not reach statistical significance (20.7 ± 14% vs. 14.8 ± 8.5%, P = 0.116). Furthermore, no linear relationship was seen between left and right atrial fibrosis burden (Figure 4). In paroxysmal AF patients, fibrosis burden was similar in the right and left atria (10.1 ± 8.6% vs. 10.8 ± 8.3%, P = 0.556).
8.6 ± 6.1%, \( P = 0.209 \)) with a linear relationship noted between the extent of fibrosis in each chamber (\( R = 0.630, P < 0.001 \), Figure 4). In the ASD group, right atrial fibrosis burden was associated with right atrial volume (\( R = 0.400, P = 0.032 \)) but not with right atrial area. There was no association between left atrial fibrosis burden and left atrial area or volume in the ASD group.

### Table 2  Comparison of measured and calculated atrial structural parameters between the study groups

| Parameter                  | ASD group       | AF group       | \( P \)-value |
|----------------------------|-----------------|----------------|---------------|
| RA fibrosis (%)            | 20.7 ± 14       | 10.1 ± 8.6     | <0.001        |
| LA fibrosis (%)            | 14.8 ± 8.5      | 8.6 ± 6.1      | <0.001        |
| RA area, cm\(^2\) (cm\(^2\)/m\(^2\)) | 34.8 ± 8.8 (17.7 ± 4.2) | 24.4 ± 5.7 (11.9 ± 2.8) | <0.001 |
| LA area, cm\(^2\) (cm\(^2\)/m\(^2\)) | 28 ± 6.7 (14.1 ± 2.8) | 26.3 ± 4.9 (12.9 ± 2.7) | 0.288 |
| RA volume, mL (mL/m\(^2\)) | 198.5 ± 58.3 (101.1 ± 28.5) | 91.2 ± 30.2 (43.9 ± 12.9) | <0.001 |
| LA volume mL (mL/m\(^2\))  | 103.7 ± 34.5 (51.4 ± 13.2) | 95.5 ± 25.2 (46.5 ± 11.5) | 0.397 |
| RVEDV, mL (mL/m\(^2\))    | 273.3 ± 80.5 (143.5 ± 42.1) | 159.9 ± 44.5 (78.3 ± 17.2) | <0.001 |
| LVEDV, mL (mL/m\(^2\))    | 136.5 ± 41.6 (69 ± 17.7) | 151.5 ± 41.4 (73.8 ± 15.6) | 0.177 |
| RVEF (%)                   | 57.8 ± 8.9      | 58.2 ± 6.5     | 0.820         |
| LVEF (%)                   | 63.2 ± 8.3      | 61.3 ± 5.1     | 0.266         |

Atrial areas and volumes indexed to body surface area are provided in brackets.

LA, left atrium; LVEDV, left ventricular end-diastolic volume; LVEF, left ventricular ejection fraction; RA, right atrium; RVEDV, right ventricular end-diastolic volume; RVEF, right ventricular ejection fraction.

### Figure 2  Comparison of atrial fibrosis (A) and atrial anatomical parameters (B) between ASD group and paroxysmal AF patients. Error bars represent mean ± standard deviation. LA, left atrium; RA, right atrium.

**Association between atrial structural remodelling and atrial arrhythmias in ASD patients**

Patients with documented atrial arrhythmias were older than those without documented atrial arrhythmias (59.4 ± 10.3 years vs. 47.7 ± 13.7 years, \( P = 0.034 \)). Right atrial area and volume were
greater in ASD patients with than without atrial arrhythmias (41 ± 5.6 cm$^2$ vs. 32.9 ± 8.8 cm$^2$, $P = 0.020$ and 257.4 ± 35.9 mls vs. 184.6 ± 55.2, $P = 0.005$, respectively). Similarly, left atrial area and volume were associated with the presence of atrial arrhythmias (area, $P = 0.041$; volume, $P = 0.027$) (Table 3, Figure 5).

In the ASD group, right atrial fibrosis burden was significantly greater in those with prior atrial arrhythmias than those without (33.4% ± 18.7% vs. 16.8 ± 10.3%, $P = 0.034$, Figure 5). In contrast, no difference in left atrial fibrosis burden was seen in ASD patients with than without atrial arrhythmias ($P = 0.755$). Although not statistically significant, a more striking difference in the predominance of right relative to left atrial fibrosis was seen in those with arrhythmia (33.4 ± 18.7% vs. 14 ± 8.6%, $P = 0.151$) while those without arrhythmia had very similar levels of fibrosis in each atria (16.8 ± 10.3%, vs. 15.2 ± 8.7, $P = 0.588$). ROC analysis identified a right atrial fibrosis threshold of 32% as predictive of atrial arrhythmias with a 92%
specificity and a 71% sensitivity (AUC 0.764) (Figure 6). No significant relationship was seen between the shunt fraction or defect size and the presence of arrhythmias (all \( P > 0.05 \)).

**Association between age, shunt fraction, and atrial fibrosis in ASD patients**

In the ASD group, a significant correlation was seen between age and right atrial area and volume (\( R = 0.430, P = 0.011 \) and \( R = 0.491, P = 0.004 \), respectively); however, there was no significant relationship between shunt fraction (Qp:Qs) and right atrial area or volume.

**Discussion**

The main findings of this study are (i) the extent of bi-atrial fibrosis is greater in patients with ASDs compared to non-congenital heart disease patients with AF; and (ii) right atrial, but not left atrial, fibrosis was associated with the presence of atrial arrhythmias in ASD patients. Despite the relationship between right atrial fibrosis and atrial arrhythmias, right atrial fibrosis was not associated with the duration or magnitude of the ASD shunt.

**The significance of bi-atrial fibrosis**

To the best of our knowledge, this is the first study examining the presence and extent of bi-atrial fibrosis in ASD patients. We identified significantly greater bi-atrial fibrosis, with a predominance for the right atrium, in ASD patients compared to non-congenital heart disease patients with paroxysmal AF.

CMR-defined left atrial fibrosis is described in non-congenital heart disease AF patients and is associated with arrhythmia recurrence post-ablation.\(^{10,19–21}\) In contrast, very few studies have detailed the presence or extent of right atrial fibrosis in any patient population.

**Table 3 Measured and calculated parameters in ASD patients with and without atrial arrhythmia**

|                | ASD with AAs | ASD without AAs | \( P \)-value |
|----------------|--------------|------------------|---------------|
| RA fibrosis (%)| 33.4 ± 18.7  | 16.8 ± 10.3      | 0.034         |
| LA fibrosis (%)| 14 ± 8.6     | 15.2 ± 8.7       | 0.755         |
| RA area (cm\(^2\)) | 41 ± 5.6     | 32.9 ± 8.8       | 0.020         |
| LA area (cm\(^2\)) | 31.8 ± 8.5   | 26.4 ± 5.3       | 0.041         |
| RA volume (mL) | 257.4 ± 35.9 | 184.6 ± 55.2     | 0.005         |
| LA volume (mL) | 135.5 ± 49.2 | 94.1 ± 24.1      | 0.027         |

AA, atrial arrhythmia; LA, left atrium; RA, right atrium.

Despite the association between right atrial fibrosis and atrial arrhythmia, neither age nor shunt fraction were associated with right or left atrial fibrosis in the ASD group (all \( P > 0.05 \)).

**Figure 5** Barcharts demonstrating differences in measured and calculated parameters between ASD patients with (blue) and without (red) atrial arrhythmia. AA, atrial arrhythmia; LA, left atrium; RA, right atrium.
using late gadolinium enhancement imaging. In the largest series doc-
umenting right atrial fibrosis to date, a lesser degree of right com-
pared to left atrial fibrosis was seen in 134 patients undergoing
ablation\textsuperscript{22}, with a linear relationship demonstrated between fibrosis
burden in the right and left atria.\textsuperscript{22} Right atrial fibrosis has also been
described in non-AF patients with structural or congenital heart dis-
ease. Two case series have described right atrial enhancement in
patients with pulmonary hypertension and rheumatic heart dis-
ease.\textsuperscript{23,24} In a third study, right atrial enhancement was seen in 32.4%
of patients with Ebstein’s anomaly which was additionally associated
with the presence of supraventricular arrhythmia in these patients.\textsuperscript{25}

In this study, right atrial fibrosis was significantly greater in ASD
patients versus non-congenital heart disease patients with paroxys-
mal AF, highlighting the mechanistically distinct remodelling proc-
esses between these patient populations. Furthermore, in the ASD
group studied here, no relationship was seen between the extent of
right and left atrial fibrosis, however in paroxysmal AF patients, a lin-
ear relationship was noted between fibrosis burden in each atrium. In
this study, right atrial fibrosis burden was also greater in ASD patients
with atrial arrhythmias. As our comparison group consisted of
patients with known AF, fibrotic remodelling was expected in this
group. It is notable that the extent of bi-atrial fibrotic remodelling
was greater in the ASD patients studied here despite a low preva-
lence of diagnosed atrial arrhythmias and a significantly younger age,
highlighting the strong tendency toward the onset of atrial fibrosis in
this population. The bi-atrial substrate in ASD patients is also empha-
sized by similar left atrial area and volume ($P = 0.288$ and $P = 0.397$)
with respect to the ‘positive’ comparison AF group in whom left atrial
dilatation is well described.

**Atrial fibrosis and arrhythmogenesis—clinical implications**

No studies have systematically evaluated the contribution of right
atrial fibrosis to arrhythmogenesis in any patient population. In the
ASD cohort studied here, right atrial fibrosis burden was significantly
greater in patients with a history of atrial arrhythmias than those
without, however, left atrial fibrosis was not associated with atrial
arrhythmogenesis in this cohort. These findings highlight a key differ-
ce in arrhythmia substrate between ASD patients and non-
congenital heart disease patients with AF and may have important
clinical implications for arrhythmia management strategies. While pul-
monary vein isolation remains the treatment of choice for ASD
patients presenting with AF, left-sided ablation alone may not be suffi-
cient to treat atrial arrhythmias in many ASD patients with significant
right-sided remodelling. Advanced right atrial structural and fibrotic
change may underpin the pro-arrhythmic substrate in these patients,
and a strategy of right-sided ablation in combination with pulmonary
vein isolation alone may be of benefit and warrants future
investigation.

The ROC analysis presented here identified a right atrial fibrosis
burden of 32% as predictive of atrial arrhythmias in ASD patients
with a high specificity. These findings could be useful in identifying
ASD patients without manifest arrhythmia who are likely to develop,
or already have undiagnosed, atrial arrhythmias. Such patients may
benefit from rigorous rhythm monitoring and modification of any
conventional reversible risk factors prior to ASD closure.

Increased bi-atrial volumes were associated with the presence of
atrial arrhythmias in the ASD group. While prior studies have identi-

ced left atrial size as predictive of outcome and disease severity in

![Figure 6 ROC analysis depicting sensitivity and one-specificity for right and left atrial fibrosis in the prediction of atrial arrhythmia in the ASD patients studied.](image-url)
non-congenital heart disease AF patients, a recently published study evaluating multiple indices of atrial remodelling using CMR identified only left atrial fibrosis as predictive of arrhythmia recurrence post-ablation on multi-variate analysis. Age was also associated with the likelihood of atrial arrhythmias in the present study, a finding which is consistent with prior studies of ASD patients undergoing closure. Age, however, represents a surrogate of structural remodelling rather than an accurate reflection of the specific arrhythmia substrate present in an individual patient. Based on the data presented here, right atrial fibrosis may represent a useful non-invasive clinical parameter for assessment of the risk of present or future atrial arrhythmias in ASD patients without manifest arrhythmia, regardless of age. These findings may also have implications for inter-atrial defects aside from secundum ASDs described here; however, the results presented cannot be extrapolated further without future studies exploring the interaction between atrial fibrosis and atrial arrhythmia in other specific patient groups.

The effect of ASD closure on atrial fibrotic remodelling has not been previously evaluated. Reduction in right atrial dimensions has been documented post-ASD closure, with chamber size pre-closure being a major predictor of remodelling potential. Chronic atrial stretch and dilatation stimulate fibrotic signalling pathways, and it is therefore possible that atrial fibrosis may reverse after the closure of the ASD. Conversely, the failure of reverse remodelling in patients with severe fibrosis on atrial LGE-CMR imaging may increase the future risk of atrial arrhythmias in such patients. Further studies are warranted to assess the interplay between atrial fibrosis and atrial arrhythmogenesis pre- and post-ASD closure.

Right atrial fibrosis in ASD patients

In this study, we examined the relationship between age, shunt fraction and right atrial fibrosis to determine the effect of the duration and magnitude of the shunt on right atrial remodelling, but we did not show any significant relationship between these parameters. This may reflect the complex nature of fibrotic remodelling in these patients. In non-congenital heart disease patients the pathogenesis of atrial fibrosis remains incompletely understood with multiple fibrotic signalling pathways described at a cellular level. Furthermore, histological and CMR studies have suggested that age and cardiovascular co-morbidity are not always associated with fibrotic burden in AF patients. The present data therefore suggest that additional factors beyond age and the haemodynamic consequences of the shunt influence the development and progression of right atrial fibrosis in these patients.

Supporting the hypothesis that volume and pressure loading may contribute to the development of fibrosis, in patients with pulmonary hypertension, reduced right atrial voltage, as a surrogate marker for atrial fibrosis, has been demonstrated compared to normal heart control patients. Similar findings have also been seen in both atria in the setting of increased chamber dimensions and pressures secondary to rheumatic mitral stenosis. However, in non-congenital heart disease AF patients, a study examining CMR parameters associated with outcomes post-ablation reported only a weak association between left atrial dilatation and fibrosis burden suggesting that these processes may contribute independently to structural atrial remodelling and arrhythmogenesis. This is further supported by a histologic study of surgical specimens which failed to show a relationship between atrial fibrosis and atrial dilatation in patients with ASDs with and without AF. In this study, a moderate linear relationship was seen between right atrial volume and fibrosis and between right atrial volume and age; however, no such correlation was seen between age and fibrosis, suggesting a lack of temporal relationship between the development of dilatation and fibrosis in this cohort.

Other potential contributory factors to the development of right atrial fibrosis may include genetic pre-disposition, environmental factors, and physical activity; however, their relationship to atrial fibrotic remodelling has yet to be explored in the ASD cohort.

Limitations

Atrial LGE-CMR is subject to several inherent limitations and current imaging resolution can render the assessment of high signal intensity within the thin-walled atria challenging. Black blood imaging may improve blood pool to scar contrast however has yet to be systematically evaluated. Scan duration may be prolonged during AF which may affect myocardial nulling. For the purposes of this study, however, scans with evidence of incorrect nulling or motion artefact were excluded. The number of ASD patients with documented prior atrial arrhythmias presented here was small, and this study was not powered to detect differences between those with and without atrial arrhythmias. Prolonged ambulatory monitoring was not performed as routine in all patients therefore the true number of patients with atrial arrhythmias may have been under-estimated.

Conclusion

Bi-atrial fibrotic remodelling is present to a greater extent in ASD patients compared to non-congenital heart disease patients with paroxysmal AF and right atrial fibrosis is associated with the presence of atrial arrhythmias in ASD patients. This study highlights the importance of the right atrium to arrhythmogenesis in ASD patients and the potential role of CMR imaging in the non-invasive assessment of these patients.

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Data availability

The data underlying this article will be shared upon reasonable request to the corresponding author.

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