

Macrophage interleukin-1 β mediates atrial fibrillation risk in diabetic mice

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ABSTRACT

Diabetes mellitus (DM) is an independent risk factor for atrial fibrillation (AF). The mechanisms underlying DM-associated AF are unclear. AF and DM are both related to inflammation. We investigated whether DM-associated inflammation contributed to AF risk. Mice were fed with high fat diet to induce type II DM and were subjected to IL-1 β antibodies, macrophage depletion by Clodronate liposomes, a mitochondrial antioxidant (mitoTEMPO), or a cardiac ryanodine receptor (RyR2) stabilizer (S107). All tests were performed at 36-38 weeks of age. DM mice presented with increased AF inducibility, enhanced mitochondrial reactive oxygen species (mitoROS) generation, and activated innate immunity in the atria as evidenced by enhanced monocyte chemoattractant protein-1 (MCP-1) expression, macrophage infiltration, and IL-1 β levels. Signs of aberrant RyR2 Ca²⁺ leak were observed in the atria of DM mice. IL-1 β neutralization, macrophage depletion, mitoTEMPO, and S107 significantly ameliorated the AF vulnerability in DM mice. Atrial overexpression of MCP-1 increased AF occurrence in normal mice through the same mechanistic signaling cascade as observed in DM mice. In conclusion, macrophage-mediated IL-1 β contributed to DM-associated AF risk through mitoROS modulation of RyR2 Ca²⁺ leak.

INTRODUCTION

Type II diabetes mellitus (DM) is one of the most common chronic diseases in the world (1). DM is also an independent risk factor for the development of atrial fibrillation (AF) (2, 3), increasing the risk of developing AF by 40% (4). AF is the most prevalent human arrhythmia (5) and an estimated 2.5% of patients with AF have diabetes (4). The presence of comorbid DM and AF increases the risks of major cardio-cerebrovascular events and all-cause mortality compared to either condition alone (6). DM causes electrical, structural, and autonomic remodeling in atria leading to the development of AF (7). Nevertheless, the exact cellular and molecular mechanisms inciting and maintaining DM-associated AF and diabetic atrial remodeling are not fully understood.

Recently, we have reported that DM activates inflammatory macrophages to secrete IL-1 β , resulting in overproduction of mitochondrial reactive oxygen species (mitoROS) in ventricle (8, 9). MitoROS contributes to DM-associated ventricular arrhythmic risk and heart failure with preserved ejection fraction (HFpEF) through oxidizing the downstream ryanodine receptor 2 (RyR2) channel and cardiac myosin binding protein C, respectively (9, 10). Considering the strong epidemiological interlink among DM, AF and HFpEF, it is plausible that there may be common mechanistic signals underlying DM-associated cardiac electrical and functional abnormalities.

Therefore, in this study, we investigated whether macrophage-mediated IL-1 β contributed to DM-associated AF via redox modulation of diastolic Ca²⁺ release.

RESULTS

AF inducibility was increased in DM mice

Type II DM was induced by feeding mice with high fat diet (HFD) for at least 30 weeks. This HFD-induced DM model has been demonstrated and characterized in our previous studies (8, 10). Here, we recapitulated our previous observations that HFD induced hyperglycemia (Figure 1A, fasting glucose level, 119 ± 11 mg/dL in control vs. 168 ± 16 mg/dL, $P=0.031$) and obesity (Figure 1B, body weight, 35 ± 2 g in control vs. 57 ± 1 g in DM, $P<0.0001$). Echocardiographic evaluation (Supplemental Table 1) indicated impaired cardiac diastolic function in these HFD-induced DM mice (Figure 1D, E/E', 13.6 ± 1.0 in control vs. 23.2 ± 1.7 in DM, $P=0.0006$) whereas systolic function was preserved (Figure 1C, $P=0.246$). The left atrial diameter (Figure 1E, $P=0.662$) and the atrial collagen I level (Figure 1F, 1.30 ± 0.21 in control vs. 1.06 ± 0.28 in DM, $P=0.501$; Supplemental Figure S1) were comparable between the control and DM mice. Programmed stimulation induced AF in 6 out of 6 DM mice while only in 1 out of 6 control mice (Figure 1G and 1H, $P=0.015$). These results suggested that AF vulnerability was increased in DM mice before apparent atrial structural remodeling was present.

Innate immunity was activated in DM atria

To investigate whether innate immunity was activated in DM atria, we first compared the atrial level of monocyte chemoattractant protein-1 (MCP-1), a key chemokine that regulates macrophage migration and infiltration (11). As shown in Figure 2A, the atrial MCP-1 level was significantly higher in DM mice, compared to that of control mice (1.02 ± 0.04 in control vs. 1.17 ± 0.05 in DM, $P=0.045$). An elevation of MCP-1 promotes macrophage infiltration (12). As expected, an enhanced expression of the macrophage marker CD68 was observed in DM mouse atria (Figure 2B, 0.86 ± 0.06 in control vs. 1.18 ± 0.07 in DM, $P=0.011$), indicating increased macrophage infiltration in DM atria (Supplemental Figure S2). Activated macrophages are

important sources of a potent inflammatory cytokine, IL-1 β . In our study, we found that the IL-1 β level was much higher in DM atria (Figure 2C, 2.83 ± 0.74) than control (0.91 ± 0.07 , $P=0.041$). These results suggested that macrophage-mediated inflammation was enhanced in DM mouse atria.

Macrophage-mediated IL-1 β contributed to DM-associated AF

We have previously reported that macrophage-mediated IL-1 β contributed to DM-associated diastolic dysfunction (DD) (9). DD shares some common risk factors with AF, such as DM, hypertension, obesity, et al (13). To investigate whether a similar mechanism contributes to DM-associated AF, we treated DM mice with either Clodronate liposomes or IL-1 β neutralizing antibodies for 2 weeks. We have demonstrated in our previous publication that a 2-week treatment of Clodronate liposomes reduces the number of cardiac macrophages by 50% (9). In this study, we found that macrophage depletion remarkably reduced the IL-1 β level in DM atria (Figure 3A, 1.54 ± 0.23 in DM + plain liposome vs. 1.04 ± 0.01 in DM + Clodronate liposome, $P=0.037$) to a level comparable to the control atria (1.03 ± 0.01), suggesting macrophages were a main source of IL-1 β in DM atria. Both Clodronate liposomes (Figure 3B, $P=0.021$) and IL-1 β antibodies (Figure 1G, $P=0.005$) significantly mitigated the AF inducibility in DM mice. These findings indicated that IL-1 β was the effector of macrophage-mediated inflammation in DM-associated AF.

A mitochondria-targeted antioxidant eliminated AF risk in DM mice

AF is related to increased oxidative stress (14), and oxidative stress is considered a central mediator of AF (15). Mitochondria are the major reactive oxygen species (ROS) source in cardiomyocytes (CMs) (16) and mitoROS promotes AF (17). We have previously reported increased mitoROS level in the ventricular CMs of DM mice and that IL-1 β raises the mitoROS level of ventricular CMs in a dose-dependent response (8). Similar to DM ventricles, we found that the mitoROS level was more than doubled in DM atrial CMs (Figure 4A and 4B, $100 \pm 12\%$ in control vs. $266 \pm 14\%$ in DM, $P<0.0001$). A mitochondrial specific antioxidant, mitoTEMPO,

was administered to DM mice for 2 weeks. At the end of the treatment, the atrial CM mitoROS level was significantly lowered (Figure 4A and 4B, $138 \pm 15\%$, $P < 0.0001$ vs. DM), and the AF inducibility was completely inhibited by mitoTEMPO (Figure 1G, $P = 0.005$). In addition, mitoTEMPO reduced CD68 expression in DM atria (Figure 4C, 0.98 ± 0.25 in DM vs. 0.27 ± 0.02 in DM+mitoTEMPO, $P = 0.048$), suggesting reduced macrophage infiltration by inhibiting mitoROS. These data implied the involvement of atrial mitoROS in DM-associated AF risk and a positive feedback loop between mitoROS and atrial macrophage infiltration.

Cardiac RyR2 Ca²⁺ leakage increased DM-associated AF risk

AF is associated with increased Ca²⁺ release from sarcoplasmic reticulum (SR), and RyR2 is the major Ca²⁺ release channel in the SR of CMs (18, 19). Phosphorylation of RyR2 at Ser2814 by activated Ca²⁺/calmodulin-dependent protein kinase II (CaMKII) increases SR Ca²⁺ leak in human AF (20). MitoROS activates CaMKII by oxidation with consequent RyR2 (Ser2814) phosphorylation (21). We therefore tested whether CaMKII oxidation-mediated RyR2 Ca²⁺ leakage was involved in DM-associated AF. In DM mice, the atrial expression of oxidized CaMKII (oxi-CaMKII) level (Figure 5A and 5C, 1.35 ± 0.11 in control vs. 2.36 ± 0.38 in DM, $P = 0.035$) as well as the phosphorylated RyR2 (Ser2814) (Figure 5B and 5C, 0.72 ± 0.14 in control vs. 1.44 ± 0.18 in DM, $P = 0.013$) were increased when compared to the control mice. More importantly, treating mice with S107, a RyR-calstabin interaction stabilizer, to reduce SR Ca²⁺ leak, significantly improved AF inducibility in DM mice (Figure 5D, $P = 0.028$). These data indicated that RyR2 Ca²⁺ leak, possibly mediated by phosphorylation via oxi-CaMKII, contributed to the increased AF vulnerability in DM.

Atrial MCP-1 overexpression led to AF in normal mice via the same signaling cascade

To further confirm the association between macrophages and AF, atrial-specific adeno-associated viral vectors (serotype 9, AAV9, with the promoter of atrial natriuretic factor (ANF))

were intravenously administered into otherwise normal mice. As shown in Figure 6A and 6B, MCP-1 level was specifically upregulated in the atria CMs (0.72 ± 0.20 in AAV9-plain vs. 1.47 ± 0.07 in AAV9-MCP-1, $P=0.012$) without a change in the ventricles (Figure 6A and 6C, 1.12 ± 0.25 in AAV9-plain vs. 1.29 ± 0.31 in AAV9-MCP-1, $P=0.676$). MCP-1 attracts macrophages mostly through the interaction with its receptor CCR2 (11), and previously, we have reported that MCP-1 and CCR2⁺ macrophages are increased in DM hearts (9). Consistent with this previous result, we found that *Ccr2* gene expression was significantly enhanced in MCP-1 overexpressing atria (Figure 6D, 0.38 ± 0.04 in AAV9-plain vs. 0.65 ± 0.11 in AAV9-MCP-1, $P=0.048$), implying increased CCR2⁺ macrophage infiltration. Concurrently, atrial MCP-1 overexpression (OE) mice were more prone to inducible AF. As shown in Figure 6E, 11 out of 14 MCP-1 OE mice were AF inducible compared to only 2 out of 12 control mice injected with AAV9 plain vector ($P=0.005$). These results indicated that atrial MCP-1 overexpression increased AF vulnerability, presumably via inducing macrophage infiltration.

Moreover, a similar signaling cascade as observed in DM atria was present in MCP-1 OE mice. The mitoROS level was elevated by 1.5-fold in atrial cardiomyocytes from MCP-1 OE mice (Figure 7A, $P=0.0008$) compared with the AAV9-plain vector treated mice. Both oxi-CaMKII and phosphorylated RyR2 (Ser2814) were significantly higher in MCP-1 OE atria than in control. The oxi-CaMKII increased from 1.21 ± 0.12 in control to 1.94 ± 0.10 in MCP-1 OE mice (Figure 7B and 7D, $P=0.002$) and p-RyR2 (Ser2814) increased from 0.73 ± 0.12 in control to 2.60 ± 0.79 in MCP-1 OE mice (Figure 7C and 7D, $P=0.047$). These data suggested that, similar to DM-associated AF, mitoROS-mediated RyR2 modification linked the inflammation and AF in MCP-1 OE mice.

In contrast to DM mice where AF risk may have been encouraged by cardiac diastolic dysfunction, both cardiac systolic (Figure 7E, ejection fraction, $55 \pm 2\%$ in control vs. $52 \pm 2\%$ in

MCP-1 OE mice, $P=0.366$) and diastolic function (Figure 7F, E/E', 16.5 ± 0.6 in control vs. 15.3 ± 1.6 in MCP-1 OE, $P=0.467$) were preserved in MCP-1 OE mice. Although the left atrium was slightly enlarged (Figure 7G, 1.9 ± 0.1 mm in control vs. 2.3 ± 0.1 mm in MCP-OE mice, $P=0.023$), atrial collagen level was not altered by MCP-1 OE (Figure 7H, 1.7 ± 0.1 in control vs. 1.6 ± 0.1 in MCP-1 OE mice, $P=0.853$). These results indicated that inflammation-mediated AF risk was independent of cardiac function.

DISCUSSION

In this study, we found that DM caused AF vulnerability accompanied with enhanced atrial MCP-1 and IL-1 β levels, increased atrial macrophage infiltration, elevated mitoROS production, and RyR2 phosphorylation in atrial CMs. Neutralizing IL-1 β , depleting macrophages, scavenging mitoROS, or blocking Ca²⁺ leak from RyR2 channels, improved AF vulnerability in DM mice. The above signaling cascade was further confirmed in the atrial specific MCP-1 overexpressing mice in which AF risk was significantly enhanced. Taken together, these findings indicated that activated innate immunity contributed to the DM-associated AF tendency via IL-1 β -mediated atrial electrical remodeling of RyR2 through mitoROS modulation.

Both DM and AF are associated with inflammation (22-25). DM is well known as a chronic inflammatory disease. Activation of the innate immune response is closely involved in the pathogenesis of type II DM (26). Macrophages are a major component of innate immunity and the major immune cell population in hearts (27, 28). Type II DM patients present with higher plasma MCP-1 levels and increased CD68⁺ macrophages in the atrial myocardium when compared to non-DM patients (29, 30). Macrophages can adopt pro-inflammatory or anti-inflammatory phenotype, and DM favors the pro-inflammatory macrophages (31).

There is considerable evidence to suggest that macrophages can contribute to AF (32). The main population of immune cells in human left atrial appendages of patients with AF are active

monocytes/macrophages (27, 33). Increased MCP-1 and pro-inflammatory macrophage infiltration in atria have been reported in both human and animals with AF (33-39). Blocking monocyte recruitment reduces atrial macrophage infiltration and lowers the incidence of hypertension induced AF (40). Increased macrophage pro-inflammatory polarization (Inos⁺ and Arg1⁻) is found in the mouse and canine atria after lipopolysaccharide (LPS) induced AF (41). We and others have reported a similar role of macrophages on the diabetic ventricular arrhythmic risk (8, 42). Therefore, macrophage-mediated inflammation may be a key link between DM and arrhythmia.

In the current study, we found enhanced MCP-1 and macrophage infiltration in the DM mouse atria (Figure 2A and 2B, Supplemental Figure S2). The increased IL-1 β in diabetic atria (Figure 2C) and the upregulated gene expression of CCR2, a pro-inflammatory macrophage marker, in MCP-1 overexpressing atria (Figure 6D) supports that the accumulated macrophages in DM atria were pro-inflammatory. That is consistent with our previous report of an increased shift toward pro-inflammatory macrophages in the ventricles of the same DM mouse model (9). Moreover, we observed that depleting macrophages attenuated DM-associated AF vulnerability (Figure 3B), and atrial specific overexpression of MCP-1 induced AF in normal mice (Figure 6E), suggesting the central contribution of pro-inflammatory macrophages in DM-associated AF.

Although macrophage depletion was sufficient to reduce arrhythmic risk, we cannot rule out a role for other inflammatory cell types in DM-associated AF. In another report, neutrophils are a main ROS source and play a pro-fibrotic role in AF genesis, and T cells and B cells contribute to AF via regulating innate immunity and producing autoantibodies respectively (27). Those three leukocyte subsets have been found to be involved in diabetic cardiomyopathy (31, 43).

Pro-inflammatory macrophages secrete inflammatory cytokines such as IL-1 β , IL-6, and TNF α , all of which are elevated in AF patients or associated with the outcome of AF (44-49). IL-

IL-1 β is an independent risk factor for persistent AF in patients after coronary artery bypass grafting surgery (45). AF is remarkably associated with elevated IL-6 in the patients with coronary artery disease, chronic obstructive pulmonary disease, chronic kidney diseases, and many other systemic inflammatory diseases (49-51). High levels of TNF- α are reported in patients with valvular AF (52). In LPS-induced AF, pro-inflammatory macrophages induce atrial electrical remodeling through IL-1 β and TNF- α (41). In our DM mouse model, we showed that DM-associated AF was at least partially mediated by macrophage secreted IL-1 β as evidenced by the efficacy of macrophage depletion and IL-1 β neutralization in blocking AF (Figure 1G and Figure 3B). Nevertheless, we did not rule out the role of other cytokines in DM-associated AF. Further, we did not examine other cell sources of IL-1 β . For example, cardiomyocytes can also release inflammatory cytokines through the activation of NLRP3 (NACHT, LRR, and PYD domain containing protein 3) inflammasome that may contribute to the proclivity for AF (53). Nevertheless, in the present study, macrophage depletion normalized atrial IL-1 β level (Figure 3A), establishing macrophages as the main source of IL-1 β in DM atria.

Further, we investigated the mechanism whereby IL-1 β causes AF in DM. IL-1 β is known to activate mitoROS (54-56). In obesity and DM, oxidative stress is a central mediator of AF (15). In atrial tissue, increased mitoROS is observed in AF patients and animal AF models (17, 57, 58). MitoROS can cause AF through promotion of SR Ca²⁺ leak via RyR2 oxidation or CaMKII-mediated phosphorylation (17, 59, 60). CaMKII can be activated by mitoROS via oxidation (15, 61, 62), and oxidized CaMKII (oxi-CaMKII) is elevated in AF atria (63). We have similar observations that DM elevated mitoROS production and CaMKII oxidation in atria and led to increased RyR2 phosphorylation (Figure 4 and 5). A mitochondrial antioxidant protected DM mice from inducible AF (Figure 1G), providing additional proof of a redox mechanism in DM-associated AF. In addition to redox modulate intracellular Ca²⁺ homeostasis, mitoROS can also

promote AF through perpetuating inflammation via activating the NLRP3 inflammasome and driving inflammatory cytokine release, such as IL-1 β and IL-18 (64). This is reflected in our finding that scavenging mitoROS inhibited macrophage infiltration (Figure 4C), a proof of a vicious positive feedback loop between mitoROS and macrophage-mediated inflammation in the development of DM-associated AF.

The suppression of DM-associated AF risk by RyR2 stabilization (S107) indicated the contribution of RyR2 channels to AF in DM, potentially by oxi-CaMKII-mediated phosphorylation (Figure 5). Similarly, Mesubi et al. reported that diabetic AF is dependent on oxi-CaMKII activated RyR2 Ca²⁺ leak (65). Nevertheless, we cannot rule out the possibility of direct RyR2 oxidation by ROS leading to the pathogenesis of AF, as reported by Xie et al (17).

IL-1 β can also contribute to AF by affecting other cardiac ion channels or atrial fibrosis (41, 46, 66). In LPS-induced AF, IL-1 β contributes to the atrial electrical remodeling by leading to downregulated L-type calcium channel currents and decreased atrial effective refractory period (41). Inhibiting IL-1 β -induced atrial fibrosis prevents post-operative AF (66). In our DM mouse model, atrial fibrosis was not a potent contributor to AF since atrial collagen level was not altered (Figure 1F and Supplemental Figure 1). Instead, our data suggest RyR2-mediated Ca²⁺ leak as a potential trigger mechanism for AF initiation (Figure 5). Nevertheless, the roles of other electrical remodeling in DM-associated AF were not examined and need further clarification.

Previously, we have investigated the inflammatory mechanism in DM-associated ventricular arrhythmic risk and diastolic dysfunction (8, 9). In the present study, we found that DM-associated AF shared a common mechanistic signaling cascade with diabetic diastolic dysfunction as well as ventricular arrhythmic risk, namely MCP-1 elevation, macrophage infiltration, IL-1 β secretion, mitoROS overproduction, and post-translational modification of target proteins. This finding is consistent with the epidemiological association of AF and diastolic heart failure (67). A recent

randomized double-blind placebo-controlled clinical trial (the CANTOS trial) showed anti-inflammatory therapy with an IL-1 β specific antibody (canakinumab) substantially reduced cardiovascular events (68), supporting our conclusion that IL-1 β is a key signaling component in DM-associated cardiovascular complications.

It must be recognized that mice may not be an ideal model of human electrophysiological diseases. Mouse cardiac physiology differs from human in aspects such as heart size, basal heart rate, action potential duration, ionic currents for cardiomyocyte repolarization(69). Thus, extrapolating mouse data for human electrophysiological implications needs to be done cautiously.

In summary, DM results in activation of a cardiac innate immune response associated with increased AF risk. AF vulnerability could be ameliorated by depleting macrophages, antagonizing IL-1 β , scavenging mitoROS, or inhibiting SR Ca²⁺ leak. Each of these approaches represents a possible new therapy for preventing DM-associated AF risk.

METHODS

Sex as a biological variable.

Our study only examined male diabetic mice as female C57BL/6J mice were less susceptible from HFD-induced DM (70). For atrial MCP-1 overexpressing study, both male and female mice were used, and similar findings were observed in both sexes.

Animal experimental protocol

DM was induced by feeding male C57BL/6J mice (purchased from Jackson Laboratory, Bar Harbor, ME) with high fat diet (HFD, 60 kcal% fat, Research Diet, New Brunswick, NJ) starting at 6 weeks of age, and DM was confirmed by fasting blood glucose level using a glucometer (ACCU-CHEK, Roche Applied Science). Sex- and age- matched C57BL/6J mice, fed with regular chow (Harlan, Indianapolis, IN), were used as controls. At the age of 34-36 weeks, all DM mice were randomly assigned to one of the following four treatments: 1) IL-1 β neutralizing antibodies (BioLegend, San Diego, CA), intraperitoneal injection of 300 μ g every 3 days for 2 weeks to suppress IL-1 β ; 2) A bolus intravenous injection of 0.25 mL Clodronate liposomes (reconstituted with 4.7 mL sterile water, FormuMax Scientific Inc, Sunnyvale, CA,) followed by 0.3 mL Clodronate liposomes intraperitoneal injection bi-weekly for 2 weeks to deplete macrophages; 3) MitoTEMPO, (2-(2,2,6,6-tetramethyl-piperidin-1-oxyl-4-ylamino)-2-oxoethyl-triphenylphosphonium chloride, Enzo Life Sciences, Farmingdale, NY), daily intraperitoneal injection of 1 mg/kg for 2 weeks to scavenge mitoROS; 4) S107 (Millipore, Burlington, MA), subcutaneous injection of 60 mg/kg for 1 week. S107 is known to inhibit resting Ca²⁺ leak through SR Ca²⁺ release channels RyR2 (71). USP sterile water or plain liposome injection were used as placebo controls.

A group of normal C57BL/6J mice (male and female, purchased from Jackson Laboratory, Bar Harbor, ME) were intravenously injected with adeno-associated viral vector (serotype 9, AAV9) (5×10^{11} genome copies/mouse) at the age of 9 weeks. The AAV9 vector (VectorBuilder Inc., Chicago, IL) is driven by atrial natriuretic factor (ANF) promoter to overexpress MCP-1 specifically in atrial CMs. The sex- and age-matched control mice were injected with the same copy number of AAV9- EGFP control virus.

All subsequent tests were performed at 36-38 weeks of age or at one month post virus injection.

Echocardiographic evaluation of cardiac function

Echocardiography was performed using the Vevo 2100 (VisualSonics, Toronto, Canada) ultrasound system as in previous studies (9). Mice were anesthetized with 1-2% isoflurane in oxygen at 1 L/min with the body temperature and the heart rate maintained at 37-38 °C and above 400 bpm, respectively, during the scanning. B-mode images along the left ventricular parasternal long axis and then M-mode images at the mid-papillary level were obtained to calculate ejection fraction and chamber size. E/E' was assessed in the subcostal 4-chamber view by pulsed-wave and tissue Doppler imaging to evaluate diastolic function. Measurements were averaged from five consecutive beats during expiration.

Programmed intracardiac stimulation

Programmed intracardiac stimulation was performed to assess AF inducibility as described previously (72). A standard limb electrocardiogram (ECG) was recorded from subcutaneously inserted needle electrodes. Atrial and ventricular intracardiac electrograms were recorded using a 1.1F Millar electrophysiology catheter (Millar Instruments, Houston, TX) advanced through the right jugular vein into the right ventricle. Surface and intracardiac electrophysiology parameters were recorded at sampling rate of 4000 Hz. Right atrial pacing was performed using 2-ms current

pulses delivered by an external stimulator (STG2004, Multi Channel Systems, Reutlingen, Germany) along with MCStimulus software (Multichannel System, Baden-Württemberg, Germany). AF was induced by an overdrive pacing protocol, starting with 2-second burst pacing at a cycle length of 40 ms and decreasing in each successive burst by a 2-ms decrement to a cycle length of 10 ms. Inducible AF was defined as the occurrence of rapid, fragmented atrial electrograms with irregular R-R intervals lasting at least 1 second. To determine whether AF inducibility was reproducible, mice were subjected to the same atrial burst-pacing protocols 3 times, and only the mice that exhibited ≥ 2 times of evoked AF by pacing were considered AF-positive. The programmed pacing was performed in a blinded manner.

Immunoblot analysis

Briefly, the cardiac tissue from both atria were homogenized with tissue protein extraction reagent (Thermo Fisher Scientific, Waltham, MA) and protease/phosphatase inhibitor cocktail (Thermo Fisher Scientific). Proteins were separated on SDS-PAGE gels and transferred to 0.2 μm polyvinyl difluoride membranes. After incubation with 5% nonfat milk for 1 h at room temperature, the membranes were incubated with the corresponding primary antibodies overnight at 4°C (Cell Signaling Technology: anti-MCP-1, #2029; anti- IL-1 β , #12242; anti-CD68, #97778; anti-Vinculin, #4650; Millipore Sigma: anti-oxi-CaMKII, #07-1387; Abcam: anti-GAPDH, #ab9484; anti-CaMKII, #ab52476; Badrilla: anti-RyR2 (pSer2814), #A010-31; ThermoFisher Scientific, anti-RyR2, #MA3-916), followed by incubation with appropriate horseradish peroxidase–conjugated secondary antibodies for 1 h at room temperature. Bound antibodies were visualized by chemiluminescence detection and optical density of the bands was analyzed with Image Lab Software (Bio-Rad Laboratories, Hercules, CA). The quantification data was exhibited as a ratio between target protein and housekeeping protein and normalized to the respective control.

Quantitative Real-time PCR (qPCR)

Total RNA was extracted from the left and right atrial tissues utilizing the RNeasy Plus Mini Kit (Qiagen) according to the manufacturer's instructions. The purity and concentration of the isolated RNA were assessed spectrophotometrically. Subsequent to extraction, reverse transcription was conducted to synthesize complementary DNA (cDNA) from the total RNA using the High-Capacity cDNA Reverse Transcription Kit (ThermoFisher Scientific), following the protocol provided by the manufacturer. Quantitative Polymerase Chain Reaction assays were performed to evaluate the expression levels of specific genes. These assays were carried out using the PowerUp SYBR Green Master Mix (Applied Biosystems) on a 7500Fast Real-Time PCR System (Applied Biosystems). Specific primer sets were employed to amplify target gene sequences (mouse *Ccr2* forward primer – GCTGTGTTTGCCTCTCTACCAG, reverse primer – CAAGTAGAGGCAGGATCAGGCT; mouse *Gapdh* forward primer – CTTCAACAGCAACTCCCCTCTT, reverse primer – TGTCATACCAGGAAATGAGCTTGA). The relative gene expression levels were calculated using the $2^{-\Delta C_t}$ method, with normalization to endogenous control gene expression to account for variability in cDNA input levels.

Atrial cardiomyocytes isolation

Atrial cardiomyocytes were isolated as described before (8). Briefly, hearts were excised under isoflurane (2%) anesthesia and perfused with buffer (in mM: 113 NaCl, 4.7 KCl, 0.6 Na₂HPO₄, 0.6 KH₂PO₄, 1.2 MgSO₄, 0.032 Phenol Red, 12 NaHCO₃, 10 KHCO₃, 10 HEPES, 30 Taurine, 10 2-3-butanedione monoxime) for 7 min at 2.8 mL/min flow rate using a temperature controlled Langendorff perfusion system, followed by collagenase II perfusion (1.3 mg/mL, Worthington Biochemical Co. Lakewood, NJ) for 10 min at 37°C. Both left and right atria were collected, gently cut into small pieces, and dissociated into single cells by pipetting.

Cardiomyocytes were separated from interstitial cells by settling for 10 min. The cell pellet was then collected for mitoROS measurement.

MitoSOX Red staining and mitoROS measurement

MitoROS was measured in the isolated atrial cardiomyocytes by an inverted confocal laser scanning microscope (Olympus Life Science Solutions Americas Corp., Waltham, MA) as described previously (73). Briefly, isolated cardiomyocytes were resuspended in standard Tyrode's solution, containing (in mmol/L) 140 NaCl, 5.4 KCl, 1 MgCl₂, 10 HEPES, 1.8 CaCl₂, and 5.5 glucose (pH 7.4), with serially increasing Ca²⁺ concentrations (0.2, 0.5, and 1 mM), before treated with MitoSOX Red (5 μM; Thermo Fisher Scientific) for 10 min at 37°C in a 95%/5% O₂/CO₂ incubator. MitoSOX was excited by laser at 514 nm and the emission was collected at 560 nm. Digital images were taken at 2048 × 2048 pixels using 40× objective lens with <1 μm optical sections. The relative MitoSOX Red mean fluorescent intensity was obtained from the subtraction between the mean fluorescent intensity of the cells and the background of the same images with ImageJ Fiji Software, normalized to the respective control.

Statistics

Continuous data were presented as mean ± standard error of the mean (SEM). For the dot plots, the lines indicated the mean values, and the error bars indicated SEM. Data were analyzed using a 2-tailed Student's t test or 1-way analysis of variance with Bonferroni's post hoc tests for multiple pairwise comparisons. Categorical data were compared using Fisher's exact test. All statistical analyses were performed with GraphPad Prism 5.0 (GraphPad Software, San Diego, CA). A p value < 0.05 was considered statistically significant.

Study Approval

Animal care and interventions were provided in accordance with the National Institutes of Health Guide for the Care and Use of Experimental Animals, and all animal protocols were approved by the Institutional Animal Care and Use Committee of the University of Minnesota.

Data Availability

Values for all data points in the graphs can be found in the Supplemental Supporting Data Values file.

AUTHOR CONTRIBUTIONS:

XZ designed the study, conducted most of the animal experiments, part of the immunoblot tests, mitoROS measurements on control and DM cardiomyocytes, analyzed data, interpreted results, and wrote the manuscript. HL conducted glucose test, AAV9 vectors injection, echocardiography, programmed intracardiac stimulation on MCP-1 overexpressing mice, cardiomyocyte isolation, and part of the immunoblot tests, analyzed data, interpreted results, and wrote the main body of the manuscript. GK conducted AAV9 vector design and qRT-PCR assay. ML measured mitoROS on MCP-1 overexpressing and control cardiomyocytes. FF conducted cardiomyocytes isolation and intravenous injection of AAV9 vectors. YG conducted post-surgery animal care and assisted on immunoblotting. SD designed and supervised the study, interpreted results, provided project resources and wrote the manuscript. All authors reviewed and commented on the manuscript.

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FIGURES

Figure 1. AF inducibility in DM mice. HFD induced (A) high fasting glucose level and (B) obesity in mice. Echocardiographic evaluation indicated (C) preserved ejection fraction and (D) an increased ratio of transmitral Doppler early filling velocity to tissue Doppler early diastolic mitral annular velocity (E/E'). (E) Left atrial diameter by echocardiography and (F) atrial collagen I level by immunoblotting were comparable between control and DM mice. N=5 to 6 mice per group. (G) DM mice had higher AF inducibility compared to the control mice; IL-1 β neutralizing antibody or mitochondrial antioxidant (mitoTEMPO) inhibited AF inducibility in DM mice. N is indicated within the bars. (H) Representative surface and intracardiac ECG traces showing induced AF in DM mice; arrows indicate the end of programmed stimulation; scale bar represents 100 ms. Bars are mean \pm SEM. Unpaired t-test (A-F) or Fisher's exact test (G) were used. *P<0.05, **P<0.01, ***P<0.001. AF, atrial fibrillation; Ab, antibody; Ctrl, control; DM, diabetes mellitus; ECG, electrocardiogram; EF, ejection fraction; HFD, high fat diet; LA, left atrium; MT, mitoTEMPO.

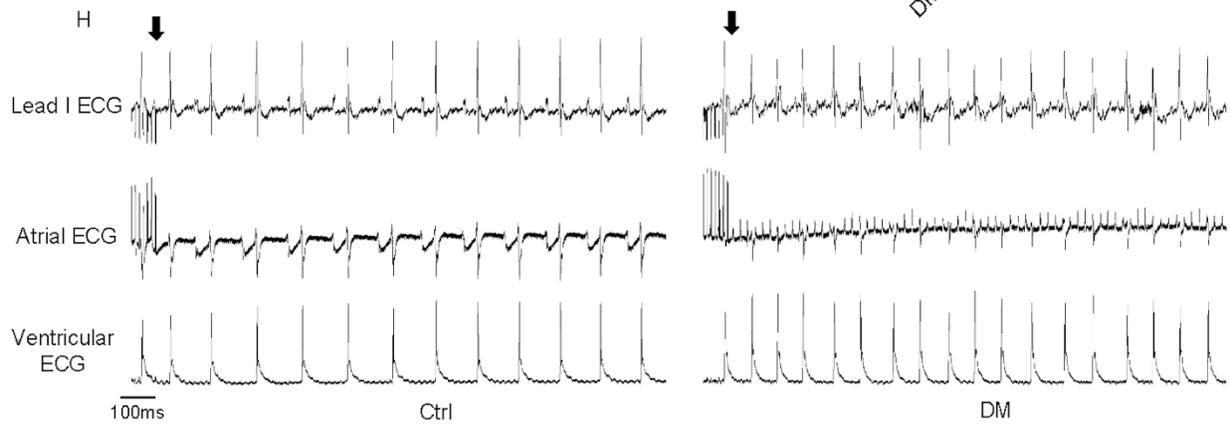
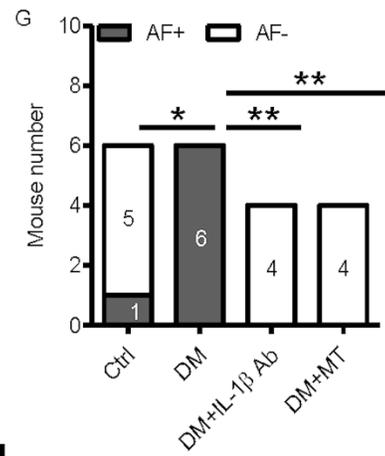
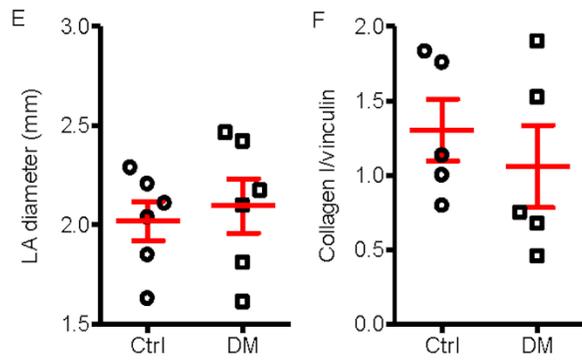
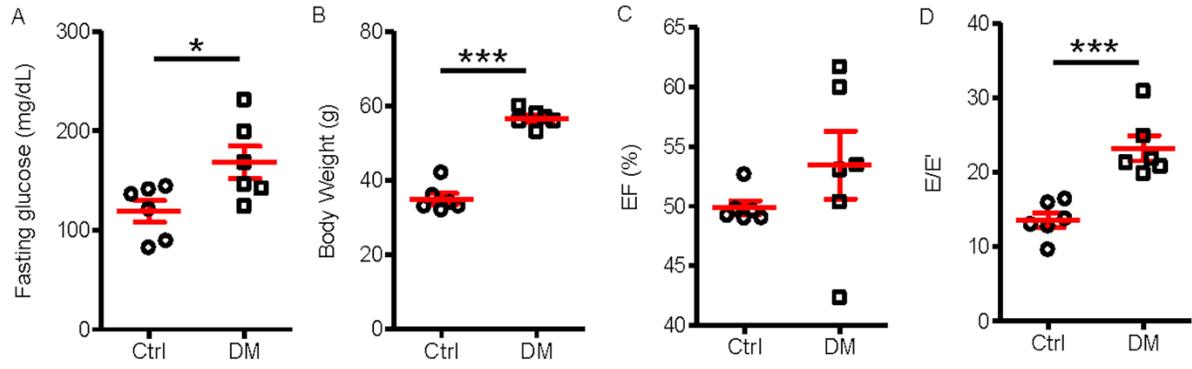


Figure 2. Inflammation was increased in DM atria. Expression level of (A) MCP-1, (B) macrophage marker CD68, and (C) inflammatory cytokine IL-1 β were increased in DM atrial tissue. Representative immunoblotting images were shown, respectively. N=4 to 5 mice per group. Bars are mean \pm SEM. Unpaired t-test was used. *P<0.05. Ctrl, control; DM, diabetes mellitus; MCP-1, monocyte chemoattractant protein-1.

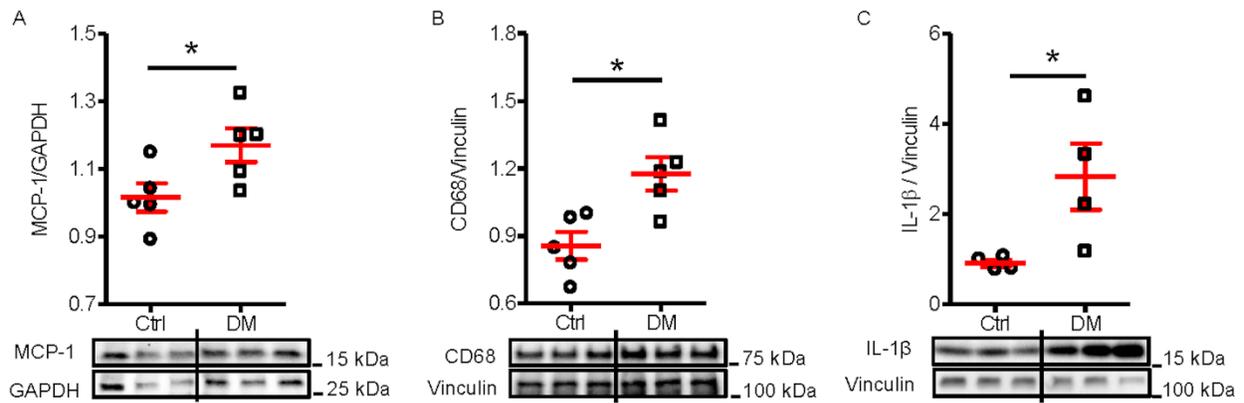


Figure 3. Macrophage secreted IL-1 β mediated DM-associated AF. (A) Atrial IL-1 β level by immunoblotting was significantly lowered in macrophage depleted DM mice treated with Clodronate liposome than the plain liposome treated DM mice. Representative immunoblotting images were shown. N=5 to 6 mice per group. (B) Macrophage depletion by Clodronate liposome inhibited AF inducibility in DM mice. N is indicated within bars. Bars are mean \pm SEM. One-way ANOVA with Bonferroni post-hoc tests (A) or Fisher's exact test (B) were used. *P<0.05, **P<0.01. AF, atrial fibrillation; Ctrl, control; DM, diabetes mellitus.

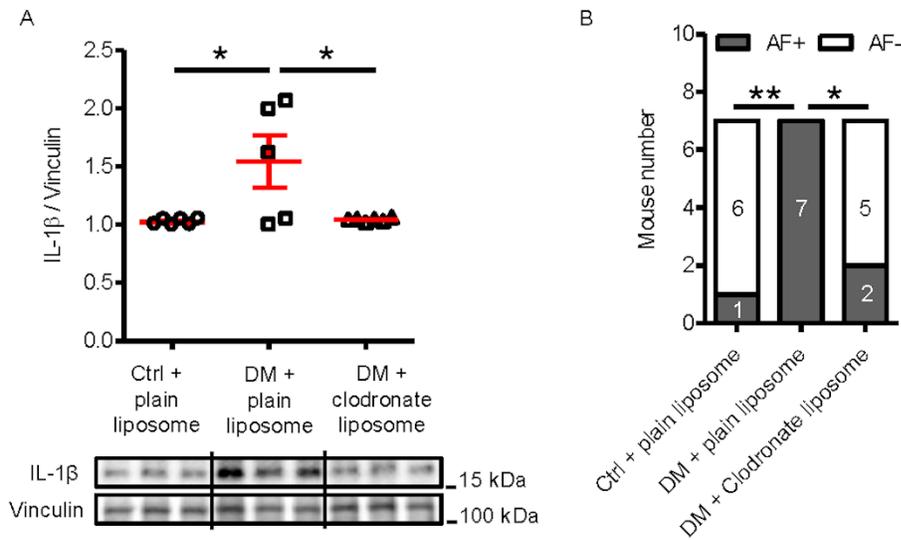


Figure 4. A mitochondrial antioxidant reduced AF inducibility. (A) Representative confocal microscopy images showing mitoROS in atrial cardiomyocytes by MitoSOX Red staining; scale bar represents 20 μ m. **(B)** MitoSOX intensity was increased in DM atrial cardiomyocytes and reversed by mitochondrial antioxidant mitoTEMPO. The atrial cardiomyocytes were isolated from 3 mice per group. **(C)** MitoTEMPO reduced the CD68 expression in DM atria; Representative immunoblotting images were shown; N=3 mice per group. Bars are mean \pm SEM. One-way ANOVA with Bonferroni post-hoc tests **(B)**, or unpaired t-test **(C)** were used. *P<0.05, ***P<0.001. Ctrl, control; DM, diabetes mellitus; MT, mitoTEMPO; mitoROS, mitochondrial reactive oxygen species.

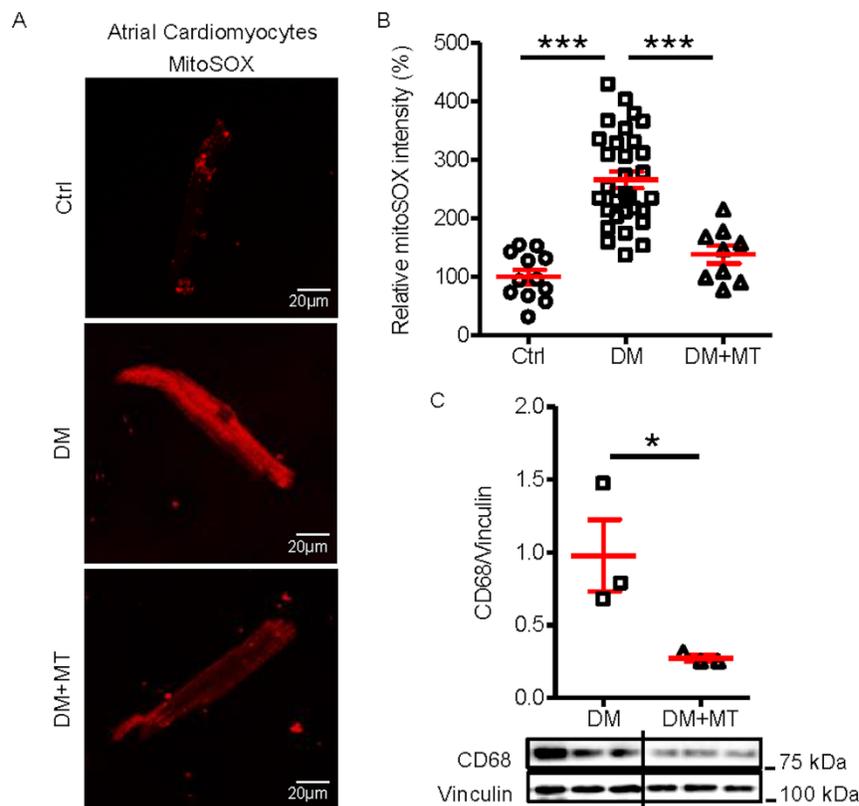


Figure 5. RyR2 mediated sarcoplasmic reticulum Ca²⁺ leak contributed to DM-associated AF. (A) Oxidized CaMKII and (B) phosphorylated RyR2 (Ser2814) level determined by immunoblotting were increased in DM mouse atria. N=5 mice per group. (C) Representative Western blot images of oxidized CAMKII, total CAMKII, p-RyR2-Ser2814, and total RyR2, respectively. (D) The RyR-calstabin interaction stabilizer S107 improved AF inducibility. N is indicated within bars. Bars are mean \pm SEM. Unpaired t test (A and B) or Fisher's exact test (D) were used. *P<0.05. AF, atrial fibrillation; oxi-CaMKII, oxidized Ca²⁺-calmodulin dependent protein kinase II; Ctrl, control; DM, diabetes mellitus; RyR2, ryanodine receptor type-2.

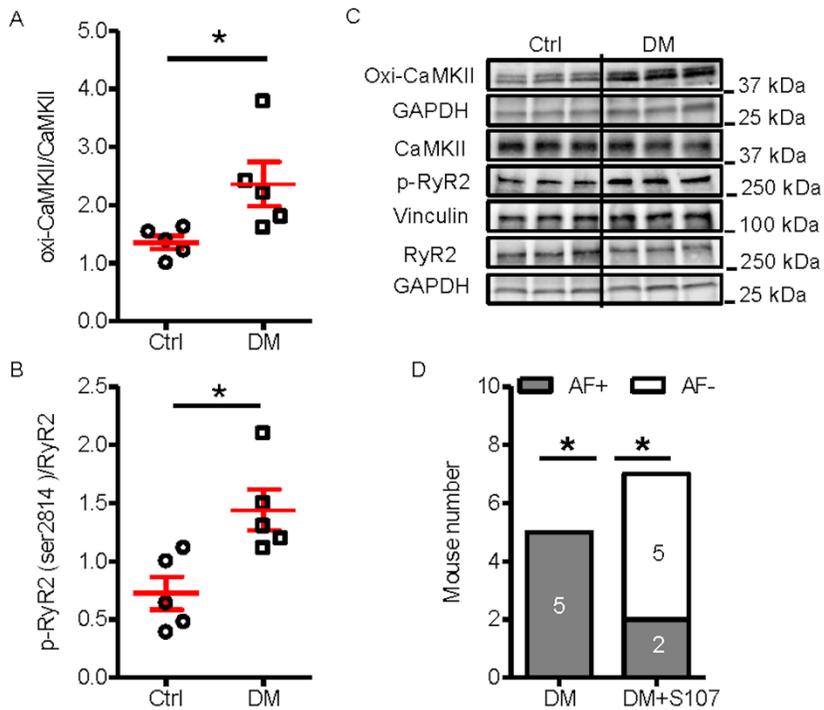


Figure 6. Atrial MCP-1 overexpression increased AF risk in normal mice. (A). Representative immunoblotting images of MCP-1 expression in mouse atria and ventricles 1 month after AAV9 vector injection. **(B)** Atrial but not **(C)** ventricular MCP-1 level was elevated in the mice receiving AAV9-ANF-MCP-1 vector injection. **(D)** Atrial *Ccr2* mRNA level was increased in the MCP-1 overexpressing mice. N = 7-8 mice per group. **(E)** MCP-1 atrial overexpressing mice exhibited high AF inducibility. N is indicated within the bars. Bars are mean \pm SEM. Unpaired t-test **(B-D)** or Fisher's exact test **(E)** were used. *P<0.05, **P<0.01. AAV9, adeno-associated virus serotype 9; AF, atrial fibrillation; MCP-1, monocyte chemoattractant protein-1.

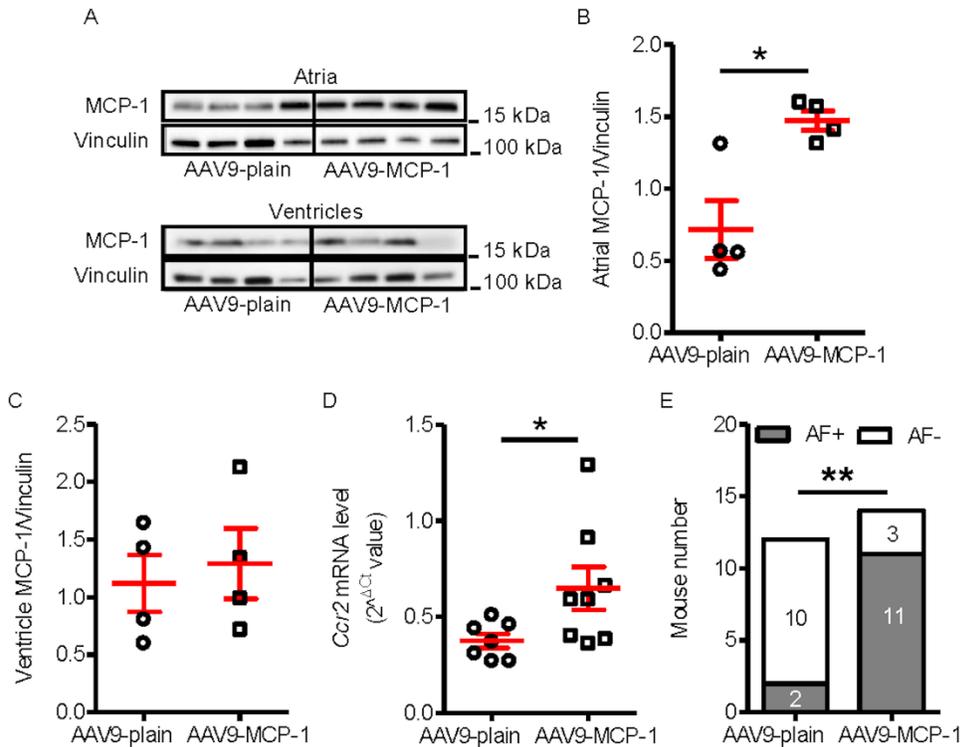


Figure 7. Cardiac characterization of atrial MCP-1 overexpressing mice. (A) MitoSOX intensity was enhanced in the atrial cardiomyocytes overexpressing MCP-1. The atrial cardiomyocytes were isolated from 2 mice per group. (B) Oxi-CaMKII and (C) p-RyR2 (Ser2814) level were increased in MCP-1 overexpressing atria. (D) Representative immunoblotting images of oxidized CaMKII, total CaMKII, p-RyR2-Ser2814, and total RyR2, respectively. (E, F, G) Echocardiographic evaluation of EF, E/E', and left atrial diameter, respectively. (H) Atrial collagen I level in AAV9-plain and AAV9-MCP-1 vectors treated mice. N= 4-9 mice per group. Bars are mean \pm SEM. Unpaired t-test (A-C, E-H) was used. *P<0.05, **P<0.01, ***P<0.001. AAV9, adeno-associated virus serotype 9; AF, atrial fibrillation; E/E', ratio of transmitral Doppler early filling velocity to tissue Doppler early diastolic mitral annual velocity; EF, ejection fraction; LA, left atrium; MCP-1, monocyte chemoattractant protein-1; oxi-CaMKII, oxidized Ca²⁺/Calmodulin-dependent protein kinase II; RyR2, ryanodine receptor 2.

