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1 **FGF10 promotes cardiac repair through a dual cellular mechanism**  
2 **increasing cardiomyocyte renewal and inhibiting fibrosis**

3  
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24 **ABSTRACT**

25

26 **Aims.** Promoting cardiomyocyte renewal represents a major therapeutic approach for heart  
27 regeneration and repair. Our study aims to investigate the relevance of FGF10 as a potential  
28 target for heart regeneration.

29 **Methods and Results.** Our results first reveal that *Fgf10* levels are upregulated in the injured  
30 ventricle after MI. Adult mice with reduced *Fgf10* expression subjected to MI display impaired  
31 cardiomyocyte proliferation and enhanced cardiac fibrosis, leading to a worsened cardiac  
32 function and remodeling post-MI. In contrast, conditional *Fgf10* overexpression post-MI  
33 revealed that, by enhancing cardiomyocyte proliferation and preventing scar-promoting  
34 myofibroblast activation, FGF10 preserves cardiac remodeling and function. Moreover, FGF10  
35 activates major regenerative pathways including the regulation of *Meis1* expression levels, the  
36 Hippo signaling pathway and a pro-glycolytic metabolic switch. Finally, we demonstrate that  
37 elevated *FGF10* levels in failing human hearts correlate with reduced fibrosis and enhanced  
38 cardiomyocyte proliferation.

39 **Conclusions.** Altogether, our study shows that FGF10 promotes cardiac regeneration and  
40 repair through two cellular mechanisms: elevating cardiomyocyte renewal and limiting  
41 fibrosis. This study thus identifies FGF10 as a clinically relevant target for heart regeneration  
42 and repair in man.

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48 **1. INTRODUCTION**

49

50 Ischemic heart disease is the leading cause of cardiovascular disease death worldwide  
51 (1). Myocardial infarction is characterized by dramatic cardiomyocyte loss associated  
52 with profound fibrotic scarring and leads to severe impairment of cardiac function and  
53 ultimately to congestive heart failure. The existence, in the adult mammalian heart, of low but  
54 detectable cardiomyocyte proliferative capacities (2) has oriented regenerative medicine  
55 toward new therapeutical strategies. Indeed, the stimulation of terminally differentiated  
56 cardiomyocyte proliferation currently represents the main therapeutic approach for heart  
57 regeneration (3). Increasing evidence demonstrating that the loss of mammalian  
58 cardiomyocyte renewal potential shortly after birth causes the loss of regenerative  
59 capacities, strongly support the hypothesis that a detailed understanding of the  
60 regulation of fetal cardiomyocyte proliferation is essential to identify targets for  
61 cardiac regeneration (4, 5). Cardiac regeneration is a complex process in which, in  
62 addition to promoting cardiomyocyte proliferation, preventing mature scar formation is  
63 essential. Interestingly, recent evidence investigating endogenous regenerative capacities in  
64 lower vertebrates suggests that reducing the fibroblast to myofibroblast transition may  
65 result in a softer scar tissue, more compliant to cardiomyocyte renewal and favorable to  
66 regeneration (6).

67 We recently uncovered a role for Fibroblast Growth Factor FGF10 signaling in regulating  
68 fetal cardiomyocyte proliferation (7). FGF10 is a paracrine FGF family member and is known  
69 to play essential roles in the development of multiple organs (8). *Fgf10* is expressed in  
70 second heart field (SHF) cardiac progenitor cells in the early embryo, however it is not  
71 essential for SHF deployment and subsequent heart tube elongation (9). In contrast, in the  
fetal heart, FGF10 controls regionalized cardiomyocyte proliferation through a cell<sub>3</sub>  
type autonomous

72 mechanism involving FOXO3 transcription factor phosphorylation and subsequent  
73 downregulation of the cyclin dependent kinase inhibitor p27<sup>kip1</sup> expression. As a result, *Fgf10*-  
74 null embryos, which die at birth due to lung aplasia, display altered heart morphology (7, 10).  
75 Interestingly, forced *Fgf10* expression in adult mice specifically promotes cardiomyocyte cell  
76 cycle reentry (7) suggesting that FGF10 may be a potential target to improve the limited innate  
77 regenerative capacities of the myocardium after injury. In this study, using an experimental  
78 mouse model of myocardial infarction (MI) together with *Fgf10*-gain and loss of function  
79 mouse models, we demonstrate that upregulation of *Fgf10* promotes cardiac regeneration  
80 and repair post-MI. Our results reveal that this effect is mediated through the elevation of  
81 cardiomyocyte proliferation and reduction of fibrosis. Moreover, analysis of *FGF10* expression  
82 in failing explanted human hearts revealed a strong correlation between elevated *FGF10*  
83 levels, reduced fibrosis and enhanced cardiomyocyte proliferation. Together these  
84 experiments identify FGF10 as a potential clinical target to enhance cardiac repair and  
85 regeneration.

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## 98 2. METHODS

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### 100 2.1 Mice

101 Animal studies were performed according to the guidelines from Directive 2010/63/EU of the  
102 European Parliament on the protection of animals used for scientific purposes. Mouse care  
103 and procedures were approved by the Departmental Direction of Veterinary Services of the  
104 French Ministry of Agriculture and the local ethics committee (APAFIS#84 74-20170 II  
105 009244646 v2). *Fgf10<sup>+/-</sup>*, *Fgf10-LacZ*, *Rosa-tdT*,  *$\alpha$ MHC-MerCreMer*, *Rosa26-rtTA* and *Tet(O)-*  
106 *Fgf10* mice were maintained on mixed genetic backgrounds. Inducible expression of *Fgf10* is  
107 achieved by feeding sequentially mice with food containing doxycycline (625 mg/kg DOX,  
108 Envigo). Floxed allele recombination in adult mice was achieved by intraperitoneal tamoxifen  
109 injection at a dose per day of 2 mg/30 g for 3 days. The Phire Animal Tissue Direct PCR Kit (Life  
110 Technologies) was used to genotype transgenic mice without prior DNA Purification. Extended  
111 genotyping procedure can be found in the [Supplemental Data](#). For cardiac tissue collection,  
112 mice were euthanized by cervical dislocation.

113

### 114 2.2 Human heart samples

115 Human tissue samples were provided by the Cardio-Thoracic Surgery Department of La  
116 Timone Hospital Marseille, in accordance with the principles outlined in the Declaration of  
117 Helsinki and with human research protocol approved by the institution under which patient  
118 informed consent was obtained. Human heart tissues were obtained from failing explanted  
119 hearts. Patient clinical features are provided in [Supplemental Table 2](#). All patients displayed  
120 initial myocardial infarction. Samples were collected in the right ventricle, the infarcted area,  
121 border zone and remote area of the freshly explanted heart and immediately processed. All

122 included hearts were arising from patients displaying left ventricular ischemic cardiomyopathy  
123 with non-altered right ventricular function.

124

### 125 **2.3 Myocardial infarction model**

126 Adult mice (3 month-old) were sedated with a mixture of ketamine (100 mg/kg) and xylazine  
127 (10 mg/Kg) via intraperitoneal injection, and following endotracheal intubation, were  
128 artificially ventilated. If necessary 1-2% isoflurane was added as maintenance anesthetic. For  
129 analgesia, buprenorphine. (0.1 mg/kg) was injected subcutaneously 30 min prior surgery.  
130 Following skin incision, lateral thoracotomy at the fourth intercostal space was performed by  
131 blunt dissection of the intercostal muscles. Under stereomicroscope control, the left anterior  
132 descending coronary artery was visualized and ligated (with 8.0 non-absorbable silk suture)  
133 2.0 mm below the left atrium, just above the bifurcation of the left diagonal arteries. Effective  
134 ligation of the coronary artery was confirmed by whitening of the LV affected region below  
135 the ligation site. Out of 145 MI-mice, 30 were excluded due to malpositioning of the ligation.  
136 The thoracic wall and skin incisions were then sutured with 6.0 non-absorbable and 4.0  
137 absorbable silk sutures, respectively. Mice were then warmed for several minutes until  
138 recovery.

139

### 140 **2.4 Echocardiography**

141 Heart function was evaluated at the CERIMED-Marseille, by transthoracic echocardiography  
142 performed on isoflurane-sedated mice using a Vevo 2100 VisualSonics. Mice were anesthetized  
143 with isoflurane in oxygen (2% for induction and 1% for maintenance) and placed on a warm pad  
144 at the supine position. All echocardiography measurements were performed in a blinded  
145 manner.

## 146 **2.5 Tissue processing**

147 Mouse hearts were dissected and analyzed using a Zeiss Lumar stereo dissecting microscope.  
148 For X-gal staining, hearts were collected and fixed for 3 hours in 4% paraformaldehyde  
149 (PFA), extensively washed in 1X PBS and stained for 12 hours at 37°C in a solution containing  
150 4mg/ml of X-gal. After staining, the samples were washed in PBS, post-fixed in PFA 4% and  
151 observed under a Zeiss Lumar stereomicroscope. For immunostaining and sirius red  
152 staining, samples were fixed in 4% PFA for 3 hours and extensively washed in 1X PBS.  
153 Paraffin embedding was performed following dehydration using a graded ethanol series  
154 (50, 70, 90 and 100%), two xylene washes and three paraffin washes (Paraplast X-tra,  
155 Sigma P3808). Cryopreservation was achieved by incubation of samples in a sucrose series  
156 (15 and 30%) and embedding in OCT (VWR, 361603E). Infarct size was estimated using  
157 ImageJ software on 6 sirius red stained sections containing the papillary muscle region and  
158 based on the ratio of the length of the left ventricular infarct area showing fibrosis by the  
159 total left ventricular length as described before (11). Extended immunostaining and sirius red  
160 staining procedures, including antibody list, can be found in the [Supplemental Data](#).  
161 Cardiomyocyte proliferation analysis was examined using Ki67, PH3 and AURKB  
162 immunofluorescence. The number of Ki67-, PH3- and AURKB-positive nuclei was counted  
163 from 8-10 sections per individual heart. Measurements are the average of 5-7 independent  
164 hearts for each indicated genotype and treatment.

165

## 166 **2.6 Quantitative Real Time PCR**

167 Total RNA was extracted using Trizol LS reagent (Life technologies). First strand cDNA was  
168 synthesized using Maxima Reverse Transcriptase (Life technologies). qRT-PCR was performed  
using the following primers and Luminaris qPCR SuperMix (Life technologies) and a Roche

169 Light Cycler 480. Each experiment was performed in duplicate and normalized to house-  
170 keeping gene. Detailed quantitative RT-PCR primers can be found in the [Supplemental Data](#).

171

## 172 **2.7 Biochemical Analysis of circulating protein levels**

173 DOX-treated *Rosa26-RTTA/Tet(O)-Fgf10* were compared to CTRL-treated *Rosa26-*  
174 *RTTA/Tet(O)-Fgf10* infarcted mice, 5 days post-injury. Blood sample was collected into serum  
175 separator tube and the serum was coagulated at room temperature for 2 hours. The  
176 homogenates were centrifuged at 1000 g for 20 min, and the resultant supernatant was  
177 collected and stored at -20°C. Highly sensitive troponin T (TnT-hs, Elecsys®) was measured on  
178 COBAS-8000 Roche®, TnT-hs was measured using an immunological sandwich method  
179 (detection threshold: 5 pg/ml, range: 5–50 ng, intra-assay variation < 10%; intra-assay range:  
180 between 2 and 4%). Circulating FGF10 levels were assessed using Elisa assay according to the  
181 manufacturer's protocols (mouse FGF10 ELISA kit, Abxbexa, abx574964), and the absorbance  
182 values were detected at 450 nm using a microplate reader. Serum levels of cardiac troponin I  
183 were addressed using western blot analysis. Equal amount of protein were subjected to SDS-  
184 PAGE. After electrophoresis, proteins were transferred to PVDF membranes and  
185 immunoblotted with Troponin I antibody (MAB1691, 1/1000). Proteins were detected by  
186 chemiluminescence using a Bio-Rad ChemiDoc analyser. Amido Black staining (Sigma 1.01167)  
187 was performed to visualize total protein. Relative densities were quantified using the ImageJ  
188 software. All data were normalized by internal controls.

189

## 190 **2.8 Cardiomyocyte isolation and culture**

191 Ventricular cardiomyocytes were obtained from 10 week-old *aMHC-MerCreMer/R26R-*  
192 *Tomato/R26R-RTTA/Tet(O)-Fgf10* males intraperitoneally injected with tamoxifen (2 mg/30 g

193 for 3 days) and the fed with normal (CTRL) or doxycycline (DOX) supplemented food for 5 days.  
194 Mice were anesthetized by intraperitoneal injection of a ketamine-xylazine cocktail (ketamine,  
195 93.75 mg/kg; xylazine, 12.5 mg/kg), and the chest was opened to expose the heart. The  
196 descending aorta and inferior vena cava were cut and the heart was rapidly flushed by  
197 injection of EDTA buffer (130 mM NaCl, 5 mM KCl, 0.5 mM NaH<sub>2</sub>PO<sub>4</sub>, 10 mM HEPES, 10 mM  
198 glucose, 10 mM BDM, 10 mM Taurine and 5 mM EDTA adjusted to pH 7.8) in the right  
199 ventricle. Ascending aorta was clamped and the heart was immediately transferred to a 60-mm  
200 dish containing fresh EDTA buffer. Digestion was achieved by sequential injection of EDTA  
201 buffer, perfusion buffer (130 mM NaCl, 5 mM KCl, 0.5 MgCl<sub>2</sub> adjusted to pH 7.8), and finally  
202 an enzymatic solution (perfusion buffer supplemented with collagenase 2 and 4 and protease  
203 XIV) into the left ventricle. The ventricles were separated from the atria, cut into small pieces,  
204 and triturated with a pipette to disperse cardiomyocytes. Ventricular cardiomyocytes were  
205 filtered (100 µm pore size filter) and allowed to sediment by gravity for 20 minutes. The  
206 supernatant was removed, and cells were suspended in three intermediate calcium  
207 reintroduction buffers (0.34, 0.68 and 1.02 mmol/l Ca<sup>2+</sup>) to gradually restore calcium  
208 concentration to physiological levels. At the end, ventricular cardiomyocytes were  
209 resuspended in a culture medium and plated in culture dishes coated with laminin (Life  
210 Technologies, 10 µg/ml).

211

## 212 **2.9 Cell culture and pharmacological stimulations**

213 Human cardiac fibroblast (HCF) cell line (Promocell®, C-12375) was cultured in Fibroblast  
214 Growth Medium 3 (Promocell®, C-23025). Cells were maintained at 37°C in a 95% air-5% CO<sub>2</sub>  
215 humidified atmosphere, fed every 2–3 days, and sub-cultured when reaching 70–80%. HCF

216 were treated with TGF- $\beta$ 1 (Miltenyi Biotec, 5 $\mu$ g/ml) and recombinant FGF10 (R&D Systems,  
217 100ng/ml).

218

## 219 **2.10 RNA sequencing**

220 Sequencing and bioinformatics analysis were performed by the Genomics and Bioinformatics  
221 facility (GBiM) from the U 1251/Marseille Medical Genetics. RNA-Seq was performed in  
222 quadruplicate on DOX-treated *Rosa26-RTTA/Tet(O)-Fgf10* infarcted area 21 days post-injury  
223 as compared to the same area from CTRL-treated *Rosa26-RTTA/Tet(O)-Fgf10*. Before  
224 sequencing, the quality of total RNA samples was assessed using a bioanalyzer (Agilent, Santa  
225 Clara, California, USA). Only RNAs with RNA Integrity Numbers (RIN) above 8 were used. For  
226 each sample, a library for poly(A)+ RNA was prepared from 1  $\mu$ g of total RNA, using the TruSeq  
227 Stranded mRNA Library Prep kit (Illumina, San Diego, California, USA), following the  
228 manufacturer's instructions. The 8 indexed libraries were pooled and sequenced on an  
229 Illumina NextSeq 500 platform, using paired-end mode (2\*75 bp reads), in order to reach 50  
230 million reads (clusters) for each library. Detailed data processing and differential gene  
231 expression (DGE) analysis can be found in the [Supplemental Data](#).

232

## 233 **2.11 Statistics**

234 All experiments and data analysis were conducted blinded. The number of replicates (n) is  
235 indicated in the figure legends and refers to the number of experimental subjects  
236 independently treated in each experimental condition. Data are presented as means  $\pm$  s.e.m.  
237 Statistical significance (p) was determined using unpaired Student's *t*-test, Student's *t*-  
238 distribution and Fisher test, as indicated in each figure legend. Statistical significance was set  
239 at \*p < 0.05, 0.001 < \*\*p < 0.01, \*\*\*p < 0.001.

## 240 3. RESULTS

241

### 242 3.1 *Fgf10* upregulation following MI

243 To study the role of FGF10 in ischemic heart disease, we first analyzed cardiac *Fgf10*  
244 expression in mice subjected to myocardial infarction (MI) through ligation of the left anterior  
245 descending coronary artery. 21 days after ligation, mice were sacrificed, hearts were removed  
246 and qRT-PCR experiments revealed upregulated endogenous *Fgf10* levels in the injured  
247 ventricle (Fold Change (FC)=3.5; [Supplemental Figure 1A](#)). Analysis of cryostat sections from  
248 *Fgf10-LacZ* hearts 21 days post-MI showed that X-gal<sup>+</sup> nuclei are exclusively present in  
249 cardiomyocytes (data not shown), suggesting that *Fgf10* expression is upregulated in  
250 cardiomyocytes under pathological conditions. Directly controlled by key developmental  
251 transcription factors including NKX2-5, TBX1 and ISL1, a cardiac enhancer, located in the first  
252 intron of *Fgf10* gene, has been identified and described to be necessary and sufficient to direct  
253 *Fgf10* expression in the developing heart. While ISL1 and TBX1 activate *Fgf10* expression in  
254 cardiac progenitor cells, NKX2-5 mediates its repression (12). In order to address a potential  
255 involvement of NKX2-5, TBX1 and ISL1 in the upregulation of *Fgf10* expression post-MI, we  
256 evaluated *Nkx2-5*, *Tbx1* and *Isl1* expression in the injured ventricle. Interestingly, while *Nkx2-*  
257 *5* expression levels were downregulated ([Supplemental Figure 1B](#)), strong upregulation of  
258 *Tbx1* and *Isl1* mRNA levels was observed 21 days post-MI ([Supplemental Figure 1C-D](#)).  
259 Consistent with cardiomyocyte dedifferentiation prior to cell cycle release (13-16), our results  
260 thus suggest that reactivation of the transcriptional embryonic program may drive *Fgf10*  
261 expression under pathological conditions.

262

263

### 264 **3.2 Decreased *Fgf10* dosage worsens cardiac function and remodeling following MI**

265 In order to evaluate the role of upregulated *Fgf10* levels under pathological conditions, mice  
266 with reduced *Fgf10* expression (FC=0.56; p=0.006; WT, n=5; *Fgf10*<sup>+/-</sup>, n=5) were subjected to  
267 MI (Figure 1A). Compared to WT-MI infarcted area, *Fgf10* expression levels in *Fgf10*<sup>+/-</sup>-MI  
268 infarcted area 21 days post-MI were significantly reduced (FC=0.2; p=0.005; WT-MI, n=5;  
269 *Fgf10*<sup>+/-</sup>-MI, n=6). 21 days after MI, infarct size measurement (*Fgf10*<sup>+/-</sup>-MI: 30±8% over WT-  
270 MI, p=0.02), together with heart/body weight and heart weight/tibia length ratios (Figure 1B-  
271 C) revealed significant worsening of cardiac remodeling in *Fgf10*<sup>+/-</sup>-MI compare to WT-MI  
272 mice. *In vivo* heart function was investigated using echocardiography (Figure 1D). Compared  
273 to WT infarcted mice, *Fgf10*<sup>+/-</sup> infarcted mice displayed worsened cardiac performance  
274 including a further decreased ejection fraction and fractional shortening and a further  
275 increased left ventricular volume (Figure 1E-G). Analysis of key heart failure marker expression  
276 using qRT-PCR experiments confirmed the worsened pathological remodeling in *Fgf10*<sup>+/-</sup>-MI  
277 compare to WT-MI mice (Figure 1H). Together, these results reveal that maximal FGF10 levels  
278 play a protective role in ischemic heart failure.

279

### 280 **3.3 Decreased *Fgf10* dosage impairs cardiomyocyte proliferation and worsens fibrosis** 281 **following MI**

282 To determine whether upregulated *Fgf10* levels in the injured ventricle could participate in  
283 cardiomyocyte renewal post-MI, cardiac cell proliferation was analyzed, in *Fgf10*<sup>+/-</sup>-MI  
284 compare to WT-MI mice, 5 and 21 days (Figure 2A) post-MI. Immunofluorescence analysis of  
285 proliferative capacity in the border zone (BZ), using the pan-cell cycle marker Ki67 (Figure 2B-  
286 D and supplemental Figure 2A), the mitotic marker PH3 (Supplemental Figure 2B-D) and the  
287 cytokinesis marker Aurora kinase B (AURKB, Figure 2E), revealed a significant impairment of

288 cardiomyocyte proliferation in *Fgf10*<sup>+/-</sup>-MI compare to WT-MI mice. Similar results were  
289 obtained when cardiomyocyte proliferation was measured in the infarcted area (IA;  
290 [Supplemental Figure 2E-F](#)). No alteration in non-myocyte proliferation capacity was detected  
291 ([Supplemental Figure 2G-H](#)). Measurement of cardiomyocyte cross-sectional area revealed  
292 that decreased *Fgf10* dosage significantly worsens cardiomyocyte hypertrophy post-MI  
293 ([Figure 2F](#)). To determine whether FGF10 haploinsufficiency impacts on the progression of  
294 cardiac fibrosis following MI, histological analysis using Sirius red staining was performed. At  
295 both 5 ([Figure 2G-I](#)) and 21 days ([Figure 2J-L](#)) post-MI, increased fibrosis was observed in  
296 *Fgf10*<sup>+/-</sup>-MI hearts compare to WT-MI hearts, correlating with upregulated collagen gene  
297 expression ([Figure 2I and L](#)). Together, these results suggest that maximal *Fgf10* levels  
298 promote cardiomyocyte renewal and prevent fibrosis post-MI, likely contributing to preserved  
299 cardiac function and decreased remodeling.

300

### 301 **3.4 *Fgf10* upregulation following MI preserves cardiac performance**

302 In order to determine whether forced *Fgf10* expression after MI would promote cardiac  
303 regeneration and repair, we took an inducible gain-of-function approach. As FGF10 is a  
304 secreted molecule, global and temporal conditional overexpression of *Fgf10* was achieved  
305 using the *Rosa26-RTTA/Tet(O)-Fgf10* mouse line treated with doxycycline-supplemented  
306 (DOX) food one day after MI during 21 days ([Figure 3A](#)). *Rosa26-RTTA/Tet(O)-Fgf10* DOX-MI  
307 mice were compared with *Rosa26-RTTA/Tet(O)-Fgf10* mice treated with control food (CTRL-  
308 MI) and qRT-PCR experiments on left ventricular tissues and biochemical analysis of serum  
309 post-MI confirmed that DOX-treated mice displayed significantly upregulated myocardial  
310 (FC=106,  $p=7 \times 10^{-6}$ ,  $n=4$  per group) and circulating *Fgf10* levels (DOX-MI:  $3.1 \pm 0.2$  ng/ml versus  
311 CTRL-MI:  $1.9 \pm 0.2$  ng/ml;  $p=0.007$ ,  $n=4$  per group). Our results demonstrated that *Fgf10*

312 upregulation prevents cardiac remodeling 21 days after MI, as depicted by infarct size  
313 measurement (DOX-MI:  $18\pm 4\%$  below CTRL-MI,  $p=0.03$ ), heart/body weight and heart  
314 weight/tibia length ratios (Figure 3B-C). *In vivo* heart function was investigated using  
315 echocardiography (Figure 3D). Compared to CTRL-treated *Rosa26-RTTA/Tet(O)-Fgf10*  
316 infarcted mice, DOX-treated *Rosa26-RTTA/Tet(O)-Fgf10* infarcted mice displayed preserved  
317 cardiac function and remodeling parameters including ejection fraction, fractional shortening  
318 and left ventricular dilation (Figure 3E-G). Analysis of key heart failure markers using qRT-PCR  
319 experiments confirmed the reduction of pathological remodeling in DOX-treated *Rosa26-*  
320 *RTTA/Tet(O)-Fgf10* infarcted mice compared to CTRL-treated *Rosa26-RTTA/Tet(O)-Fgf10*  
321 infarcted mice (Figure 3H). To confirm the specificity of the protective effect of FGF10 post-  
322 MI, *Rosa26-RTTA* transgenic mice were subjected to MI and treated with DOX-supplemented  
323 or CTRL food one day after MI during 21 days (Supplemental Figure 3A). qRT-PCR experiments  
324 performed on left ventricular tissues 21 days post-MI confirmed that DOX-treatment has no  
325 impact on myocardial *Fgf10* expression ( $FC=0.9\pm 0.2$ ,  $p=0.2$ , CTRL-*Rosa26-RTTA*-MI, DOX-  
326 *Rosa26-RTTA*-MI,  $n=4$  per group). Similarly, no improvement in *in vivo* heart function was  
327 observed 21 days post-MI. Cardiac function and remodeling of the DOX-treated *Rosa26-RTTA-*  
328 MI mice were comparable to that of CTRL-treated *Rosa26-RTTA*-MI mice (Supplemental Figure  
329 3), attesting to the positive effect of *Fgf10* upregulation in preserving cardiac function and  
330 reducing remodeling post-MI.

331

### 332 **3.5 *Fgf10* upregulation following MI promotes cardiomyocyte renewal and prevents** 333 **myocardial necrosis and fibrosis**

334 To determine if endogenous *Fgf10* upregulation post-MI promotes cardiomyocyte renewal,  
335 cardiac cell proliferation was analyzed in the BZ and IA of CTRL- and DOX-treated *R26R-*

336 *RTTA/Tet(O)-Fgf10*-MI hearts 5 (MI-5d) and 21 (MI-21d) days after injury (Figure 4A).  
337 Immunofluorescence analysis of the proliferative capacities using Ki67 (Figure 4B-D  
338 and Supplemental Figure 4A), PH3 (Supplemental Figure 4B-C) and Aurora kinase B (AURKB,  
339 Figure 4E) revealed that upregulated *Fgf10* levels post-MI significantly enhances  
340 cardiomyocyte renewal in both IA and BZ. Interestingly, while *Fgf10* upregulation  
341 post-MI enhances cardiomyocyte renewal, it has no impact or even reduces  
342 proliferation of non-myocytes (Supplemental Figure 4D-E). This observed increase in  
343 cardiomyocyte cell cycle is specifically due to *Fgf10* upregulation since no change in the level  
344 of Ki67<sup>+</sup>- or PH3<sup>+</sup>-cardiomyocytes could be detected in DOX-*Rosa26-RTTA* compared to  
345 CTRL-*R26R-RTTA/Tet(O)-Fgf10* treated MI hearts (Supplemental Figure 4F-H). Analysis of  
346 cardiomyocyte cross-sectional area frequency within the injured ventricle revealed a  
347 significant upregulation of small cardiomyocytes in the BZ and IA of DOX- compared to CTRL-  
348 treated *R26R-RTTA/Tet(O)-Fgf10*-MI hearts (Figure 4F). This observation is consistent with  
349 the presence of newly formed cardiomyocytes following upregulation of FGF10 post-MI.  
350 Newly formed cardiomyocytes have been shown to arise from a rare proliferative  
351 subpopulation of mononucleated cardiomyocytes (17-19). We evaluated the impact of  
352 increased *Fgf10* levels on cardiomyocyte nucleation in pathological conditions using  
353 isolated cardiomyocytes from CTRL- and DOX-treated *R26R-RTTA/Tet(O)-Fgf10* hearts  
354 (Figure 4G-J). Our results demonstrated that after MI elevated FGF10 levels  
355 increased mononucleated cardiomyocyte numbers (Figure 4H-I). Immunofluorescence  
356 analysis of proliferative capacity using Ki67 revealed that FGF10 significantly  
357 enhances Ki67<sup>+</sup>-mononucleated cardiomyocyte numbers post-MI (Figure 4J). Similar results  
358 were observed in normal conditions (Supplemental Figure 5A-D). To a lesser extent, FGF10  
359 also increases Ki67<sup>+</sup>-binucleated cardiomyocyte numbers (Supplemental Figure 5E). Finally,  
lineage tracing analysis using *aMHC-MerCreMer/R26R-tdT-RTTA/Tet(O)-Fgf10* mice  
confirmed the hypothesis that 15

360 the newly formed cardiomyocytes derived from pre-existing cardiomyocytes ([Supplemental](#)  
361 [Figure 5A and F](#); 8159 counted cardiomyocytes, 100% MF20<sup>+</sup>Tomato<sup>+</sup>, n=9).

362 Myocardial infarction results in massive cardiomyocyte necrosis that leads to the release of  
363 myocardial biochemical markers, including Troponin T and I, in circulating blood (20). To  
364 address whether *Fgf10* upregulation post-MI affects cardiomyocyte necrosis, serum contents  
365 of cardiac troponin T (cTnT) and I (cTnI) were determined in CTRL- and DOX-MI mice  
366 ([Supplemental Figure 6A](#)). Our results revealed that both cTnT ([Supplemental Figure 6B](#)) and  
367 cTnI ([Supplemental Figure 6C](#)) serum levels were significantly reduced in DOX- compare to  
368 CTRL-treated MI mice suggesting that, in addition to promoting cardiomyocyte renewal,  
369 FGF10 prevents cardiomyocyte necrosis post-MI.

370 We then investigated the impact of *Fgf10* upregulation post-MI on cardiac fibrosis.  
371 Histological analysis using Sirius red staining and qRT-PCR analysis were performed. Decreased  
372 fibrosis was observed in DOX-treated *R26R-RTTA/Tet(O)-Fgf10*-MI hearts 21 days post-MI,  
373 compared to CTRL-treated *R26R-RTTA/Tet(O)-Fgf10*-MI hearts ([Figure 4K-L](#)). This was  
374 accompanied by downregulated collagen gene expression ([Figure 4M](#)). Finally, *in vitro*  
375 experiments using human cardiac fibroblasts demonstrated that FGF10 is able to significantly  
376 reduce TGF- $\beta$ 1-induced cardiac fibroblast activation into  $\alpha$ -SMA (*Acta2*)-expressing  
377 myofibroblasts ([Figure 4N](#)), suggesting that FGF10 may play an upstream role in preventing  
378 fibrosis post-MI.

379

### 380 **3.6 Molecular mechanisms underlying FGF10-induced cardiac regeneration and repair**

381 To uncover the molecular mechanisms by which FGF10 promotes cardiac regeneration and  
382 repair following MI, genome wide transcriptomic analysis was performed by RNA-seq on IA  
383 from CTRL- and DOX-treated *Rosa26-RTTA/Tet(O)-Fgf10* 21 days post-injury ([Figure 5](#)).

384 Unsupervised clustering of the normalized expression values of the differentially expressed  
385 genes (DEG) strictly segregates DOX- from CTRL-treated *Rosa26-RTTA/Tet(O)-Fgf10* IA (Figure  
386 5A). Among the 2016 DEG ( $\text{Log}_2\text{FC} > 0.5$ ; adjusted p-value  $< 0.05$ ), 831 were downregulated in  
387 DOX-*Rosa26-RTTA/Tet(O)-Fgf10*, and expression of 1185 genes was increased compared with  
388 CTRL-*Rosa26-RTTA/Tet(O)-Fgf10* (Figure 5B, Supplemental Table 1). As an internal control, we  
389 detected significant upregulation of *Fgf10* transcripts ( $\text{Log}_2\text{FC} = 5.4$ , adjusted p-value  $= 6 \times 10^{-7}$ ).  
390 Consistent with the activation of cardiac regenerative and repair processes, gene ontology  
391 enrichment analysis (Figure 5C) identified categories including heart process, developmental  
392 process, mitochondria, extracellular matrix and immune process. Myocardial infarction is  
393 associated with an early inflammatory response, which is a prerequisite for healing and scar  
394 formation (21). Since our RNAseq was performed 21 days post-MI, we thus evaluated a  
395 potential role for FGF10 in modulating myocardial levels of inflammatory cytokines and  
396 immune cell recruitment 5 days post-myocardial infarction. Myocardial expression analysis of  
397 key inflammatory cytokines and immune cell markers (monocytes and macrophages) was  
398 performed in CTRL- and DOX-treated *R26R-RTTA/Tet(O)-Fgf10*-MI hearts (Supplemental  
399 Figure 7A-C) and in WT- and *Fgf10*<sup>+/-</sup>-MI hearts (Supplemental Figure 7D-F), nevertheless, no  
400 change in selected marker expression was detected. In addition to significant downregulation  
401 of genes involved in extracellular matrix remodeling, cardiac fibroblast markers including *Ddr2*  
402 and *Pdgfra* display reduced expression (Figure 5E), consistent with reduced fibrosis in DOX-  
403 versus CTRL-treated *Rosa26-RTTA/Tet(O)-Fgf10* hearts post-MI (Figure 4K-M) and our  
404 experiments using human cardiac fibroblast cultures suggesting that FGF10 may play an  
405 upstream role in preventing fibrosis post-MI (Figure 4N).

406 KEGG pathway annotation analysis (Figure 5D) revealed critical signaling pathways  
407 overrepresented among selected DEG, including known downstream FGF10 signaling

408 cascades such as the MAPK, PI3K and FOXO pathways. Consistent with the impact of  
409 FGF10 on the activation of cardiomyocyte cell cycle reentry, multiple genes related to  
410 cell cycle modulation, including downregulated expression of a gene that negatively  
411 regulates cardiomyocyte cell cycle, *Meis1* (18, 22), were identified (Figure 5E).  
412 Metabolic pathways were also identified as overrepresented. FGF10 is known to  
413 potentiate, through the activation of the PI3K/AKT/mTOR pathway, HIF1 $\alpha$  translation  
414 (23) which expression stabilization favors glycolytic metabolism (24). We found that  
415 increased *Fgf10* levels post-MI activate the PI3K pathway, including transcriptional  
416 upregulation of the mTOR gene, and significantly enhance HIF1 $\alpha$  downstream target  
417 expression including glycolysis-related genes (Figure 5E). Our data thus demonstrate that  
418 *Fgf10* upregulation post-MI favors a strong metabolic switch towards glycolysis. As described  
419 in other tissues (24), the observed upregulation of the AMPK/fatty acid signaling cascade is  
420 consistent with the completion of the regenerative process ensuring re-differentiation of  
421 newly formed contractile cardiomyocytes. The Hippo pathway has been recently described  
422 to be a critical determinant for promoting adult cardiomyocyte cell cycle reentry (25). Our  
423 data revealed that enhanced *Fgf10* levels post-MI leads to the transcriptional activation  
424 of multiple key components of the Hippo pathway, including *Park2*, which has recently  
425 been shown to play an essential role in Hippo-induced heart repair and regeneration (26)  
426 (Figure 5E).  
427 To confirm the crucial role of FGF10 in promoting the activation of signaling and cellular  
428 events required to promote cardiomyocyte cell cycle reentry, we evaluated the impact of  
429 decreased *Fgf10* dosage on the expression of genes encoding key glycolytic enzymes (*Pdk2*  
430 and *Eno3*), the transcription factor *Meis1* and the Hippo pathway member *Park2*, 21  
431 days after myocardial infarction. Our results demonstrate that, compared to WT-MI hearts,  
*Fgf10*<sup>+/-</sup>-MI

431 hearts display significantly reduced *Pdk2* and *Eno3* and *Park2* expression levels,  
432 whereas *Meis1* expression is enhanced (Supplemental Figure 8).

433 Together these results suggest that FGF10 promotes cardiac regeneration by  
434 modulating major regenerative pathways including the regulation of *Meis1* expression  
435 levels, the Hippo signaling pathway and a pro-glycolytic metabolic switch.

436

### 437 **3.7 In failing human hearts, elevated *FGF10* expression correlates with high levels of** 438 **cardiomyocyte proliferation and reduced cardiac fibrosis**

439 We then investigated *FGF10* expression levels in failing explanted human heart samples  
440 (Supplemental Table 2). Transcript levels were quantified by qRT-PCR in different  
441 microdissected regions of explanted hearts. Our results revealed elevated *FGF10* levels in  
442 the injured ventricles compared to right ventricular *FGF10* levels. Indeed 4 out of 7  
443 hearts displayed increased *FGF10* expression in the BZ and 5 out of 7 hearts displayed  
444 enhanced *FGF10* levels in the IA (Supplemental Figure 9A). We then evaluated  
445 whether human ventricular *FGF10* levels may influence cardiomyocyte renewal.  
446 Immunofluorescence experiments using Ki67 revealed that elevated *FGF10* levels  
447 significantly correlate with enhanced Ki67<sup>+</sup> cardiomyocyte numbers in the BZ (Figure 6A-  
448 B) and the IA (Supplemental Figure 9B-C). In the BZ, cardiomyocyte cross-sectional area  
449 measurement using WGA staining revealed that, except for heart sample B, elevated  
450 *FGF10* levels correlate with decreased cardiomyocyte cell size (Figure 6E and Supplemental  
451 Figure 9D-E). In addition, the analysis of cardiomyocyte size frequency Supplemental Figure  
452 9F) demonstrated that elevated *FGF10* levels correlate with a high frequency of small  
453 cardiomyocytes (<600 $\mu\text{m}^2$ , Figure 6C) and with a low frequency of large cardiomyocytes  
454 (>800 $\mu\text{m}^2$ , Supplemental Figure 9G), suggesting that, consistent with our results in mice,  
higher *FGF10* levels in human hearts favors cardiomyocyte

455 renewal. Despite low *FGF10* expression levels in the BZ of patient B, a high frequency of small  
456 cardiomyocytes are observed in that area. This unexpected result may be explained by the  
457 high level of *FGF10* expression in the IA that may influence cardiomyocyte status in the  
458 adjacent BZ. Finally, to determine whether human myocardial *FGF10* levels influence cardiac  
459 fibrosis, histological analysis using Sirius red staining was performed and fibrosis was  
460 quantified. Our results demonstrated that elevated *FGF10* levels strongly correlate with  
461 reduced fibrosis in the IA ([Figure 6D and F](#)) and the BZ ([Supplemental Figure 9H-I](#)).  
462 These results obtained in human heart samples reinforce the conclusions of our mouse  
463 experiments and support the relevance for *FGF10* in promoting cardiomyocyte renewal  
464 and preventing fibrosis.

465 **4. DISCUSSION**

466

467 In this study, we demonstrated that *Fgf10* expression post-MI promotes cardiac  
468 regeneration and repair through two cellular mechanisms: elevating cardiomyocyte  
469 renewal and limiting fibrosis. Our results suggest that FGF10 activates major regenerative  
470 pathways including the regulation of *Meis1* expression levels, the Hippo signaling  
471 pathway and a pro-glycolytic metabolic switch as well as playing a direct role in preventing  
472 cardiac myofibroblast activation. Moreover, elevated *FGF10* levels in failing explanted  
473 human heart samples strongly correlate with enhanced cardiomyocyte proliferation and  
474 reduced fibrosis. Together our study highlights the pro-regenerative capacities of FGF10  
475 and supports FGF10 as a clinically relevant target for heart regeneration in man.

476 After birth, the vast majority of cardiomyocytes undergo maturation leading to  
477 multinucleation and metabolic switch toward oxidative phosphorylation (27,  
478 28). Nevertheless, a rare population of resident adult mononucleated cardiomyocytes,  
479 generally smaller than binucleated cardiomyocytes, has been described to participate to  
480 cardiomyocyte renewal in normal aging (17, 19, 22, 29). We demonstrated that FGF10  
481 enhances adult mononucleated cardiomyocyte numbers by promoting cell division of  
482 pre-existing adult mononucleated cardiomyocytes. However, since cytokinesis of  
483 binucleated cardiomyocytes is also possible (14), we cannot exclude that FGF10  
484 may also promote binucleated cardiomyocyte cell division.

485 Cardiomyocyte metabolic reprogramming toward glycolysis, has been recently reported to be  
486 required for cardiac regeneration (30). Our data indicate that, through the activation of  
487 the mTOR/HIF1 $\alpha$  pathway activation, FGF10 post-MI favors a glycolytic metabolic switch.

FGF-

488 dependent control of c-MYC expression that, in turn, regulates expression of glycolytic  
489 enzymes may also participate in the glycolytic metabolic switch (31).

490 Our results suggest that signaling events downstream of FGF10 may negatively regulate  
491 *Meis1*, allowing the removal of a cell cycle block leading to cardiomyocyte cell cycle reentry  
492 and cardiac regeneration. The transcription factor MEIS1 participates in postnatal  
493 cardiomyocyte cell cycle exit through the activation of cyclin-dependent kinase inhibitor  
494 expression and *Meis1* deletion in cardiomyocytes is sufficient to promote cardiomyocyte  
495 mitosis in the adult heart (22). Interestingly, the rare proliferative adult cardiomyocyte  
496 population is highly hypoxic (Hif1 $\alpha$ -responsive) and displays decreased *Meis* family member  
497 gene expression (18).

498 The release of the Hippo block operating in mature cardiomyocytes seems to be a crucial  
499 checkpoint to enable cardiomyocytes to reenter the cell cycle and the modulation of Hippo  
500 pathway components critically participates in cardiac regeneration (25). Our study  
501 demonstrated significantly upregulated levels of the Hippo pathway downstream target *Park2*  
502 in *Fgf10*-overexpressing hearts. The ubiquitin ligase Parkin, encoded by the *Park2* gene, plays  
503 an essential role in normal postnatal cardiac mitochondrial and metabolic maturation by  
504 promoting mitophagy (32). *Park2* was also reported to play a critical role in the adaptive  
505 response after MI by promoting clearance of damaged mitochondria via autophagy (33).  
506 Recently, Leach *et al.*, revealed that *Park2* is essential for the Hippo-induced heart  
507 regeneration (26). In our study, *Park2* may thus also participate to the metabolic switch in  
508 response to forced *Fgf10* expression.

509 Decreased cardiomyocyte cell size has been shown to be an indicator of enhanced  
510 cardiomyocyte proliferation (17, 19, 22, 29). Our results demonstrating that FGF10  
511 significantly increases the number of small cardiomyocyte in the injured ventricle strongly

512 supports FGF10-induced cardiomyocyte renewal. Cardiomyocyte cell size is nevertheless  
513 controlled by a balance between atrophic and hypertrophic signaling (34). Here, a role of  
514 FGF10 on the modulation of atrophic gene expression cannot be excluded. Indeed, among  
515 diverse genes described to regulate cardiac atrophy, we identified that FGF10 overexpression  
516 21 days post-MI significantly upregulates *Murf1* transcript levels ( $\text{Log}_2\text{FC}=2.7$ , adjusted p-  
517 value=0.003).

518 In addition to promoting cardiomyocyte renewal, our data suggest that FGF10 exposure  
519 significantly decreases cardiac myofibroblast activation. Of particular interest, *Fgf10*-  
520 overexpression post-MI results in the significant downregulation of *Smoc1* and *Smoc2*,  
521 silencing of which has been recently shown to be required to prevent myofibroblast  
522 transformation (35, 36). Here, we cannot exclude a role for FGF10 in epicardial priming  
523 required for neovascularization (37) and the secretion of pro-regenerative signals in  
524 pathological conditions (38). Furthermore, FGF10 anti-inflammatory properties (39, 40)  
525 may potentially participate in the regenerative process induced by FGF10 treatment.

526 Alternatively, or in addition, the ability of FGF10 to promote functional cardiomyocyte  
527 differentiation during ESC/iPSC differentiation (41) and cardiac reprogramming (42), may  
528 also participate in the observed FGF10-induced cardioprotective effect.

529 In addition to ischemic-related pathologies, the therapeutic effect of FGF10 has been  
530 extensively studied in wound healing, venous ulcers, mucositis, or ulcerative colitis, leading to  
531 early human clinical studies clearly demonstrating FGF10 clinical safety and thus supporting  
532 its utilization in clinics (43, 44). The fact that in human terminal heart failure, elevated  
533 myocardial *FGF10* levels associate with enhanced cardiomyocyte proliferative capacities and  
534 reduced fibrosis reinforces our results obtained in mice. In contrast to mouse models, few  
535 experiments have addressed the capacity of human cardiomyocytes to respond to

536 regenerative signals (45, 46). Our results identify FGF10 as a potential regulator of  
537 cardiomyocyte cell cycle and fibrosis in the adult human heart.

538 Together, our results indicate that FGF10 preserves cardiac remodeling and performance of  
539 the injured heart, strongly supporting FGF10 as a clinical relevant target to promote cardiac  
540 regeneration and repair in human patients.

541

**542 DATA AVAILABILITY**

543

544 The data underlying this article are available in the article and in its online [supplementary](#)  
545 [material](#).

546

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548

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561

**562 CONFLICT OF INTEREST**

563

564 The authors have declared that no conflict of interest exists.

565

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## FIGURE LEGENDS

**Figure 1: Decreased *Fgf10* dosage worsens cardiac function and remodeling following myocardial infarction.** (A) Schematic of the experimental plan. WT and *Fgf10*<sup>+/-</sup> adult mice were subjected to myocardial infarction (MI) and analysis were performed 21 days after surgery. (B) Heart weight/body weight ratio. WT-MI, n=26; *Fgf10*<sup>+/-</sup>-MI, n=24. (C) Heart weight/tibia length ratio. WT-MI, n=20; *Fgf10*<sup>+/-</sup>-MI, n=23. (D) M-mode images of echocardiographic experiments (Scale bars, x: 0.1 s; y: 1 mm). (E) Ejection fraction. (F) Fractional shortening. (G) Left ventricular systolic volume. WT-SHAM, n=14; *Fgf10*<sup>+/-</sup>-SHAM, n=7; WT-MI, n=8; *Fgf10*<sup>+/-</sup>-MI, n=6 (H) qRT-PCR analysis, on left ventricular tissues, of *Nppa* (n=5/group), *Nppb* (n=6/group) and *Myh7* (n=5-6/group) expression. \*, p<0.05; \*\*, 0,001<p<0.01; \*\*\*, p<0.001; Student's *t*-test.

**Figure 2: Decreased *Fgf10* dosage impairs cardiomyocyte proliferation and worsens fibrosis following MI.** (A) Schematic of the experimental plan. WT and *Fgf10*<sup>+/-</sup> adult mice were subjected to myocardial infarction (MI) and analysis were performed 5 and 21 days after surgery. (B-D) Immunofluorescence experiments were performed to evaluate in the border zone *in vivo* cardiomyocyte proliferation (MF20<sup>+</sup>; yellow arrowheads) 5 days (C; MI-5d; WT, n=6; *Fgf10*<sup>+/-</sup>, n=5) and 21 days (D; MI-21d; WT, n=5; *Fgf10*<sup>+/-</sup>, n=6) post-MI using Ki67. (E) Immunofluorescence experiments using Aurora B marker were performed to evaluate *in vivo* cardiomyocyte proliferation (MF20<sup>+</sup>; yellow arrowheads) 5 days post-MI (n=6 mice/group). Scale bars, 10 μm (B) and 5 μm (E). (F) Cardiomyocyte cross-sectional area frequency (MI-21d; WT, n=6; *Fgf10*<sup>+/-</sup>, n=5; compared using Fisher statistical test). (G-H) Histological sirius red staining was performed 5 days post-MI (WT, n=6; *Fgf10*<sup>+/-</sup>, n=5, Scale bar, 1000 μm). (I) qRT-

PCR analysis 5 days post-MI of *Col1A1* (WT, n=5; *Fgf10*<sup>+/-</sup>, n=7) and *Col3A1* (WT, n=6; *Fgf10*<sup>+/-</sup>, n=6) expression in the border zone. (J-K) Histological sirius red staining was performed 21 days post-MI (WT, n=5; *Fgf10*<sup>+/-</sup>, n=5, Scale bar, 1000  $\mu$ m). (L) qRT-PCR analysis 21 days post-MI of *Col1A1* (WT, n=7; *Fgf10*<sup>+/-</sup>, n=5), *Col3A1* (WT, n=6; *Fgf10*<sup>+/-</sup>, n=5) and *Col6A5* (WT, n=6; *Fgf10*<sup>+/-</sup>, n=5) expression in the infarcted area. ns, non-significant; \*, p<0.05; \*\*, 0,001<p<0.01; \*\*\*, p<0.001; Student's *t*-test.

**Figure 3: Upregulation of *Fgf10* levels post-MI preserves cardiac function and remodeling.**

(A) Schematic of the experimental plan. *R26R-RTTA/Tet(O)-Fgf10* mice were subjected to myocardial infarction (MI). One day after MI, mice were fed with normal (CTRL) or doxycycline supplemented food (DOX) required to induce *Fgf10* overexpression and analyzed 21 days later. (B) Heart weight/body weight ratio. MI-CTRL, n=18; MI-DOX, n=25. (C) Heart weight/tibia length ratio. MI-CTRL, n=16; MI-DOX, n=25. (D) M-mode images of echocardiographic experiments (Scale bars, x: 0.1 s; y: 1 mm). (E) Ejection fraction. (F) Fractional shortening. (G) Left ventricular systolic volume. SHAM-CTRL, n=7; SHAM-DOX, n=6; MI-CTRL, n=12; MI-DOX, n=14. (H) qRT-PCR analysis, on left ventricular tissues, of *Nppa* (MI-CTRL, n=6; MI-DOX, n=7), *Nppb* (MI-CTRL, n=7; MI-DOX, n=7) and *Myh7* (MI-CTRL, n=6; MI-DOX, n=7) expression. ns, non-significant; \*, p<0.05; \*\*, 0,001<p<0.01; \*\*\*, p<0.001; Student's *t*-test.

**Figure 4: Upregulation of *Fgf10* levels post-MI promotes cardiomyocyte cell cycle reentry and prevents fibrosis.**

(A) Schematic of the experimental plan. *R26R-RTTA/Tet(O)-Fgf10* mice were subjected to myocardial infarction (MI). One day after MI, mice were fed with normal (CTRL) or doxycycline supplemented food (DOX) required to induce *Fgf10* overexpression and

analyzed 5 and 21 days later. (B-E) Immunofluorescence experiments were performed to evaluate, 5 (MI-5d) and 21 (MI-21d) days post-MI, in the border zone (BZ) and in the infarcted area (IA), cardiomyocyte (MF20<sup>+</sup>; yellow arrowheads) proliferation using Ki67<sup>+</sup> (C, MI-5d; BZ CTRL n=5, BZ DOX n=5, IA CTRL n=5, IA DOX n=5 and D, MI-21d; BZ CTRL n=6, BZ DOX n=7, IA CTRL n=6, IA DOX n=6) and AURKB<sup>+</sup> (E, n=5/group). (F) Cardiomyocyte cross-sectional area (n=6-7 mice/group). Scale bars, B: 10  $\mu$ m; E: 5  $\mu$ m and F: 25  $\mu$ m. (G) *R26R-RTTA/Tet(O)-Fgf10* mice were subjected to myocardial infarction (MI). One day after MI, mice were fed with normal (CTRL) or doxycycline (DOX) supplemented food for 5 days. (H-J) Cardiomyocytes were isolated and immunofluorescence experiments were performed to evaluate mononucleated cardiomyocyte numbers (I) and their proliferative capacities (J); (n=5-6/group). (K-L) Fibrosis was investigated 21 days post-MI using histological sirius red staining. n=5/group. Scale bars, 1000  $\mu$ m. (M) qRT-PCR analysis of *Col1A1* (n=6/group), *Col3A1* (n=6/group) and *Col6A5* (CTRL n=6 Dox n=7) expression in the infarcted area. (N) Human fibroblast cultures revealed that FGF10 prevents TGF- $\beta$ 1-induced fibroblast activation, (n=3/group). ns, non-significant; \*, p<0.05; \*\*, 0,001<p<0.01; \*\*\*, p<0,001; Student's *t*-test.

**Figure 5: RNA-seq analysis reveals FGF10-induced transcriptional regulation of major regenerative pathways.** *R26R-RTTA/Tet(O)-Fgf10* mice were subjected to myocardial infarction (MI). One day after MI, mice were fed with normal (CTRL) or doxycycline (DOX) supplemented food required to induce *Fgf10* overexpression. 21 days post-MI, RNA-seq analysis was performed in the infarcted area. (A) Heatmap showing hierarchical clustering of DEG in biological replicates (n=4/group). (B) Volcano plot of DEG sorted according to fold change and significance (FDR adjusted p-value). DEG (FDR < 0.05, n=2016) are shown in red, and non-significant changes are shown in black. (C) Enrichment analysis of gene ontology

terms for differentially regulated genes. Upregulated and downregulated genes in MI-DOX vs MI-CTRL are represented in red and blue, respectively. **(D)** Circular plot of 42 DEG showing the relationship between expression changes (left semicircle perimeter) and KEGG pathways (right semicircle perimeter). Changes in expression are represented for each gene as  $\text{Log}_2\text{FC}$ . **(E)** qRT-PCR experiments showing the validation of major candidate genes ( $n=4-6/\text{group}$ ).

**Figure 6: Upregulation of *FGF10* in human failing hearts correlates with increased cardiomyocyte proliferation, reduced cardiomyocyte size and reduced fibrosis.** Human explanted failing heart samples from right ventricle (RV), remote area (RA), border zone (BZ) and infarcted area (IA) were collected from 7 patients (A-G). **(A)** Cardiomyocyte proliferation in the BZ was evaluated using immunofluorescence experiments and the cell cycle marker Ki67. **(B)** Elevated *FGF10* levels correlate with enhanced cardiomyocyte proliferation in the BZ. **(C)** Cardiomyocyte cross-sectional area was measured in the BZ using the cell membrane marker WGA. Elevated *FGF10* levels correlate with high frequency of small cardiomyocyte ( $<600\mu\text{m}^2$ ). **(D)** Cardiac fibrosis in the IA was assessed using histological Sirius red staining. Elevated *FGF10* levels correlate with reduced fibrosis in the IA. **(E)** Representative pictures of WGA staining, according to patient-corresponding *FGF10* levels depicted in Supplemental Figure 8A, have been classified from low to high expression as represented by the above grey triangle. Scale bar 10  $\mu\text{m}$ . **(E-F)** Representative pictures of Sirius red staining, according to patient-corresponding *FGF10* levels depicted in Supplemental Figure 8A, have been classified from low to high expression as represented by the above grey triangle. Scale bars 100  $\mu\text{m}$ . Statistical significance ( $p$ ) was determined using Student's  $t$ -distribution.

FIGURE 1

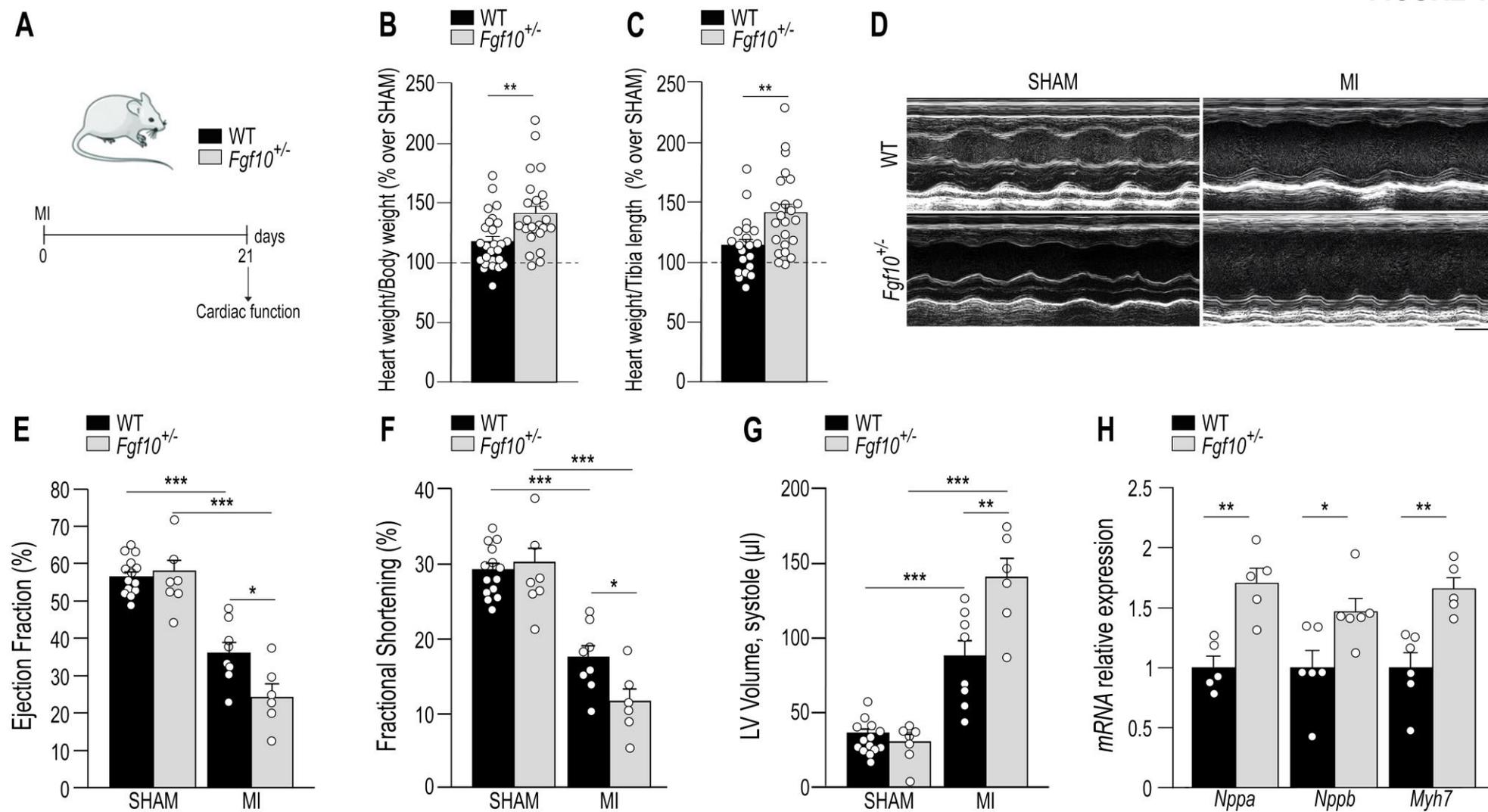


FIGURE 2

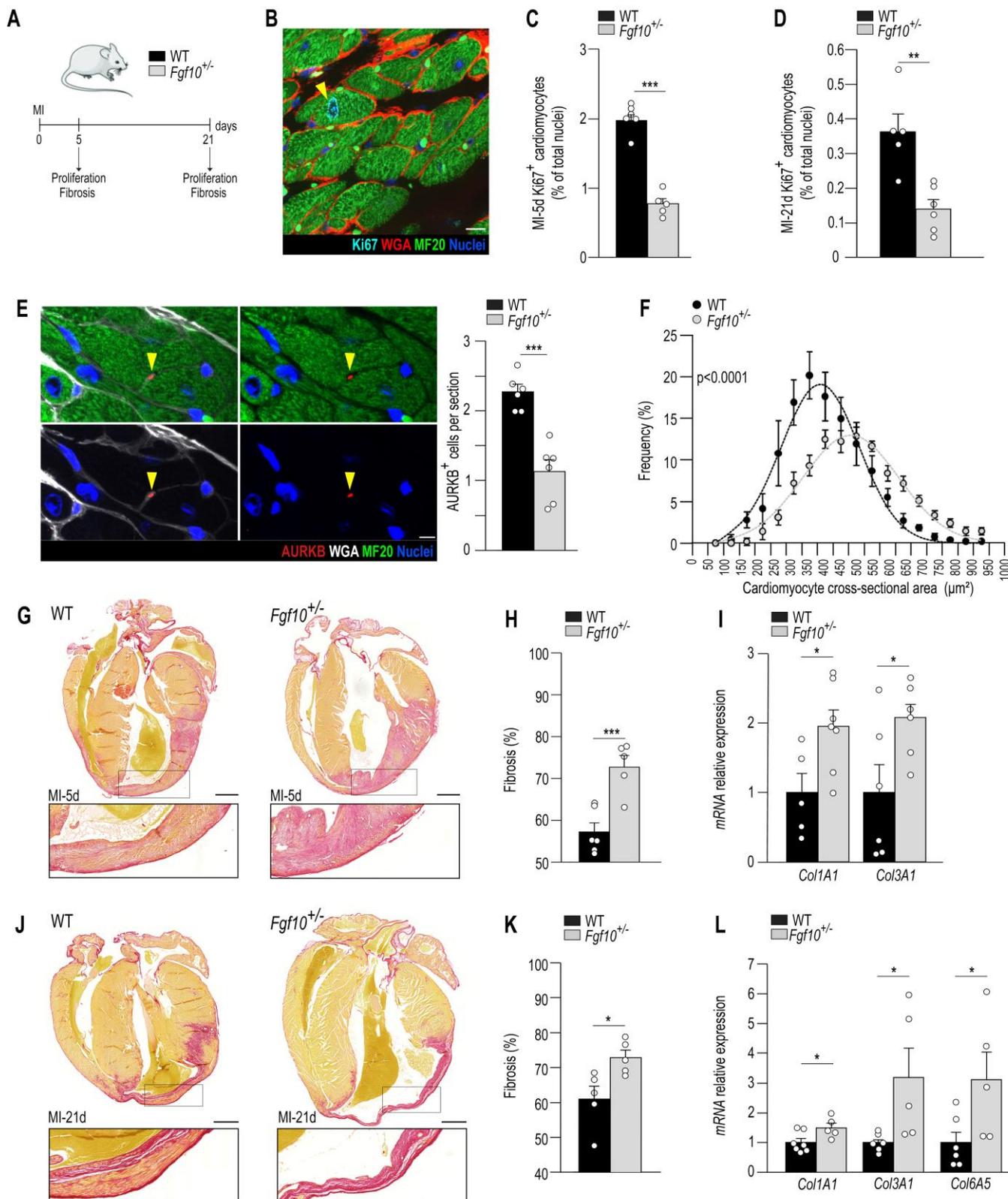


FIGURE 3

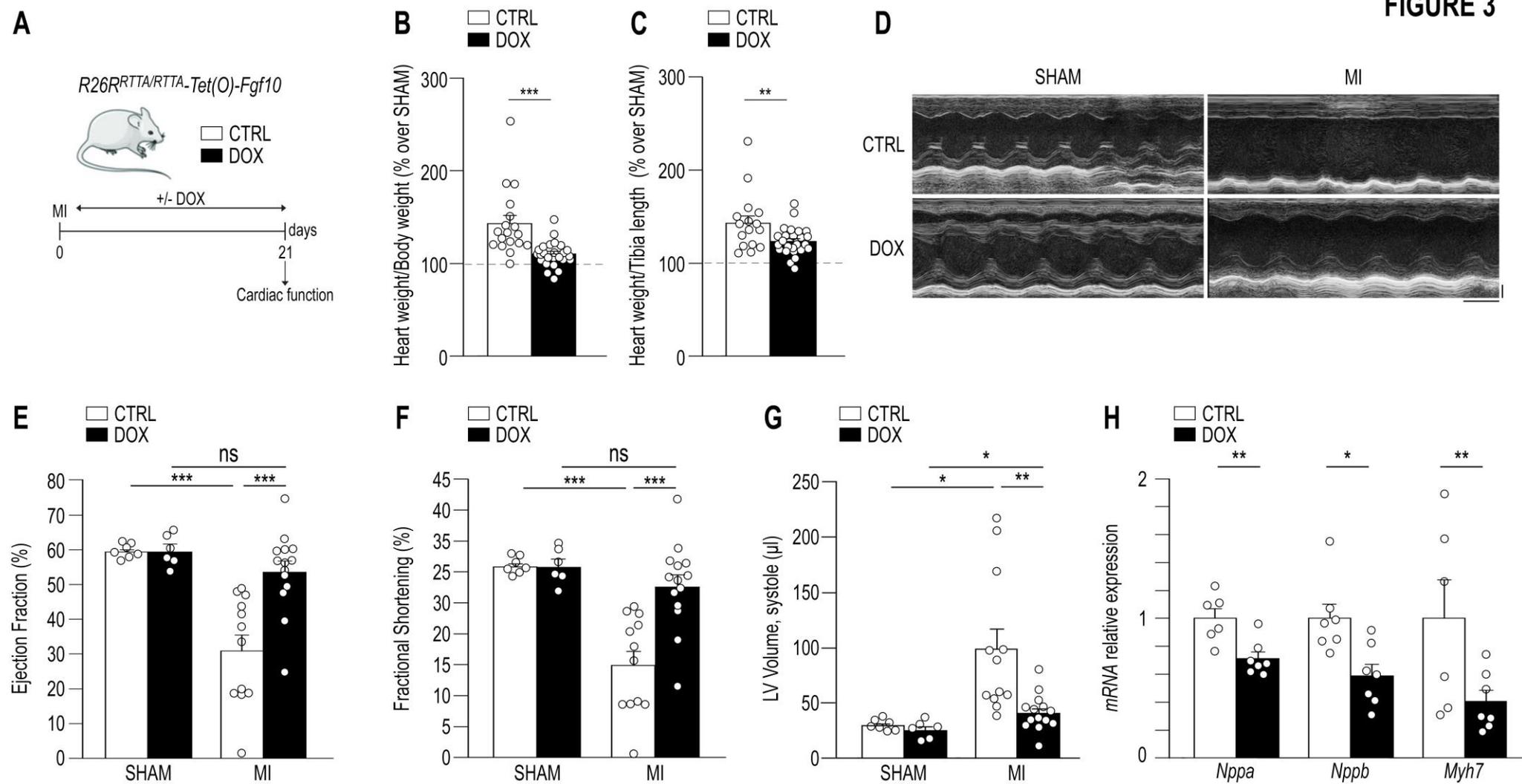


FIGURE 4

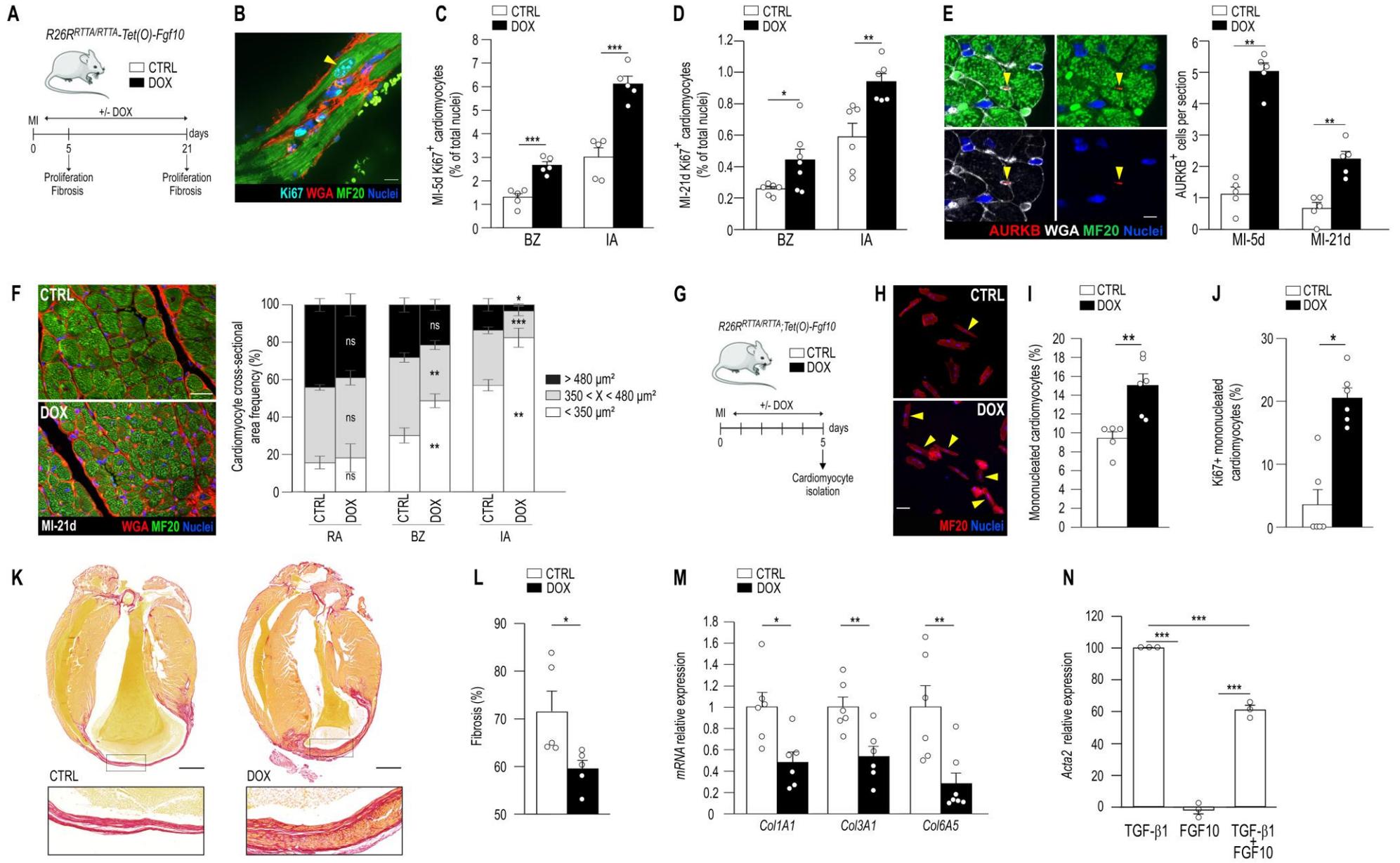


FIGURE 5

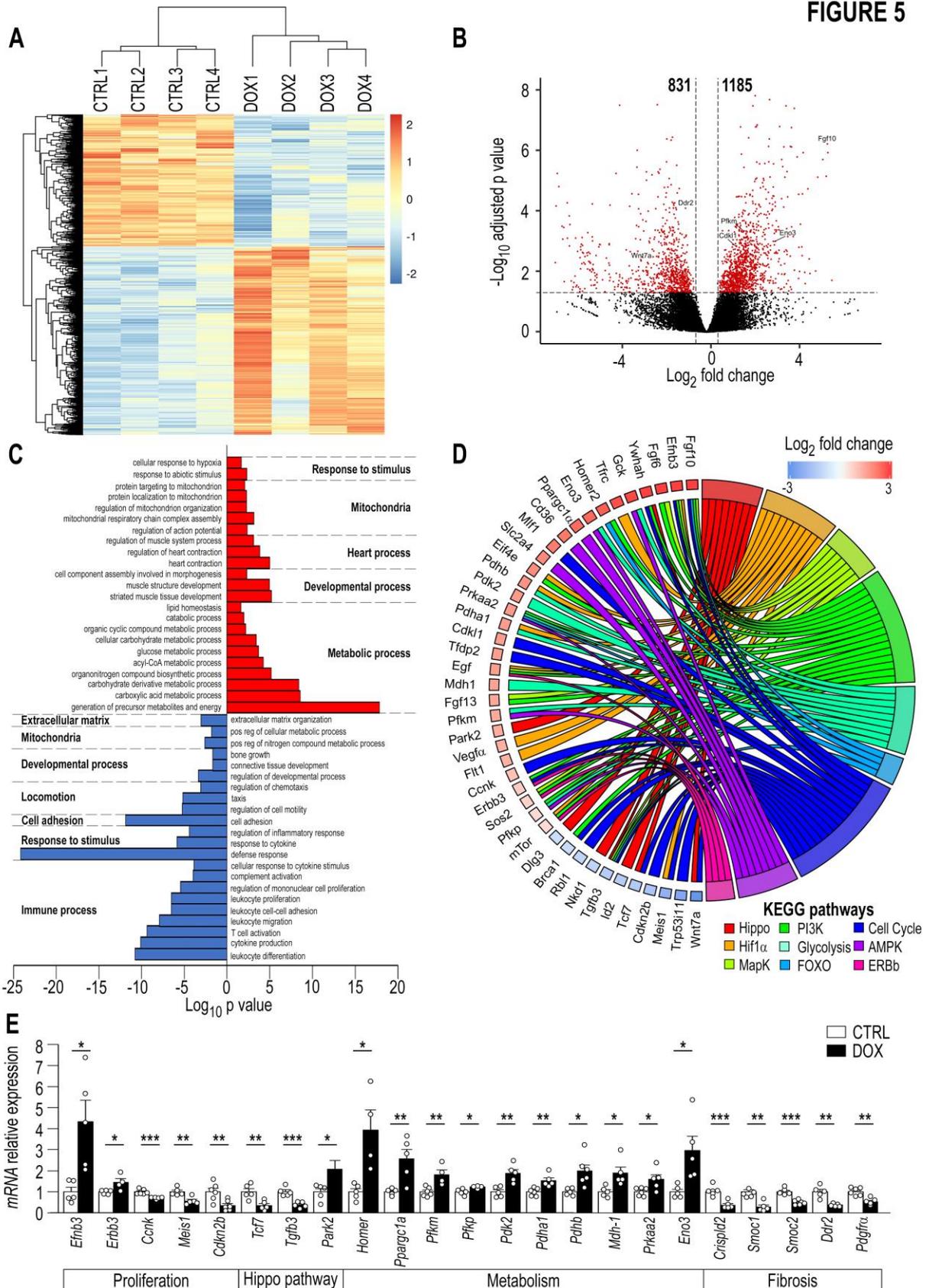
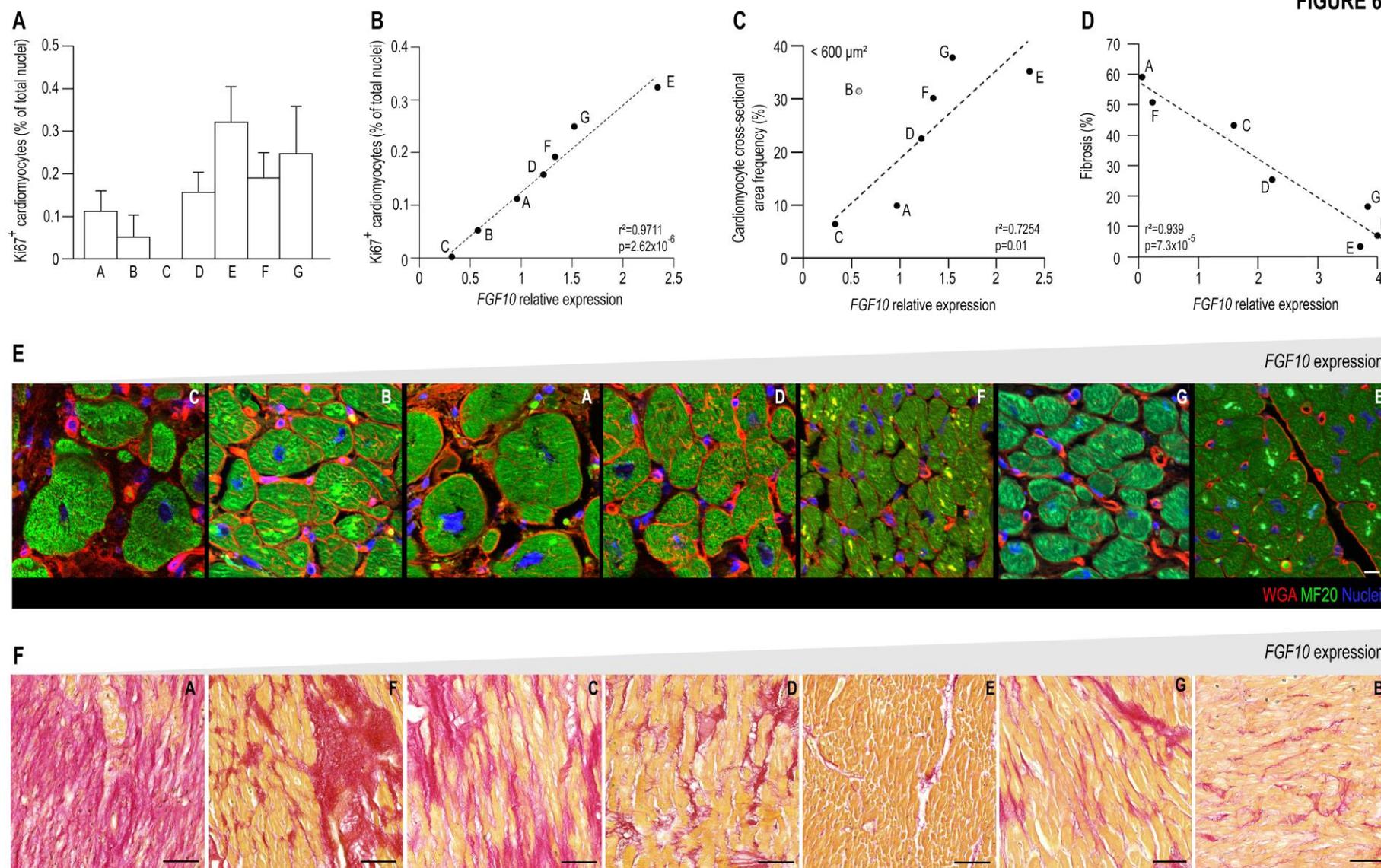
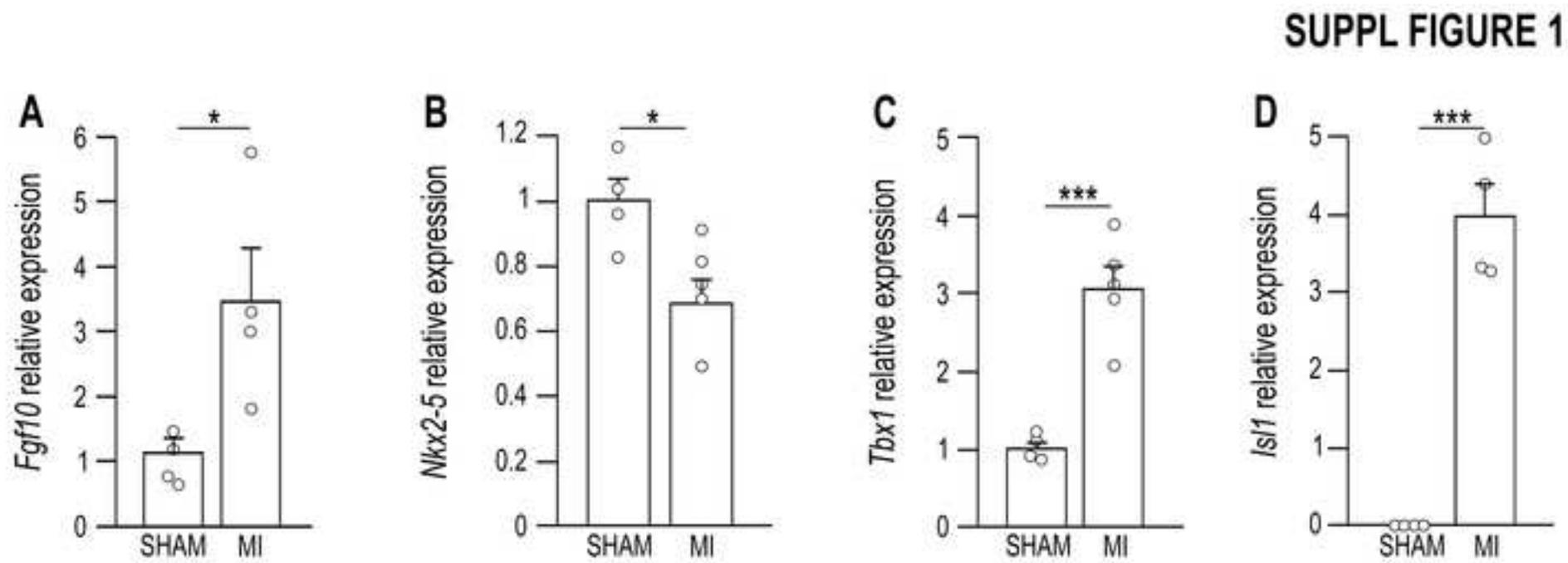
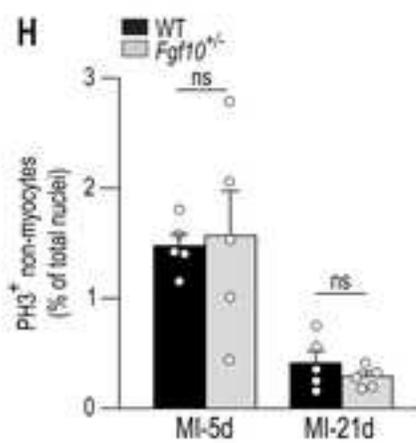
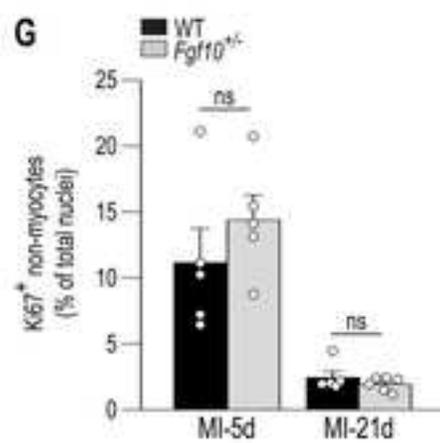
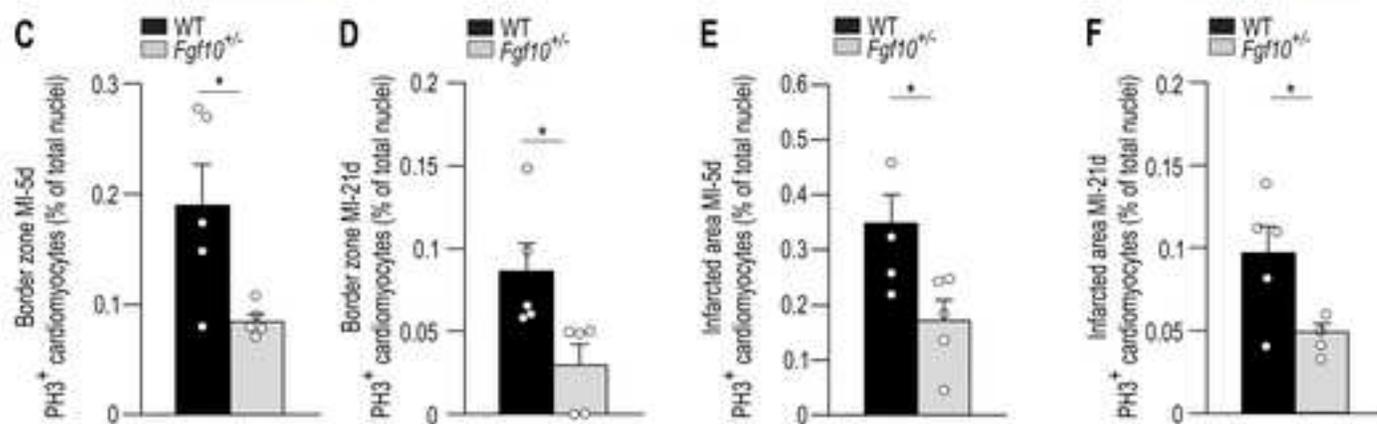
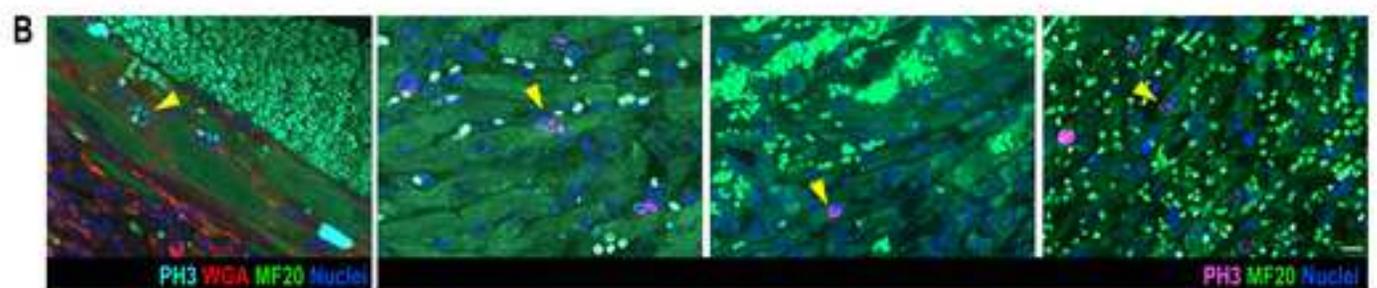
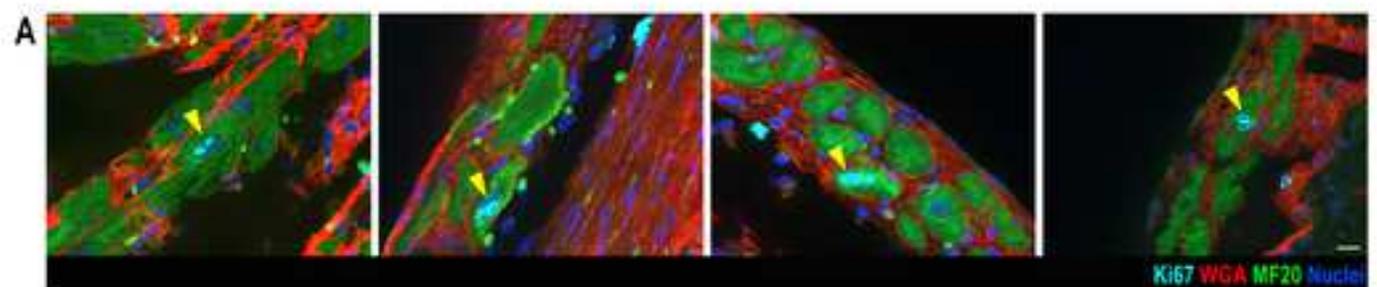


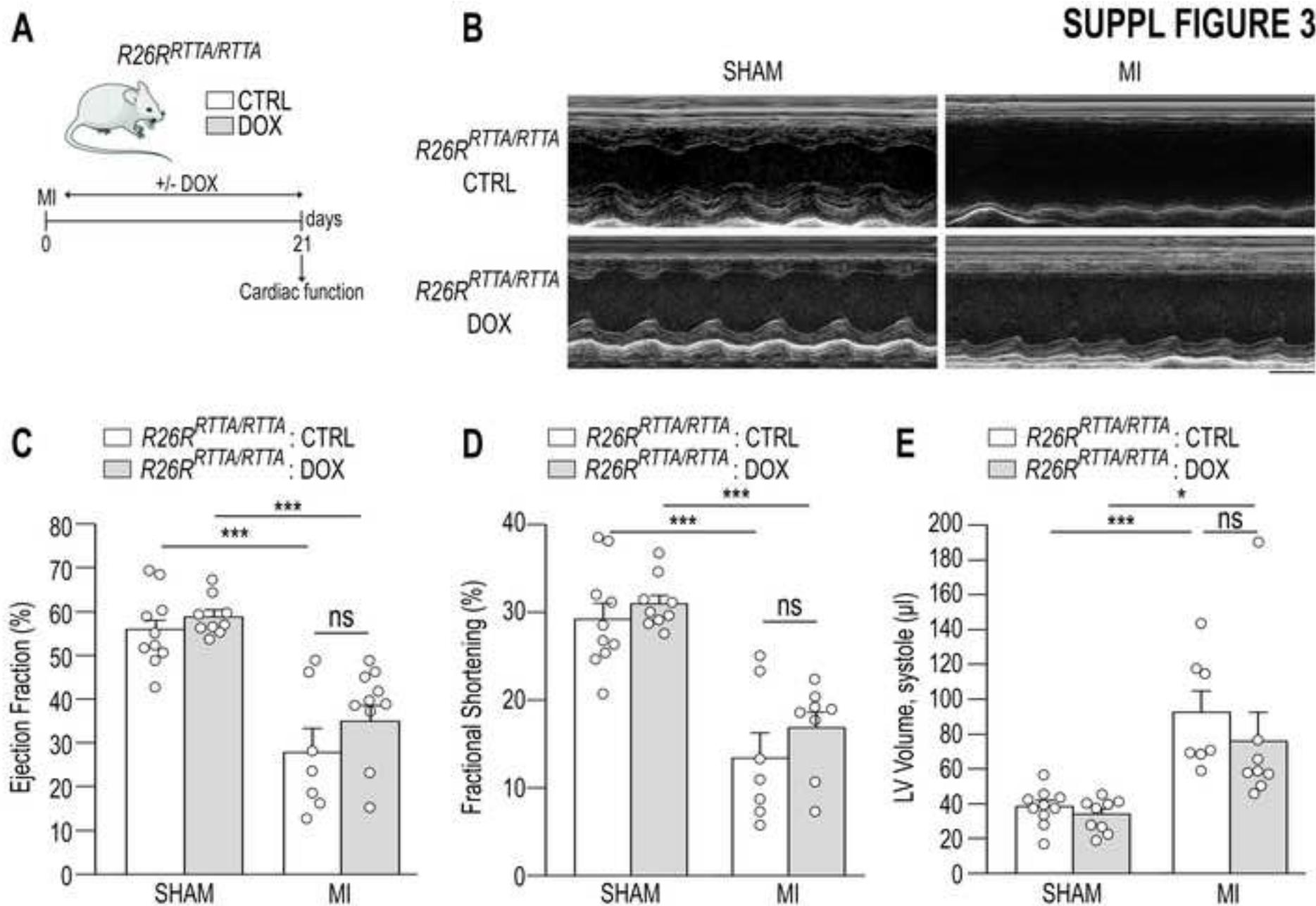
FIGURE 6



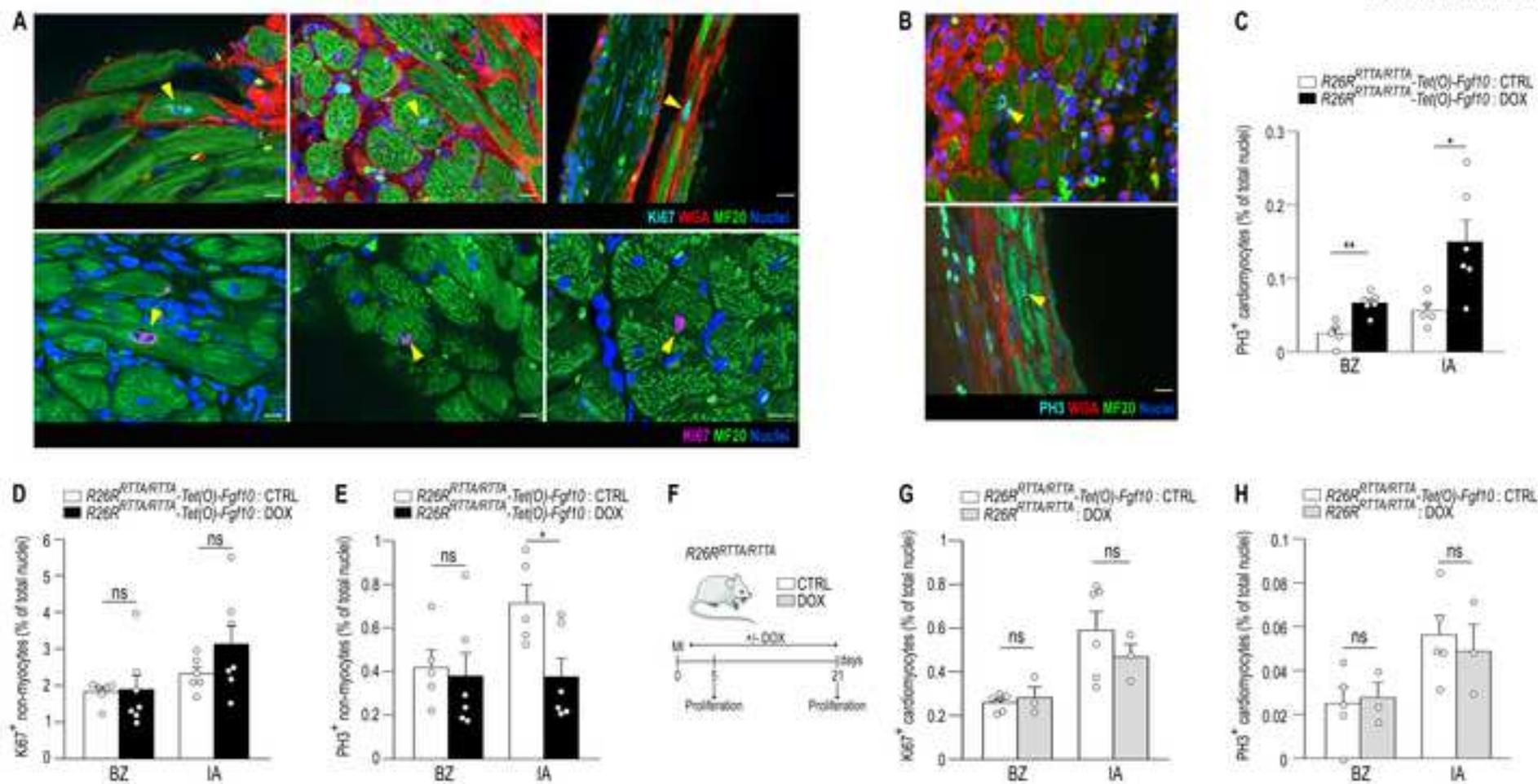


## SUPPL FIGURE 2

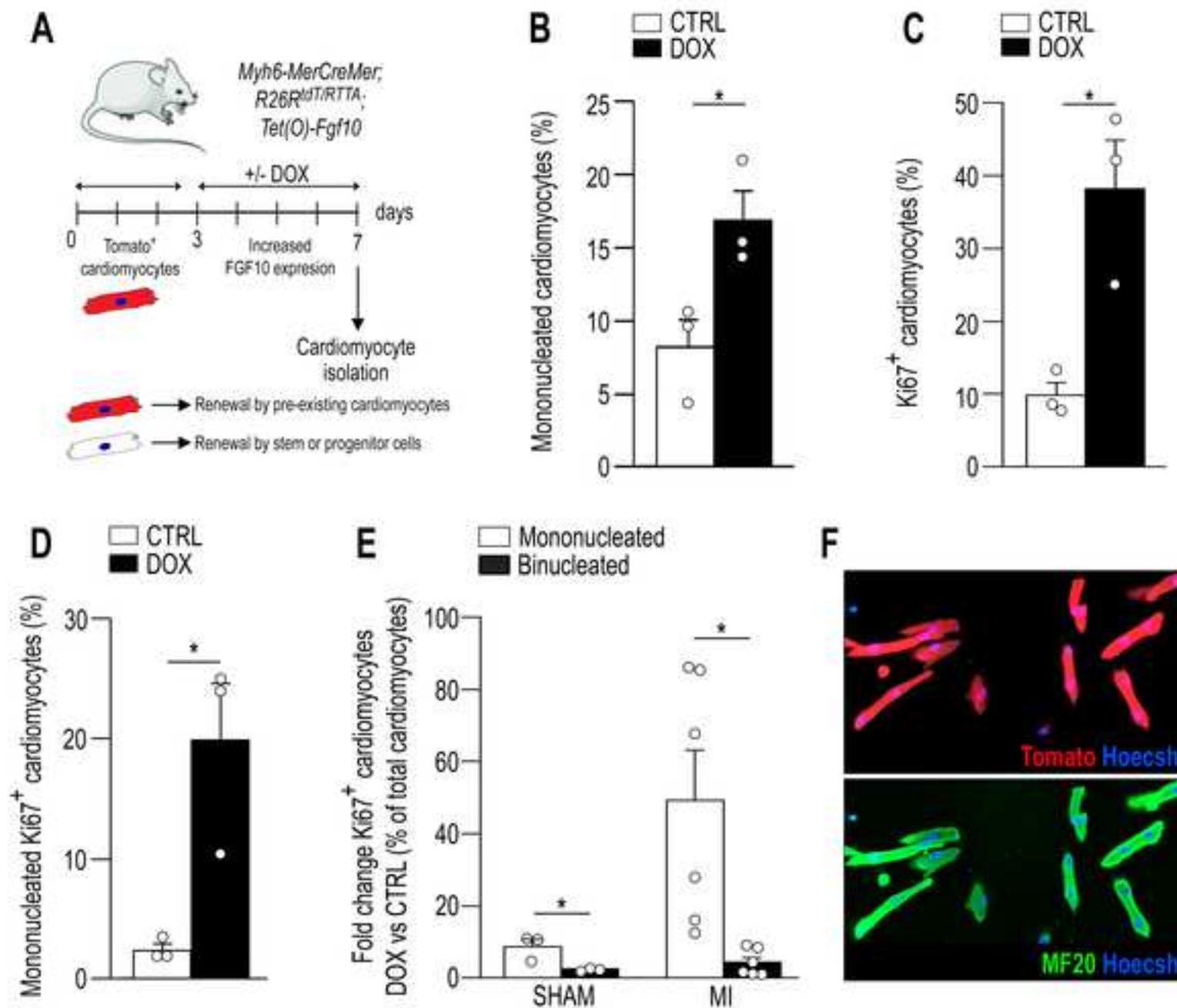


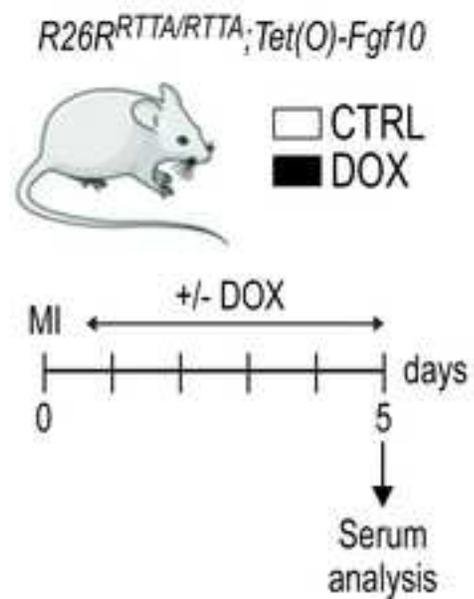
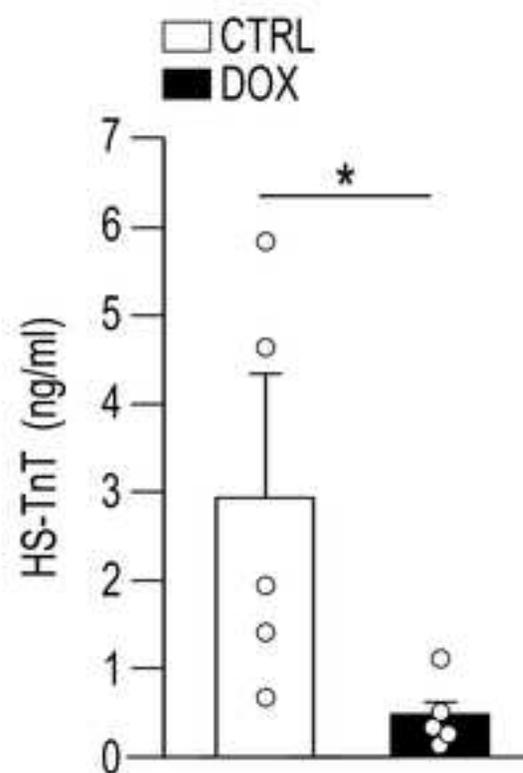
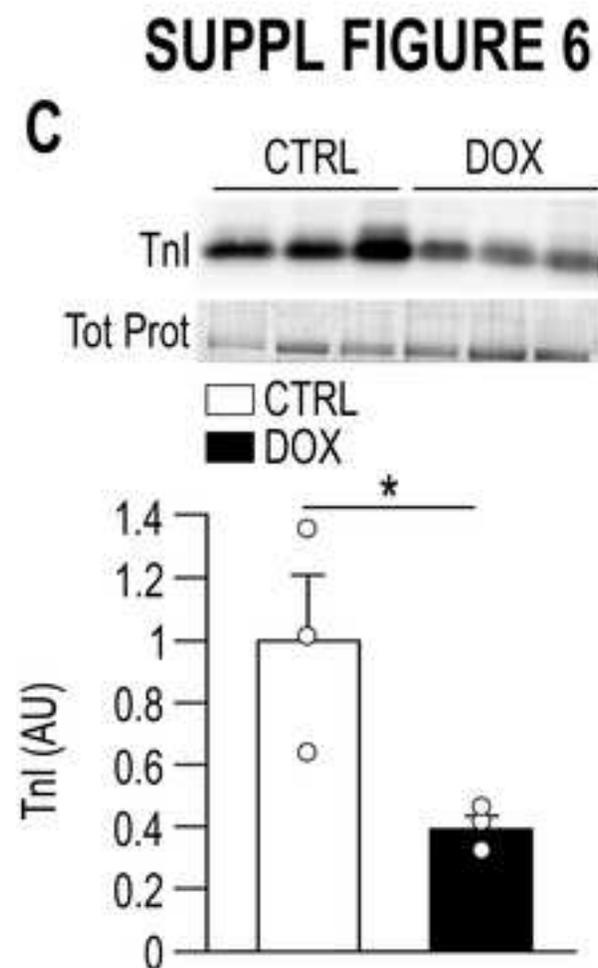


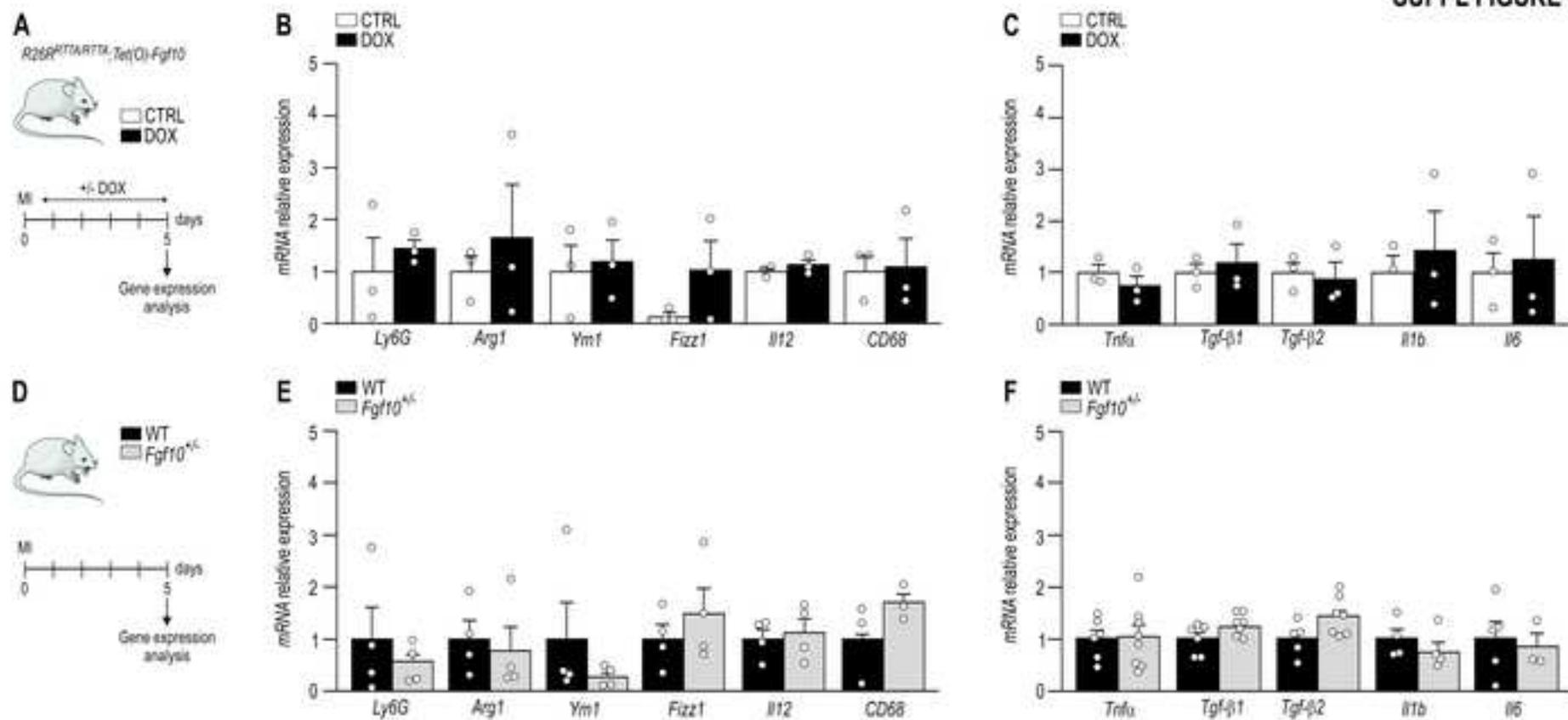
SUPPL FIGURE 4

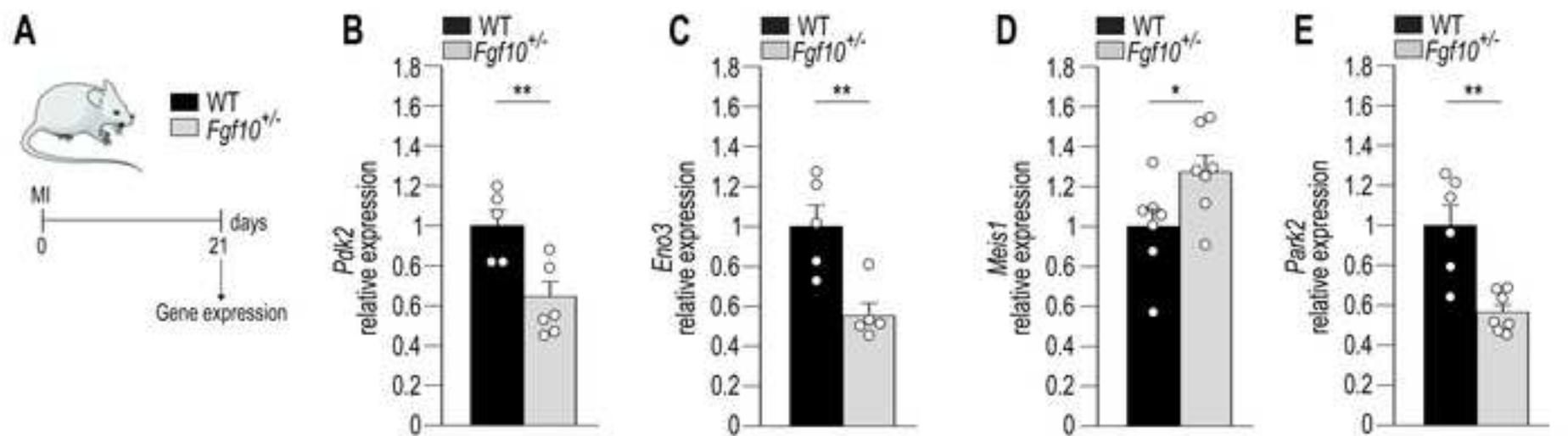


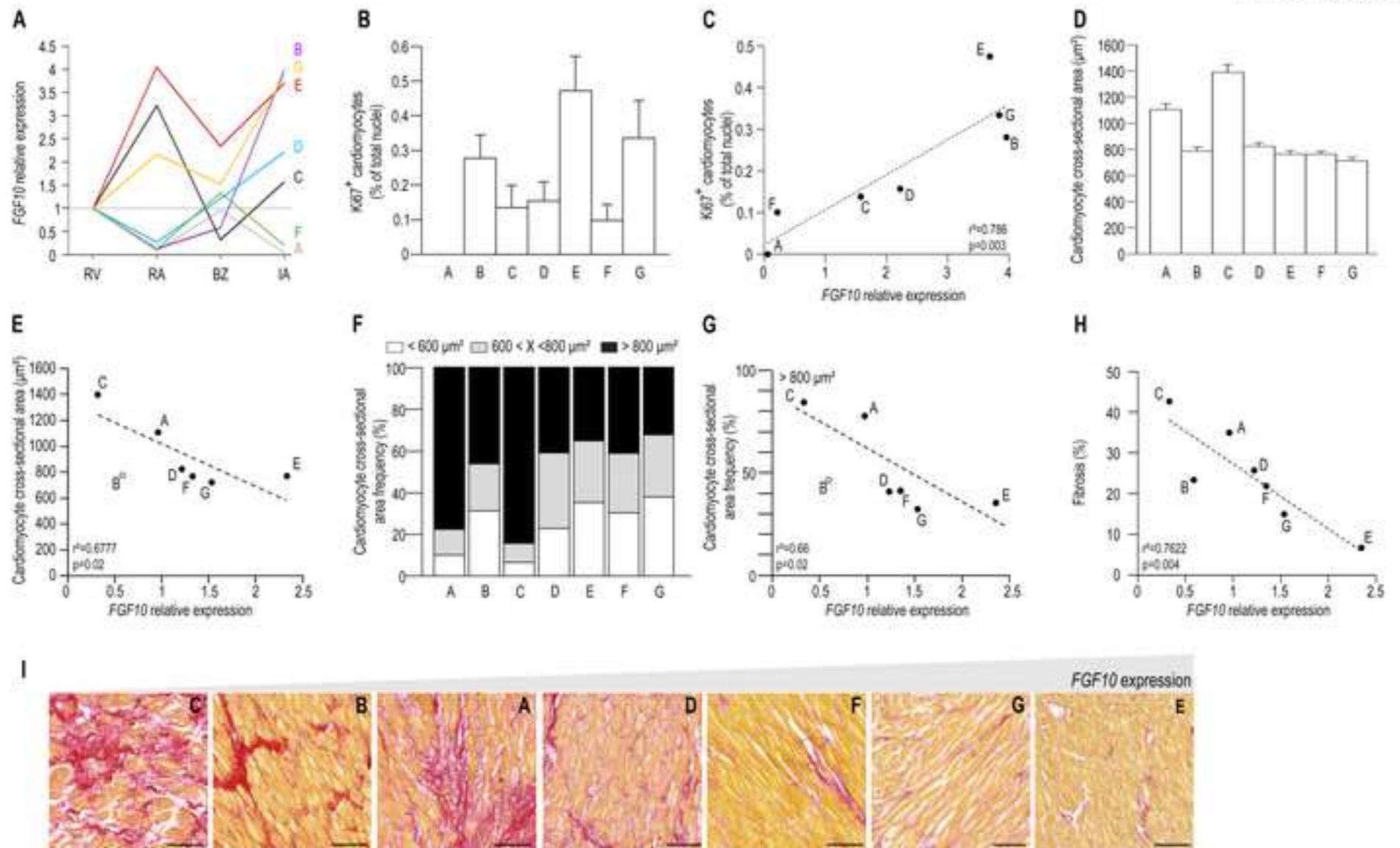
## SUPPL FIGURE 5

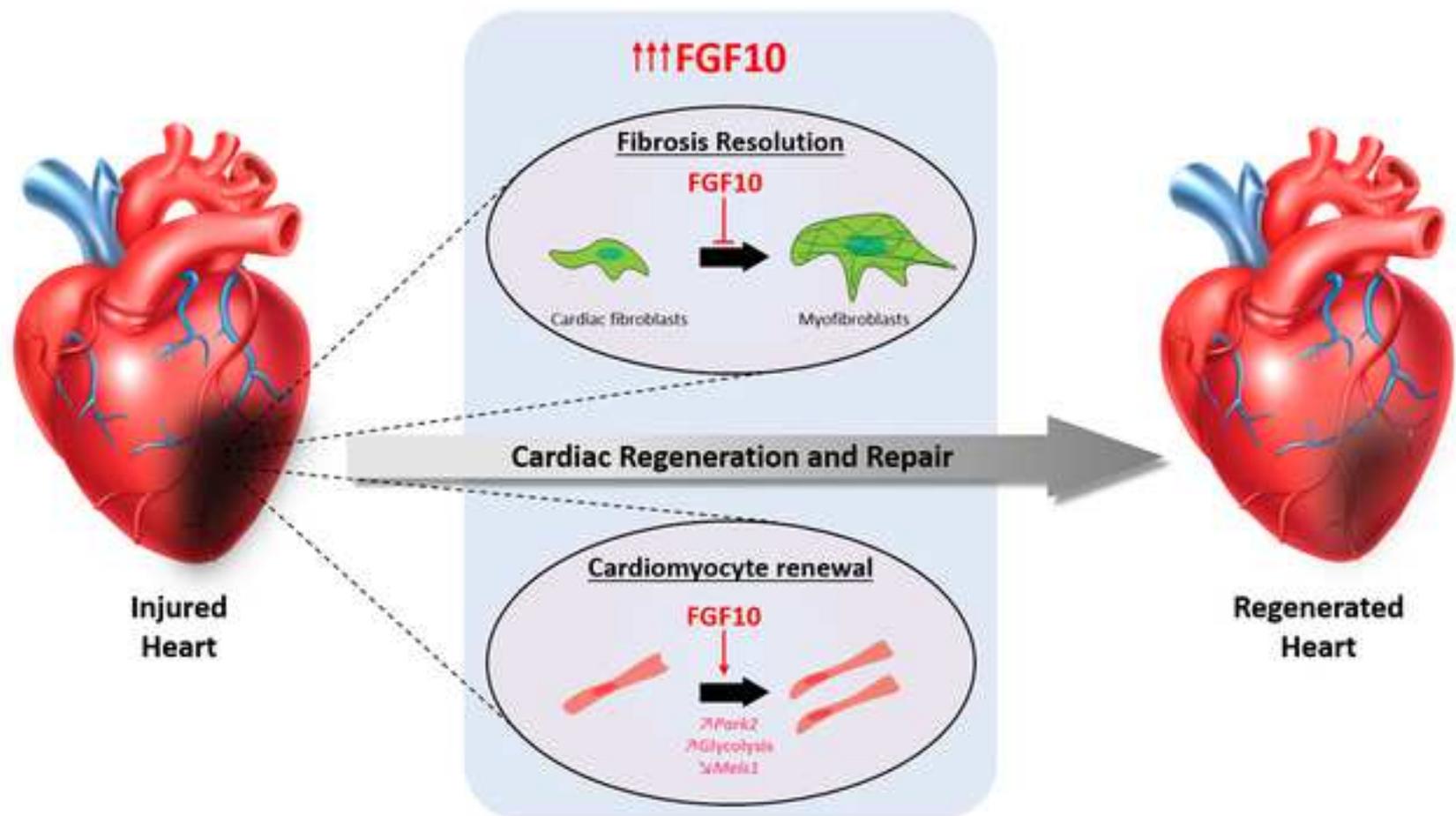


**A****B****C**









# **FGF10 promotes cardiac repair through a dual cellular mechanism increasing cardiomyocyte renewal and inhibiting fibrosis**

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## ONLINE SUPPLEMENTAL METHODS

**Mice.** The genotyping PCR steps include pre-denaturation at 94°C for 5 minutes, 30 cycles of denaturation (94°C for 45 seconds), annealing (60°C for 45 seconds) and extension (72°C for 45 seconds) followed by a final extension step at 72°C for 7 minutes. PCR products were separated using agarose gel electrophoresis to detect the specific amplified fragments.

Primers for genotyping are listed in **Table 1**.

| Mouse line                 | Primer  | Sequence (5' - 3')            |
|----------------------------|---------|-------------------------------|
| <i>Fgf10<sup>+/-</sup></i> | WT-FOR  | CTCCAGTATGTTCTTCTGATGAGAC     |
|                            | Mut-FOR | TACGGACAGTCTTCTTCTGGTCCC      |
|                            | REV     | GAGCTTGCTGGGGGAACTTCCTGACTAGG |
| <i>Fgf10-LacZ</i>          | FOR     | ATCCTCTGCATGGTCAGGTC          |
|                            | REV     | CGTGGCCTGATTCATTCC            |
| <i>Rosa26-rtTA</i>         | WT-FOR  | AAGTCGCTCTGAGTTGTTATCAG       |
|                            | WT-REV  | GGAGCGGGAGAAATGGATATGA        |
|                            | Mut-REV | CGGGTTGTAAACCTTCGATTCCG       |
| <i>Tet(O)-Fgf10</i>        | FOR     | GACGCCATCCACGCTGT             |
|                            | REV     | TGCTGCCAGTTAAAAGATGC          |
| <i>Rosa26-tdT</i>          | WT-FOR  | AAGGGAGCTGCAGTGGAGTA          |
|                            | WT-REV  | CCGAAAATCTGTGGGAAGTC          |
|                            | Mut-FOR | CTGTTCTGTACGGCATGG            |
|                            | Mut-REV | GGCATTAAAGCAGCGTATCC          |

|                  |     |                     |
|------------------|-----|---------------------|
| <i>αMHC-</i>     | FOR | AGGTTCGTTCACTCATGGA |
| <i>MerCreMer</i> | REV | TCGACCAGTTTAGTTACCC |

**Table 1: Genotyping PCR primer sequences.**

**Sirius red staining.** Serial 13 μm sections were obtained and mounted on poly-lysine-treated slides. After dewaxing (xylene, 2 times) and rehydration in an ethanol series (100, 90, 70, 50% and H<sub>2</sub>O), paraffin sections were incubated in a 0.1% Sirius Red solution dissolved in saturated aqueous solution of picric acid for 1 hour at room temperature. Subsequently, sections were washed 3 times in acidified water (0.5% acetic acid), dehydrated in ascending concentrations of ethanol (70%, 90% and 100%) and cleared in xylene. Sections were mounted in resinous medium (Entellan). Collagen and non-collagen components were red- and orange-stained, respectively.

**Immunofluorescence.** Serial 13 μm paraffin sections were obtained and mounted on slides. After dewaxing (xylene, 2 times) and rehydration in an ethanol series (100, 90, 70, 50% and H<sub>2</sub>O), antigen was retrieved by boiling samples in Vector Antigen Unmasking Solution (Vector Laboratories, H-3300) for 15 min. Slides were allowed to cool to room temperature for 20 min and washed in PBS-Tween 0.05% (PBST). For blocking, samples were incubated for at least 1 hour in TNB (0.1M Tris-HCl, 0.15M NaCl, 0.5% (w/v)) blocking reagent (PerkinElmer FP1020) prior to incubation with antibodies in TNB overnight at 4°C. This was followed by 3 times PBS-T washes. Slides were then incubated with secondary antibody diluted in TNB for 1 hour at room temperature, followed by 3 washes in PBST and nuclei were counterstained with Hoescht (1/1000) and mounted using FluoroMount (Southern Biotech). Sections were imaged using a Zeiss AxioImager fluorescent microscope with an Apotome module.

Serial 13  $\mu\text{m}$  cryostat sections were obtained from OCT embedded hearts. Sections were kept at room temperature for 15 min to dry and then washed with PBS. Slides were incubated for at least one hour in blocking solution (3% BSA-0.05% Saponin) prior to incubation with primary antibodies in blocking solution overnight at 4°C. This was followed by 3 washes in PBST. Slides were then incubated with secondary antibody in blocking solution for 1 hour at room temperature, followed by 3 washes in PBST. Nuclei were counterstained with Hoescht (1/1000) and mounted with FluoroMount (Southern Biotech). Sections were imaged using a Zeiss AxioImager fluorescent microscope with an Apotome module.

Cells attached onto coverslips were rinsed once in phosphate-buffered saline solution (PBS) for 5 min, fixed in paraformaldehyde 4% (5 min) and washed in PBS (3 times 5 min). The cells were then permeabilized in Triton X-100 0.5% (15 min), washed in PBS (2 times 5 min) and once in PBS-BSA 1% (5 min). Next, they were incubated 1 hour at 37°C with primary antibodies. After three washes in PBS and one in PBS-BSA 1%, the cells were revealed incubated with secondary antibodies (30 min, 37 °C). After three additional washes in PBS, nuclei were counterstained with Hoescht (1/1000) and the coverslips were mounted with FluoroMount (Southern Biotech) and then imaged using a Zeiss AxioImager fluorescent microscope with an Apotome module. Primary and secondary antibodies are listed in **Table 2**.

| Primary antibodies     |         |        |                        |
|------------------------|---------|--------|------------------------|
| $\alpha$ -actinin      | Mouse   | 1/500  | Sigma A7811            |
| AURKB                  | Rabbit  | 1/400  | Abcam ab2254           |
| Caspase 3              | Rabbit  | 1/100  | Cell signalling 9665   |
| $\beta$ -galactosidase | Rabbit  | 1/500  | MP Biomedicals 0855976 |
| $\beta$ -galactosidase | Chicken | 1/1000 | Abcam ab9361           |

|                                    |        |       |                                |
|------------------------------------|--------|-------|--------------------------------|
| Ki67                               | Rabbit | 1/100 | Abcam ab15580                  |
| MF20 sarcomeric myosin heavy chain | Mouse  | 1/50  | DSHB                           |
| Phospho Histone H3                 | Rabbit | 1/400 | Upstate cell signalling 06-570 |
| WGA-AlexaFluor555                  |        | 1/50  | Thermofisher W32464.           |
| Secondary antibodies               |        |       |                                |
| Anti-Rabbit Alexa Fluor 488        | Donkey | 1/500 | ThermoFisher A-21206           |
| Anti-Mouse Alexa Fluor 488         | Donkey | 1/500 | ThermoFisher A-21202           |
| Anti-Mouse Alexa Fluor 647         | Donkey | 1/500 | ThermoFisher A-31571           |
| Anti-Rabbit Alexa Fluor 647        | Donkey | 1/500 | ThermoFisher A-21208           |

**Table 2: Primary and secondary antibodies.**

**Quantitative Real Time PCR.** Quantitative RT-PCR primers are listed in **Table 3.**

| Gene          | Species | Primer   | Sequence (5' - 3')          |
|---------------|---------|----------|-----------------------------|
| <i>Acta2</i>  | mouse   | Acta2-F  | ACTCTCTTCCAGCCATCTTTCA      |
|               | human   | Acta2-R  | ATAGGTGGTTTCGTGGATGC        |
| <i>Angpt1</i> | mouse   | Angpt1-F | GGAAGATGGAAGCCTGGAT         |
|               |         | Angpt1-R | ACCAGAGGGATTCCCAAAC         |
| <i>Ccnk</i>   | mouse   | Ccnk-F   | GTTTGGAGATGACCCAAAGG        |
|               |         | Ccnk-R   | AAGTCAAACCTTTATGGTCTGCAGTAA |
| <i>Cdkn2b</i> | mouse   | Cdkn2b-F | AATAACTTCTACGCATTTTCTGC     |
|               |         | Cdkn2b-R | CCCTTGGCTTCAAGGTGAG         |
| <i>Col1A1</i> | mouse   | Col1A1-F | CATGTTTCAGCTTTGTGGACCT      |

|                 |       |            |                          |
|-----------------|-------|------------|--------------------------|
|                 |       | Col1A1-R   | GCAGCTGACTTCAGGGATGT     |
| <i>Col3A1</i>   | mouse | Col3A1-F   | TGGTCCTGCTGGAAAGGAT      |
|                 |       | Col3A1-R   | GAGGTCCAGGCAGTCCAC       |
| <i>Col6A5</i>   | mouse | Col6A5-F   | CCTCCTGGTCGGAGAGGT       |
|                 |       | Col6A5-R   | TTCACAGGGGGAATATATAGGTTG |
| <i>Crispld2</i> | mouse | Crispld2-F | AGGTTGAGGCCAGAGTTCC      |
|                 |       | Crispld2-R | GCCTTCAGCCACAATAAGAG     |
| <i>Ddr2</i>     | mouse | Ddr2-F     | ATGTTGGCAGGCAAGACAG      |
|                 |       | Ddr2-R     | TCAGGTCGCTGTAGATTTCC     |
| <i>Efnb3</i>    | mouse | Efnb3-F    | TGGALECTCGGCGAATAAGAG    |
|                 |       | Efnb3-R    | CCCCGATCTGAGGATAAAGC     |
| <i>Eno3</i>     | mouse | Eno3-F     | ACACAGCCAAGGGTCGATT      |
|                 |       | Eno3-R     | TCCACAGCCTTCAGCACTC      |
| <i>ErbB3</i>    | mouse | ErbB3-F    | CACGAGAACTGCACCCAAG      |
|                 |       | ErbB3-R    | TCTGCTTGGCCTAACAGTCT     |
| <i>Fgf10</i>    | mouse | Fgf10-F    | GAGAAGAACGGCAAGGTCAG     |
|                 | rat   | Fgf10-R    | TTTCCCCTTCTTGTTTCATGG    |
|                 | human | FGF10-F    | GAAGGAGAACTGCCCCGTACA    |
|                 |       | FGF10-R    | GGCAACAACCTCCGATTTCTACT  |
| <i>Hprt</i>     | mouse | Hprt-F     | CTGGTGAAAAGGACCTCTCG     |
|                 |       | Hprt-R     | TGGCAACATCAACAGGACTC     |
| <i>Homer2</i>   | mouse | Homer2-F   | CCAGAGACAAGTCCCAGGAG     |
|                 |       | Homer2-R   | CCATTGACGCTGGATGCT       |

|               |       |          |                           |
|---------------|-------|----------|---------------------------|
| <i>IL-1b</i>  | mouse | IL-1b-F  | AGTTGACGGACCCCAAAG        |
|               |       | IL-1b-R  | TTTGAAGCTGGATGCTCTCAT     |
| <i>IL-6</i>   | mouse | IL-6 F   | GATGGATGCTACCAAAGTGGAT    |
|               |       | IL-6 R   | CCAGGTAGCTATGGTACTCCAGA   |
| <i>Isl1</i>   | mouse | Isl1-F   | AGCAACCCAACGACAAAAGT      |
|               |       | Isl1-R   | CCATCATGTCTCTCCGGACT      |
| <i>Mdh1</i>   | mouse | Mdh1-F   | TGCTCTACTCATTCCCTGTCTG    |
|               |       | Mdh1-R   | CCTTTGCTGTCAGGTCCATC      |
| <i>Meis1</i>  | mouse | Meis1-F  | ATGGGTTCCCTCGGTCAATG      |
|               |       | Meis1-R  | CATTTCTCAAAAATCAGTGCTAAGA |
| <i>Myh6</i>   | mouse | Myh6-F   | CCTCAAGCTCATGGCTACAC      |
|               |       | Myh6-R   | TTGCCTCCTTTGCCTTTACC      |
| <i>Myh7</i>   | mouse | Myh7-F   | AGGCAAAGAAAGGCTCATCC      |
|               |       | Myh7-R   | TGGAGCGCAAGTTTGTGATA      |
| <i>Nkx2.5</i> | mouse | Nkx2.5-F | CAAGTGCTCTCCTGCTTTCC      |
|               |       | Nkx2.5-R | CTTTGTCCAGCTCCACTGC       |
| <i>Nppa</i>   | mouse | Nppa -F  | CAACACAGATCTGATGGATTTCA   |
|               |       | Nppa -R  | CCTCATCTTCTACCGGCATC      |
| <i>Nppb</i>   | mouse | Nppb -F  | GTCAGTCGTTTGGGCTGTAAC     |
|               |       | Nppb -R  | AGACCCAGGCAGAGTCAGAA      |
| <i>Park2</i>  | mouse | Park2-F  | CGCGTAGGTCCTTCTCGAC       |
|               |       | Park2-R  | GAAAGGCTGGGCCTAGATACA     |
| <i>Pdgfra</i> | mouse | Pdgfra-F | AAGACCTGGGCAAGAGGAAC      |

|                 |       |            |                         |
|-----------------|-------|------------|-------------------------|
|                 |       | Pdgfra-R   | GAACCTGTCTCGATGGCACT    |
| <i>Pdha1</i>    | mouse | Pdha1-F    | GTAAGGGGCCCATCCTGA      |
|                 |       | Pdha1-R    | TCTTCTCGAGTGCGGTAGC     |
| <i>Pdhb</i>     | mouse | Pdhb-F     | TGATGAAGACAAATCATCTCGTG |
|                 |       | Pdhb-R     | AGGGGCATCAAGGAAGTTG     |
| <i>Pdk1</i>     | rat   | Pdk1-F     | CCGATTCAAGTTCACGTCAC    |
|                 |       | Pdk1-R     | ACCTCCCCGGTCACTCAT      |
| <i>Pdk2</i>     | mouse | Pdk2-F     | TGGCTAAGCTCCTGTGTGAC    |
|                 |       | Pdk2-R     | CATGTGAATGGGCTGGTTG     |
| <i>Pecam1</i>   | mouse | CD31-F     | CGGTGTTCAGCGAGATCC      |
|                 |       | CD31-R     | ACTCGACAGGATGGAAATCA    |
| <i>Pfkm</i>     | mouse | Pfkm-F     | GGACAATCTGCAAGAAAGCA    |
|                 |       | Pfkm-R     | TGATGCTCTTCATGGGTCAT    |
| <i>pfkp</i>     | mouse | Pfkp-F     | GAGGGACCCCATCTGCAT      |
|                 |       | Pfkp-R     | GTAGCTTCCAGCAAGGCAAT    |
| <i>Ppargc1a</i> | mouse | Ppargc1a-F | AGCCTGCGAACATATTTGAGA   |
|                 |       | Ppargc1a-R | ATGAGGGCAATCCGTCTTC     |
| <i>PPIA</i>     | Human | PPIA-F     | ATGCTGGACCCAACACAAAT    |
|                 |       | PPIA-R     | TCTTTCACCTTTGCCAAACACC  |
| <i>Prkaa2</i>   | mouse | Prkaa2-F   | CGACTACATCTGCAAACATGG   |
|                 |       | Prkaa2-R   | CAGTAATCCACGGCAGACAG    |
| <i>Smoc1</i>    | mouse | Smoc1-F    | GATAAGGTCATCTCACTGCCTGA |
|                 |       | Smoc1-R    | AAGCTGCCAAGGCTACCAC     |

|                               |       |                 |                          |
|-------------------------------|-------|-----------------|--------------------------|
| <i>Smoc2</i>                  | mouse | Smoc2-F         | CGTGGAATTGCAAAGATG       |
|                               |       | Smoc2-R         | CCTGCTCCTGGGTATACTTCC    |
| <i>Tbx1</i>                   | mouse | Tbx1-F          | TTTGTGCCCCTAGATGACAA     |
|                               |       | Tbx1-R          | ACTCGGCCAGGTGTAGCA       |
| <i>Tcf7</i>                   | mouse | Tcf7-F          | AGGAGCTGCAGCCATATGAT     |
|                               |       | Tcf7-R          | TGACTGGCTTCTTAGCCTCCT    |
| <i>TGFb1</i>                  | mouse | TGFb1-F         | TGGAGCAACATGTGGAAGCTC    |
|                               |       | TGFb1-R         | GTCAGCAGCCGGTTACCA       |
| <i>TGFb2</i>                  | mouse | TGFb2-F         | AGGAGGTTTATAAAATCGACATGC |
|                               |       | TGFb2-R         | TAGAAAGTGGGCGGGATG       |
| <i>TGFb3</i>                  | mouse | TGFb3-F         | CCCTGGACACCAATTACTGC     |
|                               |       | TGFb3-R         | TCAATATAAAGGGGGCGTACA    |
| <i>Tnf<math>\alpha</math></i> | mouse | TNF $\alpha$ -F | AGCCTCTTCTCATTCTGCTT     |
|                               |       | TNF $\alpha$ -R | ATGAGAGGGAGGCCATTTG.     |
| <i>Vegfb</i>                  | mouse | Vegfb-F         | GCTCAACCCAGACACCTGTAG    |
|                               |       | Vegfb-R         | AGGAGGTTTCGCCTGTGCT      |
| <i>Vegfc</i>                  | mouse | Vegfc-F         | GAGTCGGGACTGGGCTTC       |
|                               |       | Vegfc-R         | GACACAGACCGCAACTGCT      |
| YWHAZ                         | human | YWHAZ-F         | GTGGACATCGGATACCCAAG     |
|                               |       | YWHAZ-R         | AAGTTGGAAGGCCGGTTAAT     |

**Table 3: Quantitative RT-PCR primer sequences.**

**Data processing and differential gene expression (DGE) analysis.**

70 millions of reads (clusters) have been sequenced, on average, by sample. The quality of sequencing reads was assessed using fastQC<sup>1</sup>. Reads were mapped to the mouse reference genome (GRCm38/mm10) using STAR (v2.5.3a)<sup>2</sup> and bam files were indexed and sorted using Sambamba (v0.6.6)<sup>3</sup>. Number of read fragments per gene (GENCODE annotations) was determined after mapping using Stringtie (v1.3.1c)<sup>4</sup>. Differential gene expression analysis was performed using DESeq2<sup>5</sup>. p-values were adjusted for multiple testing using the method by Benjamini and Hochberg<sup>6</sup> and genes with an FDR (False Discovery Rate) adjusted p-value below 0.05 were considered as significantly differentially expressed. The heatmap of Differentially Expressed Genes using was generated using the Pheatmap R package, while the volcano plot representing the Log<sub>2</sub>FC (log<sub>2</sub> of the expression fold change) and the adjusted p-value of the Wald test has been prepared by using the EnhancedVolcano R package. Enrichment (Gene set enrichment Analysis, GSEA) and overrepresentation (Singular Enrichment Analysis, SEA) in GO term analysis were performed using a Mann-Whitney test and hypergeometric test respectively, thanks to the ClusterProfiler R package. In the case of over-representation, the test was set on genes having a FDR adjusted p-value below 0.001, the value commonly accepted as threshold for significance. Results of GSEA and SEA, have been represented, for a set of selected genes, as Circos plot with GOplot R package.

<sup>1</sup>Andrews S. Fastqc: A Quality Control Tool for High Throughput Sequence Data. Available online at <https://www.bioinformatics.babraham.ac.uk/projects/fastqc>. 2010.

<sup>2</sup>Dobin A and Gingeras TR. Mapping RNA-seq Reads with STAR. Current Protocols in Bioinformatics. 2015; 51(1), 11.14.1-11.14.19.

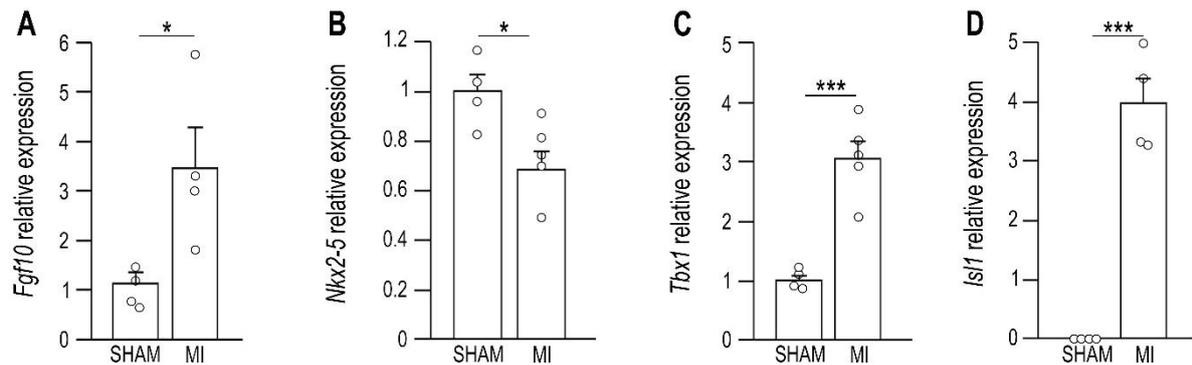
<sup>3</sup>Tarasov A, Vilella AJ, Cuppen E, Nijman IJ and Prins P. Sambamba: fast processing of NGS alignment formats. *Bioinformatics*. 2015; 31(12): 2032–2034.

<sup>4</sup>Pertea M, Pertea GM, Antonescu CM, Chang TC, Mendell JT and Salzberg SL. StringTie enables improved reconstruction of a transcriptome from RNA-seq reads. *Nature Biotechnology*. 2015; 33(3), 290–295.

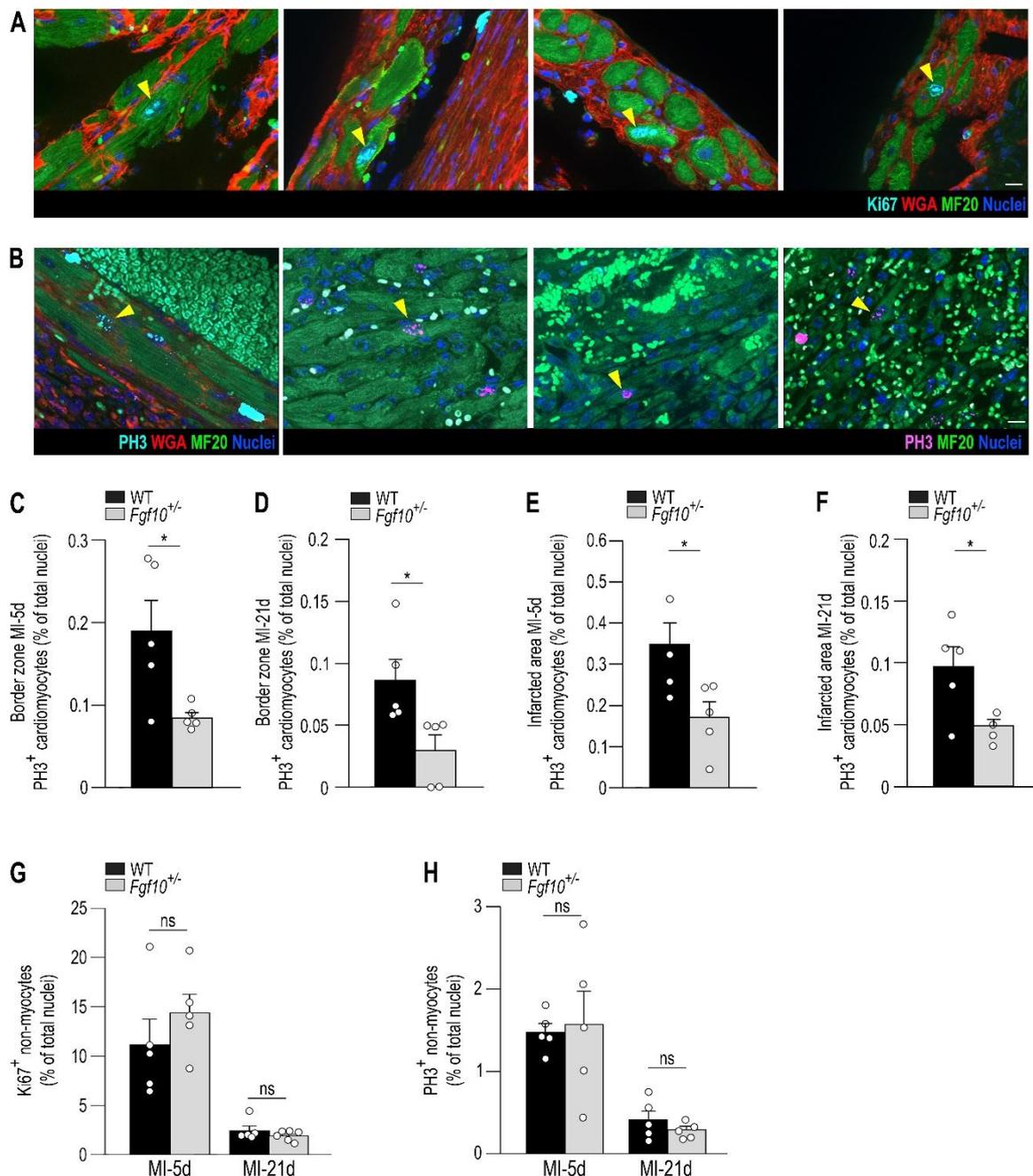
<sup>5</sup>Love MI, Huber W and Anders S. Moderated estimation of fold change and dispersion for RNA-seq data with DESeq2. *Genome Biol*. 2014; 15(12): 550.

<sup>6</sup>Benjamini Y and Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *J R Stat Soc B*. 1995; 57, 289-300.

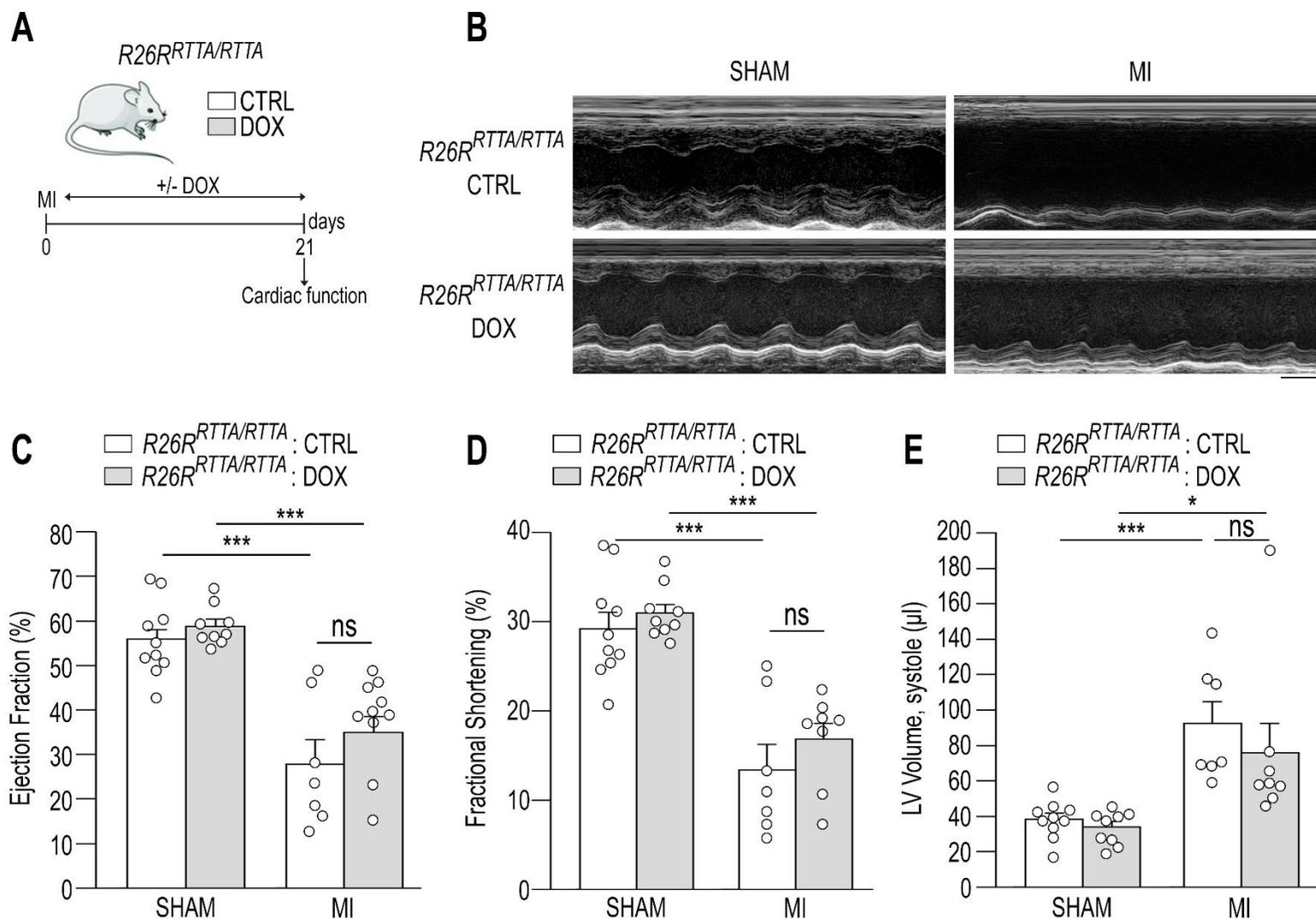
## ONLINE SUPPLEMENTAL FIGURES



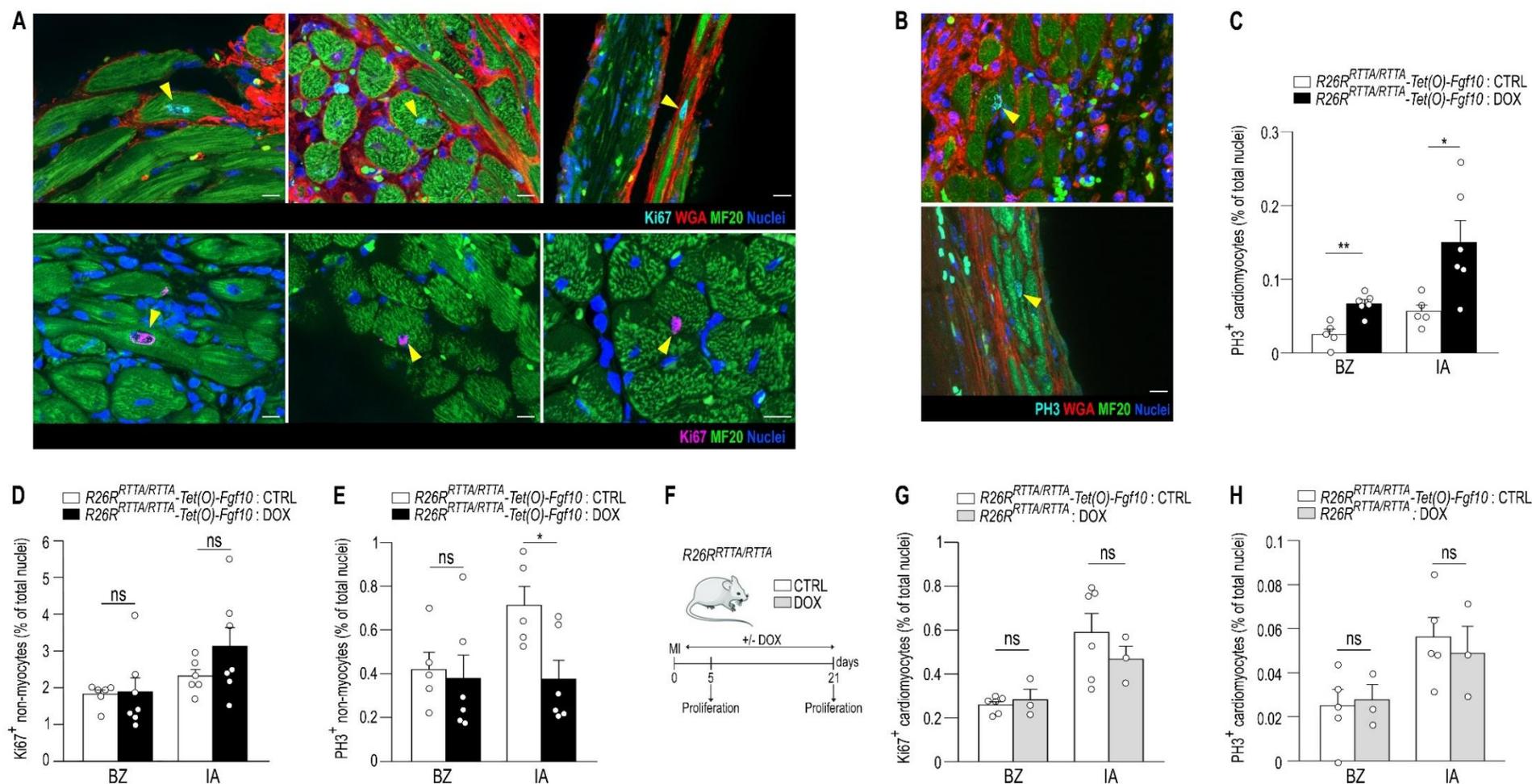
**Supplemental Figure 1: *Fgf10* expression is upregulated after myocardial infarction (MI).** qRT-PCR experiments on left ventricular MI hearts showing (A) *Fgf10*, (B) *Nkx2-5*, (C) *Tbx1* and (D) *Is1* expression 21 days after MI (n=4-5 per group). *Is1* expression is normalized to right ventricular expression. \*, p<0.05; \*\*\*, p<0.001; Student's t-test.



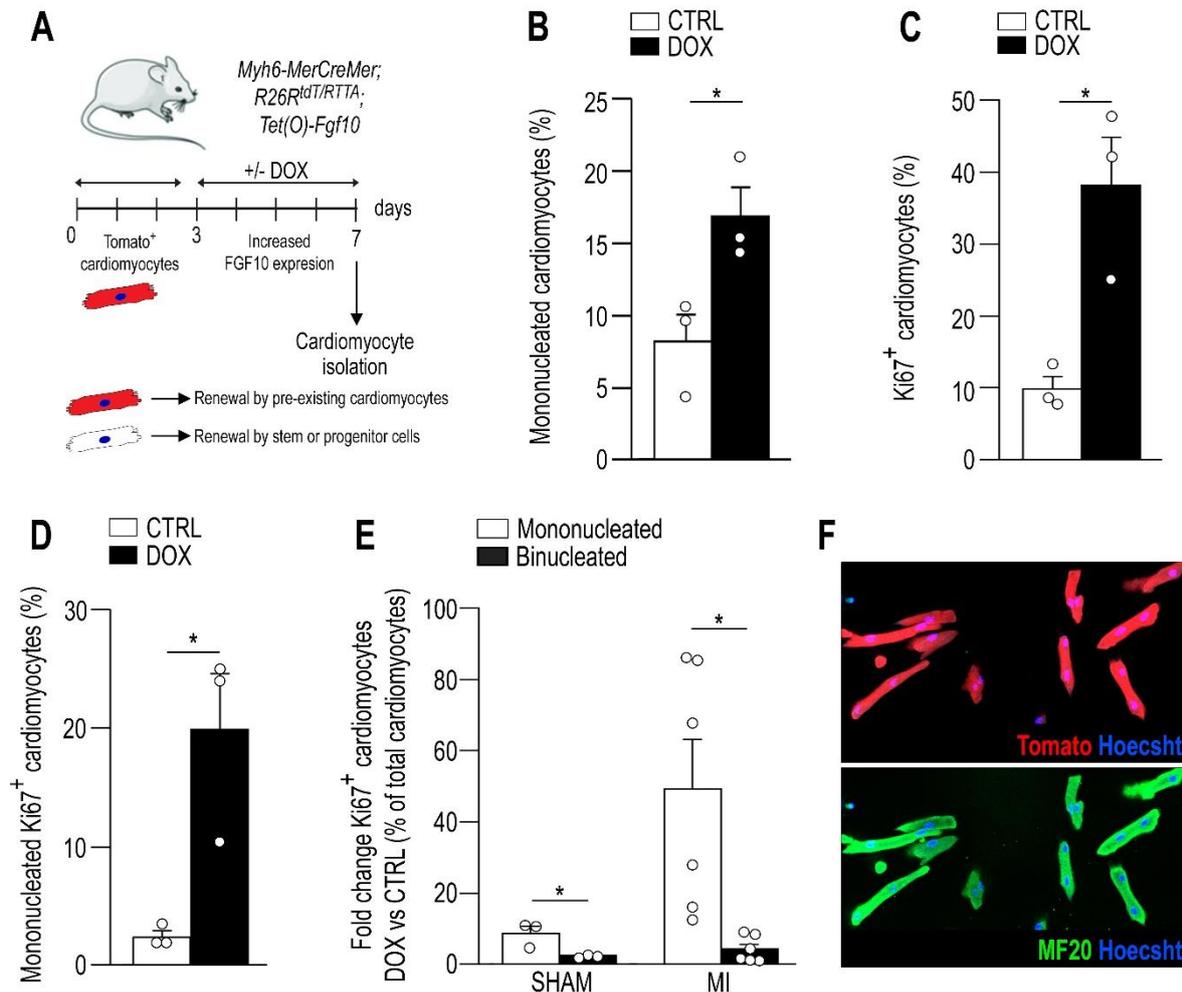
**Supplemental Figure 2: Decreased *Fgf10* dosage impairs maximal cardiomyocyte proliferation post-MI.** WT and *Fgf10*<sup>+/-</sup> adult mice were subjected to myocardial infarction. Immunofluorescence experiments on paraffin sections were performed to evaluate, in the border zone, *in vivo* cardiomyocyte proliferation (MF20<sup>+</sup>; yellow arrowheads) post-MI using Ki67 (A) and PH3 (B). Border zone *in vivo* cardiomyocyte proliferation (PH3<sup>+</sup>MF20<sup>+</sup>; yellow arrowheads) 5 days (C; n=5/group) and 21 days (D; n=5/group) post-MI. Infarcted area *in vivo* cardiomyocyte proliferation (PH3<sup>+</sup>MF20<sup>+</sup>; yellow arrowheads) 5 days (E; MI-5d; n=5/group) and 21 days (F; MI-21d; n=5/group) post-MI. *In vivo* non-myocyte proliferation (MF20<sup>-</sup>), in the border zone, was determined 5 (WT, n=5; *Fgf10*<sup>+/-</sup>, n=5) and 21 (WT, n=5; *Fgf10*<sup>+/-</sup>, n=6) days post-MI using Ki67 (G) and PH3 (H). Scale bars 10  $\mu$ m. ns, non-significant; \*, p<0.05; Student's t-test.



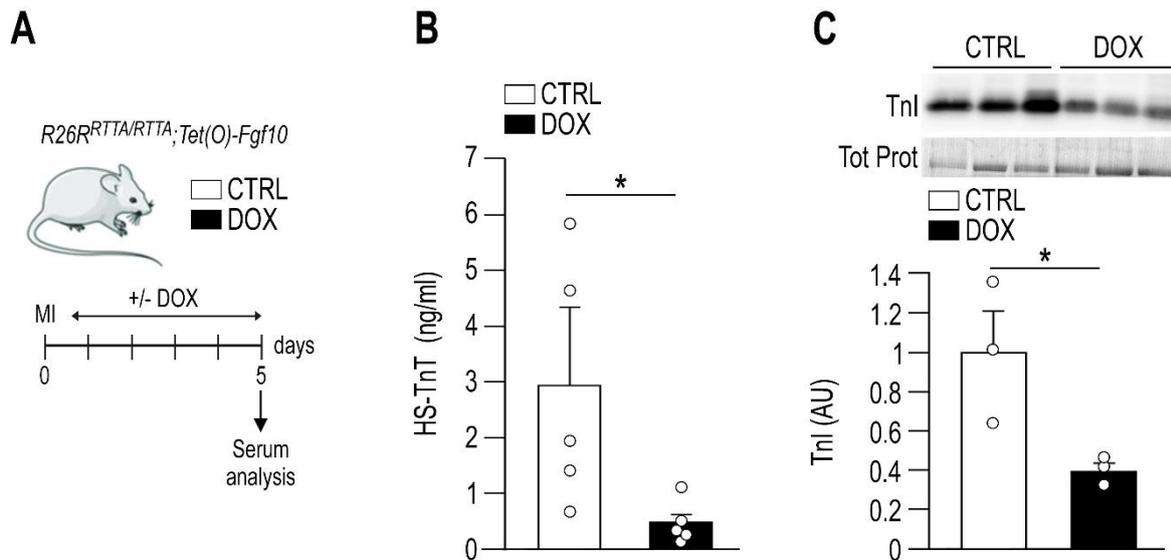
**Supplemental Figure 3: Upregulation of *Fgf10* levels post-MI preserves cardiac function and remodeling.** (A) Schematic of the experimental plan. *R26R-RTTA* mice were subjected to myocardial infarction (MI). One day after MI, mice were fed with normal (CTRL) or doxycycline supplemented food (DOX). (B) M-mode images of echocardiographic experiments (Scale bars, x: 0.1 s; y: 1 mm). (C) Ejection fraction, (D) fractional shortening and (E) left ventricular systolic volume. SHAM-CTRL, n=10; SHAM-DOX, n=9; MI-CTRL, n=7; MI-DOX, n=8. ns, non-significant; \*, p<0.05; \*\*\*, p<0.001; Student's *t*-test.



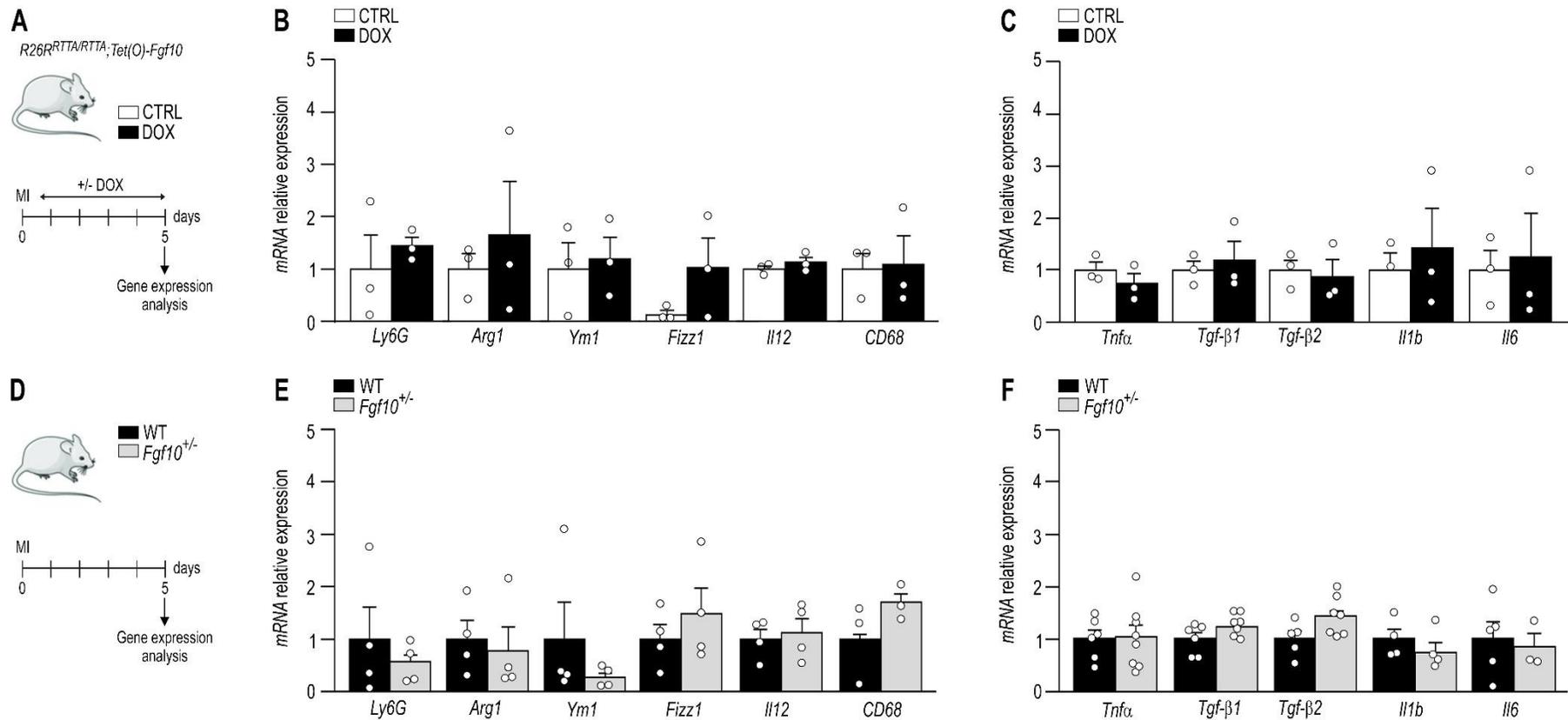
**Supplemental Figure 4: Upregulation of *Fgf10* levels post-MI promotes cardiomyocyte cell cycle reentry.** (A-E) *R26R-RTTA/Tet(O)-Fgf10* mice were subjected to myocardial infarction (MI). One day after MI, mice were fed with normal (CTRL) or doxycycline (DOX) supplemented food. Immunofluorescence experiments on paraffin sections were performed 21 days post-MI to evaluate cell proliferation in the border zone (BZ) and in the infarcted area (IA). Cardiomyocyte proliferation was detected using Ki67 (A) and PH3 markers (B-C; *R26R-RTTA/Tet(O)-Fgf10*:CTRL n=5; *R26R-RTTA/Tet(O)-Fgf10*:DOX n=6). Scale bars: 10 μm. (D-E) Non-myocyte proliferation was detected by Ki67<sup>+</sup> (D; *R26R-RTTA/Tet(O)-Fgf10*:CTRL n=6; *R26R-RTTA/Tet(O)-Fgf10*:DOX n=7) and PH3 (E, *R26R-RTTA/Tet(O)-Fgf10*:CTRL n=5; *R26R-RTTA/Tet(O)-Fgf10*:DOX n=6) markers. (F-H) *R26R-RTTA* mice were subjected to myocardial infarction (MI). One day after MI, mice were fed with normal (CTRL) or doxycycline (DOX) supplemented food. Immunofluorescence experiments on paraffin sections were performed, 21 days post-MI, to evaluate cell proliferation in the border zone (BZ) and in the infarcted area (IA; *R26R-RTTA/Tet(O)-Fgf10*:CTRL n=6, *R26R-RTTA*:DOX n=3). ns, non-significant; \*, p < 0.05; \*\*, 0,001 < p < 0.01; Student's *t*-test.



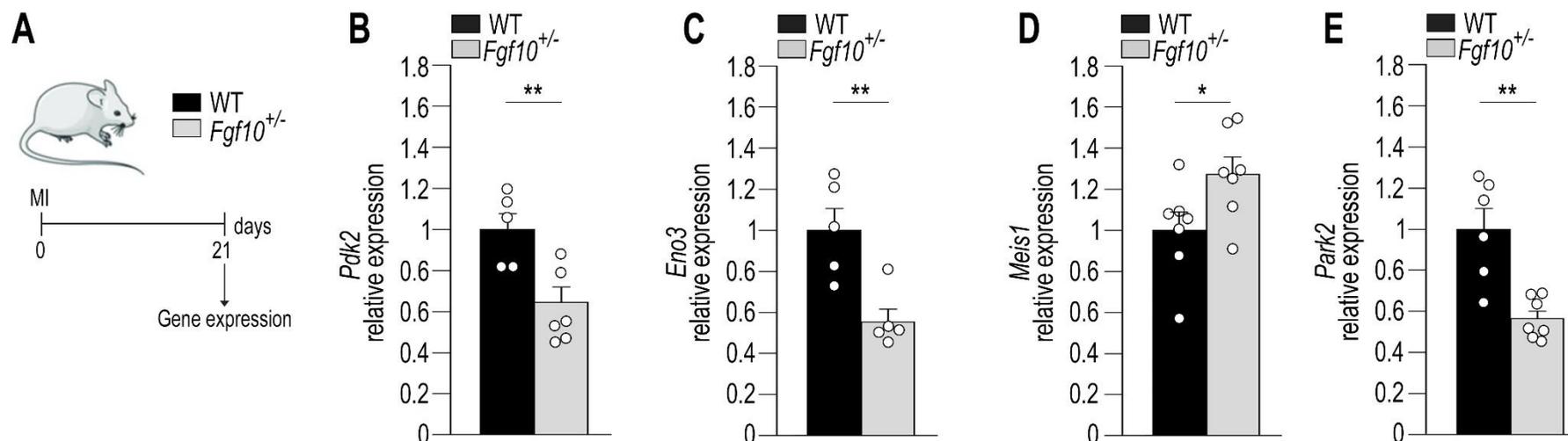
**Supplemental Figure 5: Upregulation of *Fgf10* levels promotes cardiomyocyte renewal.** (A)  $\alpha$ MHC-MerCreMer/R26R-tdT/R26R-RTTA/Tet(O)-*Fgf10* mice were injected with Tamoxifen (Tam) and then fed with doxycycline (DOX) supplemented food for 5 days. (B-D) Cardiomyocytes were isolated and immunofluorescence experiments were performed to evaluate mononucleated cardiomyocyte proliferative capacities. (E) Cardiomyocytes were isolated and immunofluorescence experiments were performed to evaluate mono- and binucleated cardiomyocyte proliferative capacities in normal (SHAM; n=3) and myocardial infarction (MI; n=6) conditions. (F) Cardiomyocytes were isolated and immunofluorescence experiments were performed to evaluate cardiomyocyte lineage.



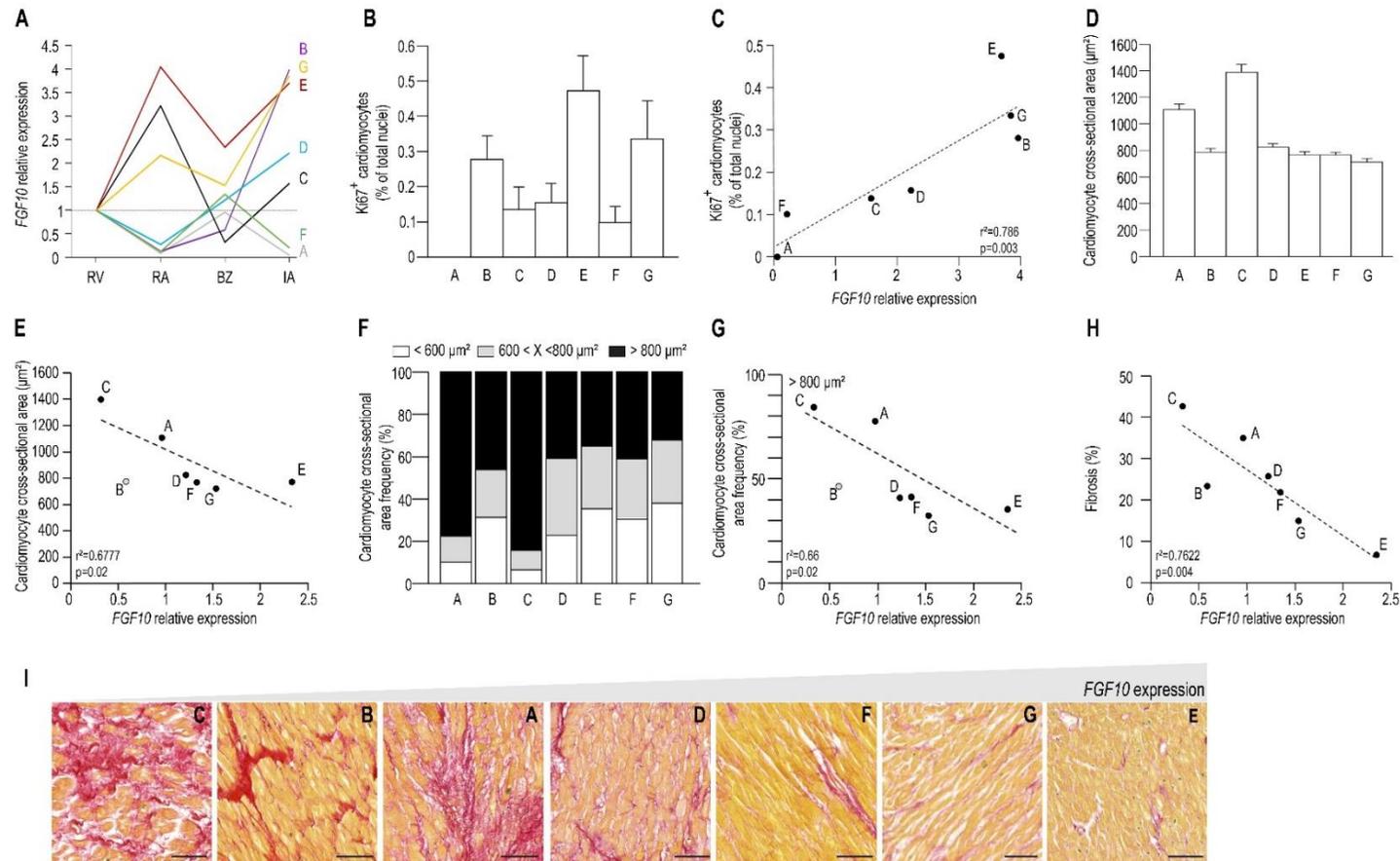
**Supplemental Figure 6: Upregulation of *Fgf10* levels post-MI prevents cardiomyocyte cell death.** (A) *R26R-RTTA/Tet(O)-Fgf10* mice were subjected to myocardial infarction (MI). One day after MI, mice were fed with normal (CTRL) or doxycycline (DOX) supplemented food for 5 days. (B) High-sensitive cardiac troponin T (HS-TnT) serum level analysis (n=5 per group). (C) Western blot experiment revealing reduced cardiac Troponin I (TnI) serum levels in DOX-compare to CTRL-treated animals post-MI (n=3 per group). \*, p<0.05; Student's *t*-test.



**Supplemental Figure 7: Impact of modulated *Fgf10* expression on myocardial inflammation post-MI.** (A-C) *R26R-RTTA/Tet(O)-Fgf10* mice were subjected to myocardial infarction (MI). One day after MI, mice were fed with normal (CTRL) or doxycycline (DOX) supplemented food for 5 days. qRT-PCR analysis of key inflammatory cell (B) and cytokine (C) gene expression in the infarcted area 5 days post-MI. n=3-8 per group. (D-F) WT and *Fgf10*<sup>+/-</sup> adult mice were subjected to myocardial infarction. qRT-PCR analysis of key inflammatory cell (E) and cytokine (F) gene expression in the infarcted area 5 days post-MI. n=3-8 per group.



**Supplemental Figure 8: Impact of decreased *Fgf10* dosage on *Pdk2*, *Eno3*, *Meis1* and *Park2* expression following MI.** (A) Schematic of the experimental plan. WT and *Fgf10*<sup>+/-</sup> adult mice were subjected to myocardial infarction (MI) and analysis were performed 21 days after surgery. qRT-PCR analysis 21 days post-MI of (B) *Pdk2* (WT, n=5; *Fgf10*<sup>+/-</sup>, n=6), (C) *Eno3* (WT, n=5; *Fgf10*<sup>+/-</sup>, n=5), (D) *Meis1* (WT, n=7; *Fgf10*<sup>+/-</sup>, n=7) and (E) *Park2* (WT, n=6; *Fgf10*<sup>+/-</sup>, n=7) expression in the infarcted area. ns, non-significant; \*, p<0.05; \*\*, 0,001<p<0.01; Student's *t*-test.



**Supplemental Figure 9: *FGF10* upregulated levels in human failing heart correlate with increased cardiomyocyte proliferation, reduced cardiomyocyte size and reduced fibrosis.** Human explanted failing heart samples from right ventricle (RV), remote area (RA), border zone (BZ) and infarcted area (IA) were collected from 7 patients (A-G). (A) qRT-PCR experiments revealed upregulated *FGF10* levels in the BZ (4 patients out of 7) and the IA (5 patients out of 7). (B) Cardiomyocyte proliferation in the infarcted area was evaluated using immunofluorescence experiments on paraffin sections and the cell cycle marker Ki67. (C) Elevated *FGF10* levels correlate with enhanced cardiomyocyte proliferation in the IA ( $r^2=0.786$ ,  $p=0.003$ ). (D) Cardiomyocyte cross-sectional area measurement in the border zone using the cell membrane marker WGA suggests that reduced cardiomyocyte cell size correlates with elevated *FGF10* levels (E;  $r^2=0.6777$ ,  $p=0.02$ ). (F) For all patients, the proportion of small ( $<600\mu\text{m}^2$ ), medium ( $600 < X < 800\mu\text{m}^2$ ) and large ( $>800\mu\text{m}^2$ ) cardiomyocytes was determined. (G) Elevated *FGF10* levels correlate with low frequency of large cardiomyocyte ( $>800\mu\text{m}^2$ ,  $r^2=0.66$ ,  $p=0.02$ ). (H-I) Histological Sirius red staining showed that elevated *FGF10* levels correlate with reduced fibrosis in the border zone ( $r^2=0.7622$ ,  $p=0.004$ ). Pictures, according to patient-corresponding *FGF10* levels depicted in (A), have been classified from low to high expression as represented by the above grey triangle. Scale bars 100  $\mu\text{m}$ . Statistical significance ( $p$ ) was determined using Student's  $t$ -distribution.