 Persistent Microvascular Obstruction After Myocardial Infarction Culminates in the Confluence of Ferric Iron Oxide Crystals, Proinflammatory Burden, and Adverse Remodeling

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Background—Emerging evidence indicates that persistent microvascular obstruction (PMO) is more predictive of major adverse cardiovascular events than myocardial infarct (MI) size. But it remains unclear how PMO, a phenomenon limited to the acute/subacute period of MI, drives adverse remodeling in chronic MI setting. We hypothesized that PMO resolves into chronic iron crystals within MI territories, which in turn are proinflammatory and favor adverse remodeling post-MI.

Methods and Results—Canines (n=40) were studied with cardiac magnetic resonance imaging to characterize the spatiotemporal relationships among PMO, iron deposition, infarct resorption, and left ventricular remodeling between day 7 (acute) and week 8 (chronic) post-MI. Histology was used to assess iron deposition and to examine relationships between iron content with macrophage infiltration, proinflammatory cytokine synthesis, and matrix metalloproteinase activation. Atomic resolution transmission electron microscopy was used to determine iron crystallinity, and energy-dispersive X-ray spectroscopy was used to identify the chemical composition of the iron composite. PMO with or without reperfusion hemorrhage led to chronic iron deposition, and the extent of this deposition was strongly related to PMO volume (r>0.8). Iron deposits were found within macrophages as aggregates of nanocrystals (~2.5 nm diameter) in the ferric state. Extent of iron deposits was strongly correlated with proinflammatory burden, collagen-degrading enzyme activity, infarct resorption, and adverse structural remodeling (r>0.5).

Conclusions—Crystallized iron deposition from PMO is directly related to proinflammatory burden, infarct resorption, and adverse left ventricular remodeling in the chronic phase of MI in canines. Therapeutic strategies to combat adverse remodeling could potentially benefit from taking into account the chronic iron-driven inflammatory process.

(Circ Cardiovasc Imaging. 2016;9:e004996. DOI: 10.1161/CIRCIMAGING.115.004996.)

Key Words: cytokines ■ hemorrhage ■ inflammation ■ iron ischemia-reperfusion injury ■ myocardial infarction

Infarct size has long known to be an independent predictor of adverse left ventricular (LV) remodeling in the post–myocardial infarction (MI) period.1 In addition to infarct size, several clinical and preclinical studies have shown that the extent of microvascular obstruction (MO) is an important independent predictor of adverse LV remodeling.2–4 Emerging evidence now supports the notion that MO may be more predictive of major adverse cardiovascular events than infarct size itself.5,6 In spite of its importance, how MO, a phenomenon limited to the acute/subacute period of MI, imparts adverse remodeling throughout the post-MI period, particularly after its resolution, is not well understood.

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Recent studies have shown that MO is frequently accompanied by reperfusion hemorrhage7,8 and that it is these types of MIs that remodel the worst and are at the greatest risk for major adverse cardiovascular events.5,6,9 Serial imaging studies along with histological evidence have shown that reperfusion...
hemorrhage leads to chronic iron deposition, which is associated with prolonged recruitment of macrophages.\textsuperscript{10,11} However, the physicochemical characteristics of the iron deposits within the infarcted myocardium, the phenotypes of the macrophages in iron-rich infarct regions, and their relation to infarct remodeling or the global structural/functional LV remodeling are not known. Moreover, MO is not always accompanied by acute reperfusion hemorrhage, but infarctions with MOs in the absence of hemorrhage also have significantly poor outcome over infarctions without MO.\textsuperscript{6} Thus, even if post-MI iron influences remodeling of hemorrhagic MI in the chronic period, this would not explain the outcomes associated with infarctions with MO but no hemorrhage.

Among the methods used for noninvasively characterizing MO, the hypointense core within late-gadolinium enhancement (LGE) cardiac magnetic resonance (CMR) imaging at 7 to 10 days post-MI (referred below as persistent [late] MO, PMO) has emerged as a reliable means for detecting MOs that are most significantly associated with adverse outcomes.\textsuperscript{5,6} In this study, we investigated the fate of acute MIs with PMO (with and without reperfusion hemorrhage) in the chronic phase to elucidate the interplay between (1) the compositional changes in PMO territories, (2) inflammatory response, and (3) adverse remodeling of infarct zone and LV. Specifically, we hypothesized that (1) every PMO (with or without reperfusion hemorrhage) resolves into crystallized iron in ferric state with the amount of iron deposition dependent on the size of PMO and (2) the magnitude of iron deposition is related to proinflammatory burden and is a potent, independent factor influencing adverse infarct and LV remodeling. To systematically examine our hypothesis, we used 2 canine models of infarction with PMO (with and without hemorrhage) and serial CMR to characterize the spatiotemporal relationships among PMO, iron deposition, and infarct and LV remodeling indices. We used histopathology to (1) validate the iron deposition and (2) study the relationship between iron-rich chronic MI regions against proinflammatory macrophages, cytokines, and collagen degradation. In addition, we used atomic resolution transmission electron microscopy (TEM) to determine the crystallinity of iron and assess the physical effects of iron on macrophages and energy-dispersive X-ray spectroscopy (EDS) to identify the chemical composition of the iron composite.

Methods

Animal Preparation and CMR Protocol

Canines (n=40) were studied according to the protocols approved by the Institutional Animal Care and Use Committee. Left lateral thoracotomies were performed, and the left anterior descending coronary artery (LAD) was ligated at 1.0 to 1.5 cm distal to the bifurcation of the left main coronary artery. A Doppler ultrasound probe (Crystal Biotech, Northborough, MA) was secured 2.0 to 2.5 cm distal to the LAD ligation, and no-flow occlusion was confirmed by the absence of blood flow in the distal coronary segment. Ischemia was confirmed by pale blue coloration of the LAD territory after ligation. In 20 canines (nonreperfused group), the LAD was permanently ligated, and the canines were allowed to recover after closing the chest cavities. In the remaining 20 canines (reperfused group), ischemia–reperfusion injury was induced by releasing the ligation after 3 hours and re-establishing blood flow in the LAD as confirmed by Doppler blood flow measurements. All canines underwent CMR at 7 days (acute) and 56 days (chronic) post-MI (Supplement I in the Data Supplement for study timeline) on a 3T clinical MRI system (MAGNETOM Verio, Erlangen, Siemens Healthcare). ECG-triggered breath-held 2-dimensional (2D) cine-steady-state free precession, T2*-weighted, and LGE images were acquired (Supplement II in the Data Supplement for imaging parameters). Animals were euthanized following the day 56 CMR scan, and their hearts were excised for ex vivo tissue examination.

CMR Image Analyses

All CMR image analyses were performed on cvi42 image processing software (Circle Cardiovascular Imaging Inc, Calgary, AB, Canada). LV structural remodeling was quantified using end-diastolic sphericity index (EDSI) measurements from cine-steady-state free precession images (14). LV functional remodeling was quantified using end-diastolic volume (EDV), end-systolic volume (ESV), and ejection fraction (EF) measurements from cine-steady-state free precession images normalized to the body surface area. Percentage change in the LV structure and function parameters (AEDSI, AEDV, ΔESV, and ΔEF) between the acute and chronic phases post-MI were also calculated.

Semiautomatic thresholding was used to identify infarcted myocardium and PMO from LGE images (Supplement III in the Data Supplement for additional details). For the sake of simplicity, the classic PMO arising from the no-reflow phenomenon in reperfused MIs is henceforth referred to as PMO, whereas the PMO observed on the day 7 LGE images in nonreperfused MIs is referred to as NR-PMO (nonreperfused persistent microvascular obstruction). Hypointense regions on T2*-weighted images confined to the hyperintense LGE territory, indicative of iron arising from blood degradation within infarcted myocardium, were quantified using semiautomatic thresholding (for thresholds, Supplement III in the Data Supplement).

On the basis of the presence or absence of PMO and iron within the infarcted territories at 7 days post-MI, canines from both the reperfused and nonreperfused groups were classified as PMO+/T2*+ (both PMO and T2* loss were present), PMO+/T2*− (PMO was present, but T2* loss was absent), PMO−/T2*+ (PMO was absent, but T2* loss was present), and PMO−/T2*− (both PMO and T2* loss were absent); the prefix NR was used to distinguish the nonreperfused groups from the reperfused groups. Infarct, PMO, and iron volumes were calculated at both acute and chronic phases across all the groups as the percentage of total LV myocardial volume. Infarct resorption was quantified as the absolute change in infarct volume normalized to LV volume (%LV) between acute and chronic phases. T2* values of the remote myocardium, entire infarcted myocardium, and the iron deposits within the infarcted myocardium were also measured.

Histopathologic Validation and Quantification of Inflammatory Burden and Collagen Degradation

Freshly explanted hearts from the canines were sectioned along the short-axis direction from base to apex into 1-cm-thick slices. Infarcted and remote territories were identified on the basis of tetracycline chloride (TTC) staining. Ex vivo 2D T2*-weighted images (same parameters were used as those for the in vivo images) were subsequently acquired from the slices positive for MI on TTC staining. On the basis of the presence of hypointense cores within the infarcted territories on the ex vivo T2*-weighted images, slices were classified as those with and without iron deposition (T2*+ and T2*-; respectively). Paraffin-embedded serial sections (5 μm) from representative segments of infarcted and remote areas were stained with hematoxylin and eosin stain for necrosis, elastin Masson trichrome stain for fibrosis, and Perls stain for iron deposition. For immunostaining, sections were probed with antibodies against the markers of newly recruited neutrophils and monocytes (Mac387), iron-specific (CD163) and proinflammatory macrophages (those expressing inflammatory cytokines, IL-1β and tumor necrosis factor (TNF-α) and matrix metalloproteinase (MMP-9; Supplement IV in the Data Supplement for additional details). Quantitative histological analyses were performed from representative histological sections with TTC evidence of MI from 10 reperfused and 10 nonreperfused animals, after digitization of slides on ScanScope AT (Aperio Technologies, Vista, CA). Morphometric analysis was performed using Definiens Tissue Studio (Definiens, Parsippany, NJ) software. Predefined stain-specific
algorithms and classification tools were created using Definiens eCog-
nition Network Language to identify positive and negative stained area
under the marker (for every 1 µm²) within each tissue region in an au-
tomated fashion to reduce operator bias. Thresholds were set to clas-
sify the following: blue for iron, and 3,3'-diaminobenzidine stain for
Mac387, CD163, IL-1β, TNF-α, and MMP-9.

**TEM, Atomic Resolution Imaging, and EDS**

Samples positive for iron from ex vivo sections were further dis-
sected into 1 mm³ cubes and fixed in 2.5% glutaraldehyde (Electron
Microscopy Sciences, Hatfield, PA) and processed by washing them
with dH₂O and a gradual dehydration by using ethanol series (25%,
33, 50, 75, and 3×100% ethanol). The traditional stains for contrast
enhancement such as OsO₄ were purposely omitted to preserve the re-
dox state of the biominerals. Samples were then infiltrated in LR white
acrylic resin (Electron Microscopy Sciences), and polymerized at 60°C
for 24 hours. The hardened resin blocks were sectioned on a Leica EM
UC6 ultramicrotome using a 45° diamond knife (DiATOME, Hatfield,
PA). Seventy-nanometer-thick sections were collected on copper grids
coated with ultrathin carbon film on holey carbon support film (Ted Pella
Inc, Redding, CA) and imaged on a Tecnai T-12 TEM (FEI, Hillsboro,
OR) with a LaB6 filament, operating at 120 kV. Images were collected
digitally with a 2×2K Ultrascan 1000 CCD (Gatan, Pleasanton, CA).
For the atomic resolution imaging, the previously identified areas of
interest were correlatively imaged using Titan scanning transmission
electron microscope (FEI), operating at 300 kV. The diffraction patterns
of the nanocrystalline material were collected while operating scanning
transmission electron microscope in the selected area electron diffrac-
tion mode, to identify the mineral crystallinity. The chemical elemental
analysis was performed with energy-dispersive spectroscopy, using a
Si(Li) detector (EDAX, Mahwah, NJ), coupled to the STEM.

**Statistical Analyses**

All statistical analyses were performed using IBM SPSS Statistics (ver-
sion 21.0; IBM Corporation, Armonk, NY). Because the within-group
sample sizes were <20 in this study, we have used nonparametric tests
for all comparisons. Mann–Whitney U test was used to compare inde-
pendent samples, and Wilcoxon signed-rank test was used for pairwise
comparisons. Univariable and multivariable linear regression analyses
were performed to determine the associations among different mea-
surement variables. Statistical significance was set at P<0.05. All data
are expressed as median with first and third quartiles.

**Results**

None of the data presented here is from our previous work.¹⁰
Three canines within the reperfused group and 4 canines from the
nonreperfused group died within the first week post-MI.
The remaining 17 canines from the reperfused group and 16
canines from the nonreperfused group sustained MIs as con-
firmed by LGE images on day 7. These animals were followed
≤56 days post-MI.

**PMO Leads to Iron Deposition Within Chronic MI**

In the reperfused group, 9 canines were classified as PMO+/T2*+, 4 canines were classified as PMO+/T2*−, and 4 canines
were classified as PMO−/T2*− at 7 days post-MI. No canine
was classified as PMO−/T2*+ on day 7 post-MI. Representa-
tive T2*-weighted and LGE images from the PMO+/T2*+, PMO+/T2*−, and PMO−/T2*− groups in both acute and chronic
phases are shown in Figure 1, along with corresponding ex

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Figure 1. Chronic iron deposition in reperfused myocardial infarctions (MI). Representative in vivo raw and processed late-gadolinium
enhancement (LGE) and T2*-weighted images from reperfused canines acquired in both acute and chronic phases post-MI are shown.
Arrows point to the sites of MI and iron deposition on LGE and T2*-weighted images, respectively. Corresponding ex vivo histological sec-
tions stained with tetrazolium chloride (TTC), elastin Masson trichrome (EMT), and Perls stain are also shown. Scale bars in the microscopic
histological images correspond to 50 µm. Note the significant chronic iron deposition in the PMO+/T2*− group, despite the absence of
acute reperfusion hemorrhage. Perls stain confirmed the presence of chronic iron deposition (blue deposits pointed at by the arrows) in the
PMO+/T2*+ and PMO−/T2*− groups, but not in the PMO−/T2*− group. EMT stains showed significant fibrosis in the infarcted territory com-
pared with a mild diffuse fibrosis in the remote territory which were not visually evident on LGE. Asterisks in the T₂*-weighted images point
to the sites of off-resonance artifacts that were manually excluded in the final analysis. PMO indicates persistent microvascular obstruction.
vivo histological sections stained with TTC, elastin Masson trichrome, and Perls stains. No PMO could be observed on LGE images in all the 3 groups in the chronic phase. In the PMO+/T2*+ group, significant T2* losses indicative of iron deposition could be visually observed in all the canines within the infarcted territories in both acute and chronic phases. Although none of the canines in the PMO+/T2*+ showed T2* losses within the infarct in the acute phase, all the canines subsequently showed significant T2* losses within the infarct in the chronic phase. None of the canines in the PMO+/T2*− group showed any T2* losses within the infarct in both acute and chronic phases. TTC images confirmed the presence of infarction in all the groups (Figure 1). Perls staining validated the presence of iron deposition in the chronic phase in the PMO+/T2*+ and PMO+/T2*− groups and the absence of iron deposition in the PMO+/T2*− group (Figure 1).

In the nonreperfused group, 15 canines were classified as NR-PMO+/T2*+, and 1 canine was classified as NR-PMO−/T2*−. No canine was classified as either NR-PMO+/T2*− or NR-PMO−/T2*− on day 7 post-MI. Representative T2*-weighted and LGE images from the NR-PMO+/T2*+ and NR-PMO−/T2*− groups in both acute and chronic phases are shown in Figure 2, along with corresponding ex vivo histological sections stained with TTC, elastin Masson trichrome, and Perls stains. No PMO could be observed on LGE images in both the groups in the chronic phase. In the NR-PMO+/T2*+ group, significant T2* losses indicative of iron deposition could be visually observed in all the canines within the infarcted territories in both acute and chronic phases. The only canine in the NR-PMO+/T2*+ group did not show any T2* loss within the infarct in both acute and chronic phases. TTC images confirmed the presence of MI in all the groups (Figure 2). Perls staining validated the presence of iron deposition in the chronic phase in the NR-PMO+/T2*+ group but not in the NR-PMO−/T2*− group.

**Extent of Chronic Iron Deposition Is Strongly Related to Acute PMO Volume in Reperfused and Nonreperfused MIs**

In the reperfused group, median acute PMO volume in the PMO+/T2*+ group was higher than that of the PMO+/T2*− group (P=0.03; Figure 3A). PMO completely resolved in the chronic phase in both PMO+/T2*+ and PMO+/T2*− groups. Relative to the acute phase, median iron volume in the chronic phase decreased in the PMO+/T2*+ group (P=0.02; Figure 3B). In contrast, median iron volume in the PMO+/T2*− group increased from 0 in the acute phase to 2.6 (1.8–3.2; P=0.04; Figure 3B). Significant relationships were observed between the PMO volume and acute iron volume (R²=0.40, P<0.001; Figure 3C) and PMO volume and chronic iron volume (R²=0.73, P<0.001; Figure 3C).

In the nonreperfused group, NR-PMO resolved completely in the chronic phase (Figure 3D). No significant difference was observed between median acute and chronic iron volumes in the NR-PMO+/T2*+ group (P=0.06; Figure 3E). Significant relationships were observed between the NR-PMO volume and acute iron volume (R²=0.86, P<0.001; Figure 3F) and NR-PMO volume and chronic iron volume (R²=0.66, P<0.001; Figure 3F).

**Iron Accumulates Within Chronic Infarction Territories as Nanocrystals**

TEM of chronic MI sections, positive for iron in ex vivo T2* CMR, revealed the presence of electron-dense materials within macrophages that were organized into nodules (=200 nm in diameter; Figure 4). The individual nodules were found to be aggregates of highly crystalline nanoparticles (=2.5 nm in diameter). Specifically, the aggregates were enclosed by

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**Figure 2.** Chronic iron deposition in nonreperfused myocardial infarctions (MI). Representative in vivo raw and processed late-gadolinium enhancement (LGE) and T2*-weighted images from nonreperfused canines acquired in both acute and chronic phases post-MI are shown. Arrows point to the sites of MI and iron deposition on LGE and T2*-weighted images, respectively. Corresponding ex vivo histological sections stained with tetraxolium chloride (TTC), elastin Masson trichrome (EMT), and Perls stain are also shown. Scale bars in the microscopic histological images correspond to 50 μm. Note the significant chronic iron deposition in the NR-PMO+/T2*+ group as observed on the in vivo T2*-weighted images. Perls stain confirmed the presence of chronic iron deposition (blue deposits pointed at by the arrows) in the NR-PMO+/T2*+ group, but not in the NR-PMO+/T2*− group. Similar to the reperfused MI, EMT stains showed significant fibrosis in the infarcted territory compared with a mild diffuse fibrosis in the remote territory, which were not visually evident on LGE. Asterisks in the T2*-weighted images point to the sites of off-resonance artifacts that were manually excluded in the final analysis. NR-PMO indicates nonreperfused persistent microvascular obstruction.
spherically shaped organelles suggestive of lysosomes (Supplement V in the Data Supplement). Scanning transmission electron microscope analysis of the particulate material showed a highly ordered atomic pattern, and the EDS spectrum revealed a strong presence of iron. The EDS confirmed the diffraction pattern (with diffraction rings at 0.150, 0.176, 0.214, 0.226, and 0.256 nm) to be an exact fit to the 6-line hydroxy ferricydrate (Figure 5), which has the chemical formula of Fe$_2$O$_3$•0.5H$_2$O.

Figure 3. Persistent microvascular obstruction (PMO) and iron volumes in reperfused and nonreperfused myocardial infarctions (MIs). Median PMO volume (%LV, A), iron volume (%LV, B), and relationships between PMO volume with acute and chronic iron volumes (C) are shown from canines with reperfused MIs (PMO+/T2*: n=9; PMO+/T2*: n=4; PMO+/T2*: n=4). Similarly, median NR-PMO volume (%LV, D), iron volume (%LV, E), and relationships between PMO volume with acute and chronic iron volumes (F) are shown from canines with nonreperfused MIs (NR-PMO+/T2*: n=15; NR-PMO+/T2*: n=1). LV indicates left ventricle; and NR-PMO, nonreperfused persistent microvascular obstruction.

Figure 4. Transmission electron microscopy images of crystalline deposits within macrophages found in the territories of chronic myocardial infarction. A. Shows a longitudinal section of the macrophage cell with pronounced intracellular electron-dense material deposits (arrows). B and C. Show enlarged area of a typical nodular pattern of material deposition. D. Shows that the nodules are composed of clusters of highly crystalline nanoparticles with an approximate diameter of 2.5 nm (E).
Iron Content, Proinflammatory Burden, and Collagen Degradation Are Highly Correlated

Representative microscopic immunohistological sections of reperfused and nonreperfused MIs obtained from canines with and without T2* losses (T2*+ and T2*−, respectively) as observed on ex vivo T2*-weighted images are shown in Figure 6. Significant collagen deposition within the infarcted territories could be observed in all cases, although Perls stain confirmed the presence of iron deposition only in the T2*+ cases. Significant colocalization of Mac387+ cells with iron deposits was observed in both reperfused and nonreperfused MIs. There was intense IL-1β and TNF-α immunoreactivity associated with Mac387+ cells. Regression analyses showed strong associations of area of iron (Perls stain) with area of Mac387+ cells ($R^2=0.87$, $P<0.001$; Figure 6A), CD163+ cells ($R^2=0.66$, $P<0.001$; Figure 6B), IL-1β activity ($R^2=0.58$, $P<0.001$; Figure 6C), TNF-α activity ($R^2=0.77$, $P<0.001$; Figure 6D), and MMP-9 activity ($R^2=0.94$, $P<0.001$; Figure 6E).

Figure 5. Physicochemical characterization of crystalline iron within macrophages. **A**, Shows atomic resolution STEM image of a representative nanocrystalline particle from a Fe nodular cluster in a macrophage intracellular space. Notice the highly ordered pattern of aligned atomic columns. **B**, Shows the energy-dispersive X-ray spectroscopy spectrum of the nodular material with the strong Fe presence. **C**, Shows a SAED obtained from the Fe nodules revealing an exact fit with the pattern of a 6-line ferrihydrite. The respective values of diffraction rings are as follows: (1) 0.150 nm, (2) 0.176 nm, (3) 0.214 nm, (4) 0.242 nm, and (5) 0.268 nm.

Figure 6. Relationship between proinflammatory burden and chronic iron deposition. Representative contiguous ex vivo histological sections stained with elastin Masson trichrome (EMT), Perls, and monoclonal antibodies for Mac387, CD163, IL-1β, tumor necrosis factor (TNF)-α, and matrix metalloproteinase (MMP-9) are shown from canines with reperfused and nonreperfused myocardial infarcts with and without T2* losses (T2*+ and T2*−, respectively) as observed in ex vivo T2*-weighted images. Note significant colocalization of Mac387+ cells, TNF-α activity, and MMP-9 activity with chronic iron deposits. Strong linear relationships ($n=20$) of the area of iron (measured from Perls stain) were observed with area of Mac387+ cells (**A**), area of CD163+ cells (**B**), area of IL-1β activity (**C**), area of TNF-α activity (**D**), and area of MMP-9 activity (**E**). Arrows indicate the presence of specific markers of interest, which are zoomed in insets.
Iron Within Chronic MI Is Associated With Adverse Remodeling of Chronic Infarction

Relationship Between Iron Volume and Infarct Remodeling

In reperfused MIs, median iron volume calculated as a percentage of the total infarct volume significantly increased between acute and chronic phases in both PMO+/T2*+ (P=0.01) and PMO+/T2*− groups (P=0.04; Figure 7A). Infarct resorption was linearly related to both acute (R²=0.45, P<0.001) and chronic iron volumes (R²=0.79, P<0.001; Figure 7B). In nonreperfused MIs, median iron volume calculated as a percentage of the total infarct volume significantly increased between acute and chronic phases in the NR-PMO+/T2*+ group (P=0.001; Figure 7C). Infarct resorption was linearly related to both acute (R²=0.28, P<0.001) and chronic iron volumes (R²=0.27, P<0.001; Figure 7D).

Iron Within Chronic MI Is Associated With Adverse Structural and Functional LV Remodeling

Relationship Between Iron Volume and Structural LV Remodeling

In the reperfused MIs, PMO+/T2*+ group had significantly larger EDSI in the chronic phase compared with the acute phase (P=0.008), but there was no significant difference in EDSI between the acute and chronic phases of infarctions is shown in (A; reperfused MI) and (C; nonreperfused MI). The relationship between infarct resorption as a function of acute and chronic iron volumes is shown in (B; nonreperfused MI) and (D; nonreperfused MI). Sample sizes for the different reperfused and nonreperfused groups are as follows: (1) reperfused MIs—PMO+/T2*+: n=9; PMO+/T2*−: n=4; PMO+/T2*: n=4 and (2) nonreperfused MIs—NR-PMO+/T2*+: n=15; NR-PMO+/T2*: n=1. NR-PMO indicates nonreperfused persistent microvascular obstruction.

Figure 7. Relationship between iron volume and infarct remodeling in reperfused and nonreperfused myocardial infarctions (MIs). Median iron volume as a fraction of infarct volume in acute and chronic phases of infarctions is shown in (A; reperfused MI) and (C; nonreperfused MI). The relationship between infarct resorption as a function of acute and chronic iron volumes is shown in (B; nonreperfused MI) and (D; nonreperfused MI). Sample sizes for the different reperfused and nonreperfused groups are as follows: (1) reperfused MIs—PMO+/T2*+: n=9; PMO+/T2*−: n=4; PMO+/T2*: n=4 and (2) nonreperfused MIs—NR-PMO+/T2*+: n=15; NR-PMO+/T2*: n=1. NR-PMO indicates nonreperfused persistent microvascular obstruction.
independent predictors of ΔEDSI. Additional details on comparisons between reperfused and nonreperfused MIs can be found Supplement VI in the Data Supplement.

**Relationship Between Iron Volume and Functional LV Remodeling**

In the reperfused MIs, canines in the PMO+/T2*+ group had significantly larger EDV, larger ESV, and lower EF compared with the canines in the PMO+/T2*− and PMO−/T2*− groups in both acute and chronic phases (Supplement VII in the Data Supplement for numbers and statistical comparisons). The PMO+/T2*+ group also had significantly larger EDV and ESV, and lower EF in the chronic phase compared with the acute phase. However, there was no significant difference in the functional remodeling parameters between the acute and chronic phases in the PMO+/T2*− and PMO−/T2*− groups. Compared with the canines in the PMO+/T2*+ and PMO−/T2*− groups, canines in the PMO+/T2*+ group had significantly higher ΔEDV, ΔESV, and ΔEF between the acute and chronic phases. Neither infarct volume nor iron volume measured

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Figure 8. Relationship between iron volume and left ventricular (LV) structural remodeling in reperfused and nonreperfused myocardial infarctions (MIs). Median end-diastolic sphericity index (EDSI) from reperfused MIs (A) and nonreperfused MIs (E), as well as ΔEDSI from reperfused MIs (B) and nonreperfused MIs (F). Significant linear relationships of ΔEDSI with both acute and chronic infarct volumes were observed in both reperfused (C) and non-reperfused MIs (G). Similarly, significant linear relationships of ΔEDSI with acute and chronic iron volumes were evident in both reperfused (D) and nonreperfused (H) MIs. Sample sizes for the different reperfused and nonreperfused groups are as follows: (1) reperfused MIs—PMO+/ T2*+: n=9; PMO+/T2*−: n=4; PMO−/T2*−: n=4 and (2) nonreperfused MIs—NR-PMO+/T2*+: n=15; NR-PMO−/T2*−: n=1.
at either acute or chronic phase could significantly predict \( \Delta \text{EDV} \), \( \Delta \text{ESV} \), or \( \Delta \text{EF} \).

In the nonreperfused MIs, canines in the NR-PMO\(^+\)/T2\(^*\)-group had larger EDV and ESV, and lower EF compared with the NR-PMO\(^+\)/T2\(^*\)-canine in both acute and chronic phases (Supplement VII in the Data Supplement for numbers and statistical comparisons). The NR-PMO\(^+\)/T2\(^*\)-canines also had significantly larger EDV and ESV in the chronic phase compared with the acute phase. However, there was no significant difference in EF between the acute and chronic phases in the NR-PMO\(^+\)/T2\(^*\)-canines. There was no difference in \( \Delta \text{EDV} \), \( \Delta \text{ESV} \), and \( \Delta \text{EF} \) between the 2 groups. Neither infarct volume nor iron volume measured at either acute or chronic phase could significantly predict \( \Delta \text{EDV} \), \( \Delta \text{ESV} \), or \( \Delta \text{EF} \). Additional details on comparisons between reperfused and nonreperfused MIs can be found in Supplement VII in the Data Supplement.

**Discussion**

In this study, we showed that PMO, with or without reperfusion hemorrhage, can lead to significant chronic iron deposition within the infarcted territories, and the extent of chronic iron deposition is strongly related to the extent of PMO observed in the acute phase. In canines with reperfused MIs, we have shown that PMO can still resolve into iron deposition within the infarcted territories in the chronic phase, even if it is not associated with reperfusion hemorrhage as seen acutely on T2*-weighted images. This was further validated by the occurrence of significant chronic iron deposition within nonreperfused MIs, which are classically known to have no any reperfusion hemorrhage.\(^7\) Using TEM and EDS analysis, we showed that such chronic iron deposits are encapsulated as nanocrystals in ferric state within macrophages in membraneous structures resembling lysosomes. We used immunohistochemistry to demonstrate significant proinflammatory burden associated with chronic iron deposition. We also showed that the chronic iron deposition post-PMO resolution is associated with infarct resorption and is a significant and independent predictor of long-term adverse LV structural remodeling.

**Iron Deposits Within Reperfused and Nonreperfused Chronic MI**

Recent studies in canines and patients with healed MIs have shown that acute reperfusion hemorrhage resolves into iron deposits within the infarcted tissue up to several months postreperfusion. However, the possibility of chronic iron deposition in the presence of PMO alone without any concurrent reperfusion hemorrhage has not been previously investigated. Although infarct resorption can partly explain the relative increase in iron volume in the PMO\(^+\)/T2\(^*\)-group, infarct shrinkage alone does not explain how the PMO\(^+\)/T2\(^*\)-MIs, which did not have any acute reperfusion hemorrhage as evidenced by T2*-weighted imaging, eventually had significant iron deposition in the scar tissue in the chronic phase. Although the exact mechanism for this occurrence remains to be investigated, 1 possibility is that the stagnant blood within the blocked no-reflow microvasculature of PMO could gradually degrade. The eventual breakdown of the microvasculature with no-reflow can externalize the degraded stagnant blood into the scar tissue and manifest itself as iron deposits.

The occurrence of chronic iron deposition within nonreperfused MIs has also not been shown previously in the literature, although it is known that PMO is equally prevalent in patients regardless of reperfusion.\(^1\) Although the PMO observed in reperfused MIs is attributed to plugging of microvasculature by inflammatory cells, erythrocytes and other microembolic debris,\(^4\) the pathological mechanism of PMO observed in nonreperfused MIs could be because of permanently occluded coronary artery that has not been reperfused. Similar to chronic iron deposition arising from PMOs without concurrent hemorrhage in reperfused MIs, the source of chronic iron deposition in nonreperfused MIs with PMO could be gradual degradation of permanently ligated vasculature and externalization of degraded stagnant blood into the scar tissue. Hence, our results suggest that chronic iron deposition is a fingerprint of PMO observed in the acute phase and could be a potential mechanism through which PMO exerts adverse effects in the long term.

**Crystallized Ferric Iron Deposits and Inflammation**

Scanning transmission electron microscope, EDS, and selected area electron diffraction studies revealed for the first time that the iron deposits within chronic MI are found as nodules composed from nanocrystals of iron in ferric form. Moreover, the TEM images also showed that iron aggregates are located within membrane-enclosed structures, suggestive of lysosomes that seem to be loaded to their physical limits (diameter>1 \( \mu m \)). These findings, along with evidence from previous studies, may help to explain the proinflammatory burden in chronic MI with iron deposits.

Lysosomes are membrane bound spherical organelles, which are rich in hydrolytic enzymes and are typically <1 \( \mu m \) in diameter. Disruption of these membranes, because of excessive uptake of hard/sharp crystalline material similar to iron deposits we characterized here, is known to be a key contributor to several inflammatory disease processes.\(^1\) Studies have shown that such disruptions can set forth cascading inflammatory responses. Ferric iron is known to impart oxidative stress through Fenton pathway leading to activation of inflamasomes and upregulation of proinflammatory cytokines (IL-1\(\beta\) and TNF-\(\alpha\)).\(^1\) Specifically, in vitro studies have demonstrated that macrophages incubated with iron activates NF-xB inflamasome, a key transcription factor promoting the expression of proinflammatory cytokines IL-1\(\beta\) and TNF-\(\alpha\). Other in vitro studies have shown that the extent of proinflammatory cytokine expression is dependent on iron concentration.\(^1\) Given our observations that the extent of inflammatory cytokines was closely related to extent of iron burden (Figure 6), in light of the existing previous mechanistic studies in the literature, it seems that that iron overloading within the macrophages may be a key mechanism by which the inflammatory response is perpetuated within chronic infarctions with a previous history of PMO. Additional studies are needed to confirm this potential mechanism.

**Proinflammatory Burden and Adverse Remodeling**

Chronic iron deposition within reperfused MIs has been previously implicated in adverse LV remodeling\(^2\) and arrhythmogenesis in healed MIs.\(^3\) In line with previous observations, our study has shown that iron deposition post PMO resolution...
is a strong predictor of LV structural remodeling. The role of iron in the onset of adverse LV remodeling and heart failure is well documented in nonischemic iron-overload cardiomyopathies.18,19 Although the exact mechanism by which iron deposition after PMO resolution in MIs mediates adverse LV remodeling remains to be investigated in vivo, active and prolonged proinflammatory activity colocalized with iron deposits with chronic infarctions observed in this study seems to be a potential mechanism. We found significant colocalization of Mac387+ cells with post-PMO iron deposition in the chronic infarcted territories, which is similar to earlier observations in chronic reperfused MIs that sustained acute reperfusion hemorrhage.10 We also found that the extent of iron deposition is directly proportional to the extent of Mac387+ colocalization. The monoclonal antibody Mac387 recognizes 3 calcium-binding proteins, which are found in newly recruited myeloid cells, but the immunoreactivity of Mac387 is significantly reduced as monocytes mature to macrophages.20 Frangogiannis et al21 have shown that the number of Mac387+ cells in the infarcted myocardium was significantly reduced at 7 days postreperfusion, and this marker can be used an index for new recruitment of leukocytes in the heart. Our finding of the presence of Mac387+ cells to be highly colocalized with iron and iron scavenger receptor CD16322 in this study shows an active and prolonged iron-driven inflammatory process within chronic infarcts that extend well beyond the acute inflammatory stage. The interaction of Mac387+ cells with post-PMO iron remains to be investigated, but because CD163 is a key marker of iron-induced macrophage activation,23 iron phagocytosis with the intention of clearance seems to be a plausible explanation. However, the imaging-guided evidence of lack of iron clearance in the chronic phase is a notable feature of acute MIs with PMO and may be the means by which long-lasting effects of PMO are felt in the chronic phase of MI.

Many proinflammatory cytokines, which have been implicated in the development of LV dysfunction and LV remodeling dysfunction, are known to be released when monocytes mature into macrophages. We found that Mac387+ cells are associated with significant IL-1β, TNF-α, and MMP-9 activities. TNF-α is a well-known proinflammatory cytokine implicated in the development of LV dysfunction, LV remodeling, and endothelial dysfunction.24 MMP-9 activity is known to be associated with extracellular matrix degradation and modulating mechanical architecture of the scar.25 IL-1β has been shown to promote matrix degradation by enhancing MMP synthesis, while reducing collagen deposition,26 and has emerged as an important therapeutic target in the chronic phase post-MI.27 These previously established mechanisms could potentially explain our findings of the direct relations between iron deposition, IL-1β, TNF-α, MMP-9, and infarct resorption. Moreover, these results suggest that the macrophages derived from Mac387+ cells are in an unrestrained proinflammatory M1 activation state that can potentially worsen LV remodeling.

Recent studies have been instrumental in shedding light on the relation between MO and inflammation. These studies have shown that in cases of reperfused MIs with MO, monocyte recruitment is delayed in the acute and subacute period; in cases where erythrocyte extravasation (hemorrhage) accompanies MO, iron accumulates within the MI territories in the chronic phase and is site of intense macrophage recruitment.11 Although adequate inflammatory activity is necessary for wound healing, long-term persistence of inflammation is detrimental to the reparative effects. Mechanistically, the extent of LV remodeling in the post-MI period is related to the timely inhibition and resolution of the inflammatory activity.28 In particular, prolonged inflammation has been shown to impair collagen deposition and scar formation resulting in reduced tensile strength and LV dilatation.28 Early studies suggest that ineffective suppression of inflammation post-MI is associated with adverse LV remodeling of the heart.29 The finding that iron deposits within chronic MI play an intermediary role in wound healing may be of substantial clinical relevance because it can unravel how PMO imparts adverse long-term effects on the infarcted heart and underscore iron as a therapeutic target in postinfarction heart failure. Importantly, our findings indicate that it would be of significant value to re-examine intracellular iron chelation30 and anti-inflammatory31 therapies over a longer period of time (ie, extending beyond the acute MI phase) in post-MI patients who are stratified on the basis of PMO presentation to curb the rate of adverse LV remodeling.

**Study Limitations**

Although this study demonstrated important associative relations, the causal relationships among iron, proinflammatory burden, and remodeling (structural and functional) were not investigated. Additional studies are needed to establish these relations. The sample size of our study is modest, which may have precluded us from observing significant associations of functional LV remodeling parameters such as EDV, ESV, and EF with infarct and iron volumes. Nevertheless, we could still observe a clear relationship of EDSI with infarct and iron volumes, which suggests that longer follow-ups (eg, 6 months) may have led to worse functional LV remodeling in animals with iron deposits. This notion is consistent with previous demonstration in the heart that the structural changes are preceded by functional consequences.32 Even though our results did not reach statistical significance, we observed a trend toward larger acute MI size in reperfused MIs than nonreperfused MIs, but this remains to be further investigated.

**Conclusions**

Territories of PMOs in the acute phase of MI, with or without reperfusion hemorrhage, resolve into iron oxide nanocrystals in ferric state in the chronic phase of MI. The amount of iron deposition is determined by the extent of PMO and is directly related to the extent of proinflammatory burden, infarct resorption, and adverse LV remodeling in canines. Crystallized iron depositions resolving from PMO might be a contributing source to the adverse remodeling of the heart and a potential therapeutic target in the chronic phase of MI.

**Acknowledgments**

A part of this research was performed at Environmental Molecular Sciences Laboratory, a national scientific user facility sponsored by
the Department of Energy’s Office of Biological and Environmental Research, located at the Pacific Northwest National Laboratory (PNNL). PNNL is operated for the Department of Energy by Battelle Memorial Institute under Contract no. DE-AC05-76RL01830.

Sources of Funding

This work was supported in part by grants from the National Heart, Lung, and Blood Institute (HL133407) to Dr Dharmakumar.

Disclosures

None.

References


Numerous studies have shown that an important prognostic feature of acute myocardial infarction is its size. However, with the advent of late-gadolinium enhancement cardiac magnetic resonance nearly 2 decades ago, key studies have revealed that in addition to infarct size, the presence of late/persistent microvascular obstruction (PMO; ie, persistence of acutely obstructed microvasculature within the myocardium despite the restoration of blood flow to the upstream epicardial coronary artery) is also an independent, negative predictor of event-free survival. More recently, meta-analysis studies have further revealed that PMOs increase the risk of major adverse cardiovascular outcomes, comprising death or hospitalization for heart failure, by more than 4-fold compared with infarct size alone. To date, the negative outcomes associated with PMOs have been tied to the diminished penetrance of macrophages to the infarct core. However, why these infarcts continue to remodel adversely even after the microvascular obstructions are resolved, typically within 2 weeks post infarction, has not been investigated. In this article, using a clinically relevant large animal model, we demonstrate for the first time that PMOs, with or without intramyocardial hemorrhage, resolve into ferric iron crystals within the infarcted myocardium. These iron crystals seem to drive a sustained proinflammatory burden and adverse LV remodeling throughout the postinfarction period well after the resolution of PMO. Our findings suggest that the crystalline iron depositions within the infarction territories may be a novel therapeutic target in decelerating the onset of heart failure in acute myocardial infarction patients with PMOs.


Persistent Microvascular Obstruction After Myocardial Infarction Culminates in the Confluence of Ferric Iron Oxide Crystals, Proinflammatory Burden, and Adverse Remodeling

Avinash Kali, Ivan Cokic, Richard Tang, Alice Dohnalkova, Libor Kovarik, Hsin-Jung Yang, Andreas Kumar, Frank S. Prato, John C. Wood, David Underhill, Eduardo Marbán and Rohan Dharmakumar

*Circ Cardiovasc Imaging*. 2016;9:
doi: 10.1161/CIRCIMAGING.115.004996

*Circulation: Cardiovascular Imaging* is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 1941-9651. Online ISSN: 1942-0080

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Supplementary Material

The following supplemental sections are provided as additional information:

Supplement 1: Study Timeline
Supplement 2: CMR Imaging Parameters
Supplement 3: CMR Image Analysis
Supplement 4: Antibodies Used for Histopathology
Supplement 5: Iron Overloading within Lysosomes
Supplement 6: Summary on Structural Remodeling
Supplement 7: Details on Functional Remodeling

Supplement 1: Study Timeline

33 Canines
  3 Hours of LAD Occlusion Followed by Reperfusion
  Reperfused MIs (n=17)
  7 days post-MI
  Classification of Reperefused MIs
    PMO+/T2+: n=9
    PMO+/T2−: n=4
    PMO−/T2+: n=4
  Acute CMR
  56 days post-MI
  Classification of Non-Reperfused MIs
    NR-PMO+/T2+: n=15
    NR-PMO−/T2−: n=1
  Chronic CMR
  Euthanasia
  Histology and Immunohistochemistry
  Transmission Electron Microscopy
  Energy Dispersive X-Ray Spectroscopy
Supplement 2: Cardiac MR Imaging Parameters

Table S1. Cardiac MR imaging parameters for studying acute and chronic reperfused and non-reperfused myocardial infarctions.

<table>
<thead>
<tr>
<th>Imaging Method</th>
<th>Cine</th>
<th>T2*-weighted</th>
<th>LGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence</td>
<td>Balanced SSFP</td>
<td>Multiple GRE</td>
<td>IR – prepared GRE</td>
</tr>
<tr>
<td>TR (ms)</td>
<td>3.1</td>
<td>12.0</td>
<td>3.0</td>
</tr>
<tr>
<td>TE (ms)</td>
<td>1.6</td>
<td>2.0 – 9.5 (ΔTE = 1.5 ms)</td>
<td>1.5</td>
</tr>
<tr>
<td>Flip Angle</td>
<td>40°</td>
<td>10°</td>
<td>25°</td>
</tr>
<tr>
<td>Bandwidth (Hz/pixel)</td>
<td>930</td>
<td>930</td>
<td>586</td>
</tr>
<tr>
<td>In-plane Resolution</td>
<td>1.4 x 1.4 mm²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slice Thickness</td>
<td>6mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Parameters</td>
<td>25-30 cardiac phases</td>
<td>6 TEs</td>
<td>Optimal TI to null the remote myocardium</td>
</tr>
</tbody>
</table>

Supplement 3: CMR Image Analysis

All cardiac MRI (CMR) image analyses were performed on cvi42 image processing software (Circle Cardiovascular Imaging Inc., Calgary, AB). Endocardial and epicardial contours were manually drawn on all images. Remote myocardium was identified on LGE images as the region showing no hyperintensity and a reference region-of-interest (ROI) was drawn in it. Infarcted myocardium was then defined on LGE images using the Mean + 5 Standard Deviations (SD) technique relative to the reference ROI. Persistent microvascular obstruction (PMO) was defined as the hypointense core within the hyperintense infarcted myocardium identified on LGE images using the Mean+5SD criterion. Infarct size was calculated by summing the volumes of the hyperintense regions on LGE images identified using the Mean+5SD criterion and the hypointense PMO cores.

The presence of iron arising from blood degradation within infarcted myocardium were identified as hypointense regions on T2*-weighted images confined to the hyperintense LGE territory. The reference ROIs drawn on LGE images were copied on to the corresponding T2*-weighted images. Spatial extent of the hypointense regions were identified on the T2*-weighted image acquired at TE=6.5ms using the Mean-2SD criterion relative to the reference ROI. Off-resonance artifacts arising due to susceptibility differences at the heart-lung interface were manually excluded.

Supplement 4: Antibodies Used for Histopathology
Table S2. Antibodies used for studying different histopathological markers

<table>
<thead>
<tr>
<th>Histopathological Marker</th>
<th>Antibody Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD163</td>
<td>Bioss, bs-2527R</td>
</tr>
<tr>
<td>Mac387</td>
<td>Abcam, ab22506</td>
</tr>
<tr>
<td>IL-1β</td>
<td>Abcam, ab34837</td>
</tr>
<tr>
<td>TNF-α</td>
<td>Abcam, ab6671</td>
</tr>
<tr>
<td>MMP-9</td>
<td>Abcam, ab38898</td>
</tr>
</tbody>
</table>

Supplement 5: Summary on Infarct Characteristics

Table S3 below provides details on infarct volume, PMO/NR-PMO volume, and iron volume in acute and chronic phases of reperfused and non-reperfused myocardial infarctions.

Table S3. Summary of infarct characteristics between reperfused and non-reperfused MI

<table>
<thead>
<tr>
<th>Phase of MI</th>
<th>Group</th>
<th>Infarct Volume (%LV)</th>
<th>PMO/NR-PMO Volume (%LV)</th>
<th>Iron Volume (%LV)</th>
<th>p-value (Reperfused vs. Non-Reperfused)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute</td>
<td>Reperfused (n=17) (Median (Q1-Q3))</td>
<td>20.7 (18.1-33.6)</td>
<td>1.7 (1.2-7.1)</td>
<td>0.45 (0.0-8.3)</td>
<td>0.052</td>
</tr>
<tr>
<td></td>
<td>Non-Reperfused (n=16) (Median (Q1-Q3))</td>
<td>16.2 (7.7-20.0)</td>
<td>2.2 (1.1-4.2)</td>
<td>1.4 (1.0-3.7)</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>p-value (Reperfused vs. Non-Reperfused)</td>
<td></td>
<td></td>
<td></td>
<td>0.86</td>
</tr>
<tr>
<td>Chronic</td>
<td>Reperfused (n=17) (Median (Q1-Q3))</td>
<td>11.3 (6.2-15)</td>
<td>0 (-)</td>
<td>2.9 (0.7-4.3)</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Non-Reperfused (n=16) (Median (Q1-Q3))</td>
<td>7.0 (2.7-9.8)</td>
<td>0 (-)</td>
<td>1.6 (0.8-3.3)</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>p-value (Reperfused vs. Non-Reperfused)</td>
<td></td>
<td></td>
<td></td>
<td>0.38</td>
</tr>
</tbody>
</table>

*Statistically significant difference (p<0.05)
Supplement 6: Summary on Structural Remodeling

Table S4 below provides details on structural LV remodeling in acute and chronic phases of reperfused and non-reperfused myocardial infarctions.

Table S4. Summary of structural LV remodeling between reperfused and non-reperfused MI

<table>
<thead>
<tr>
<th>Phase of MI</th>
<th>Group</th>
<th>End-Diastolic Sphericity Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute</td>
<td>Reperfused (n=17) (Median Q1-Q3)</td>
<td>0.43 (0.38-0.53)</td>
</tr>
<tr>
<td></td>
<td>Non-Reperfused (n=16) (Median Q1-Q3)</td>
<td>0.42 (0.39-0.47)</td>
</tr>
<tr>
<td></td>
<td>p-value (Reperfused vs. Non-Reperfused)</td>
<td>0.46</td>
</tr>
<tr>
<td>Chronic</td>
<td>Reperfused (n=17) (Median Q1-Q3)</td>
<td>0.49 (0.41-0.58)</td>
</tr>
<tr>
<td></td>
<td>Non-Reperfused (n=16) (Median Q1-Q3)</td>
<td>0.49 (0.44-0.56)</td>
</tr>
<tr>
<td></td>
<td>p-value (Reperfused vs. Non-Reperfused)</td>
<td>0.79</td>
</tr>
</tbody>
</table>

*Statistically significant difference (p<0.05)

Supplement 7: Summary on Functional Remodeling

Tables S5 through S8 below provide details on functional LV remodeling in acute and chronic phases of reperfused and non-reperfused myocardial infarctions. Table S9 compares reperfused and non-reperfused myocardial infarctions in terms of functional LV remodeling.
**Table S5. Functional LV remodeling in reperfused myocardial infarctions**

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>End-Diastolic Volume (mL/m²)</th>
<th>End-Systolic Volume (mL/m²)</th>
<th>Ejection Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acute (Median (Q1-Q3))</td>
<td>67.4 (58.4-76.3)</td>
<td>47.5 (42.4-56.5)</td>
<td>28.5 (25.1-36.8)</td>
</tr>
<tr>
<td>PMO+/T₂⁺⁺ (n=9)</td>
<td>Chronic (Median (Q1-Q3))</td>
<td>75.5 (69.4-85.1)</td>
<td>58.4 (51.3-68.9)</td>
<td>21.5 (14.6-24.2)</td>
</tr>
<tr>
<td></td>
<td>% Change (Acute to Chronic)</td>
<td>16.0 (8.7-22.2)</td>
<td>19.3 (11.8-29.3)</td>
<td>-23.5 (-32.0-13.7)</td>
</tr>
<tr>
<td></td>
<td>p-value (Acute vs. Chronic)</td>
<td>0.008*</td>
<td>0.01*</td>
<td>0.03*</td>
</tr>
<tr>
<td></td>
<td>Acute (Median (Q1-Q3))</td>
<td>56.4 (54.1-58.3)</td>
<td>33.7 (27.8-46.4)</td>
<td>40.2 (36.3-46.3)</td>
</tr>
<tr>
<td>PMO+/T₂⁺⁻ (n=4)</td>
<td>Chronic (Median (Q1-Q3))</td>
<td>60.0 (54.1-65.1)</td>
<td>35.2 (29.2-40.0)</td>
<td>42.1 (36.2-49.6)</td>
</tr>
<tr>
<td></td>
<td>% Change (Acute to Chronic)</td>
<td>5.8 (-1.0-12.3)</td>
<td>0.7 (-6.7-8.4)</td>
<td>2.2 (-7.1-9.4)</td>
</tr>
<tr>
<td></td>
<td>p-value (Acute vs. Chronic)</td>
<td>0.30</td>
<td>0.43</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>Acute (Median (Q1-Q3))</td>
<td>48.2 (46.1-49.1)</td>
<td>29.3 (24.6-31.9)</td>
<td>44.6 (41.4-53.1)</td>
</tr>
<tr>
<td>PMO+/T₂⁺⁻ (n=4)</td>
<td>Chronic (Median (Q1-Q3))</td>
<td>45.0 (41.0-48.3)</td>
<td>30.4 (20.8-39.1)</td>
<td>46.3 (39.7-53.0)</td>
</tr>
<tr>
<td></td>
<td>% Change (Acute to Chronic)</td>
<td>2.5 (-8.2-3.5)</td>
<td>-3.4 (-9.0-0.5)</td>
<td>1.4 (-6.9-7.3)</td>
</tr>
<tr>
<td></td>
<td>p-value (Acute vs. Chronic)</td>
<td>0.32</td>
<td>0.81</td>
<td>0.88</td>
</tr>
</tbody>
</table>

*Statistically significant difference (p<0.05)

**Table S6. Comparison of functional LV remodeling across groups in reperfused myocardial infarctions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Phase of MI</th>
<th>PMO+/T₂⁺⁺ vs. PMO+/T₂⁺⁻</th>
<th>PMO+/T₂⁺⁺ vs. PMO+/T₂⁺⁻</th>
<th>PMO+/T₂⁺⁻ vs. PMO+/T₂⁺⁻</th>
</tr>
</thead>
</table>
Table S7. Functional LV remodeling in non-reperfused myocardial infarctions

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>End-Diastolic Volume (mL/m²)</th>
<th>End-Systolic Volume (mL/m²)</th>
<th>Ejection Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NON-REPERFUSED MYOCARDIAL INFARCTIONS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Parameter                  | End-Diastolic Volume (mL/m²) | End-Systolic Volume (mL/m²) | Ejection Fraction (%) |

| Parameter                  | End-Diastolic Volume (mL/m²) | End-Systolic Volume (mL/m²) | Ejection Fraction (%) |

*Statistically significant difference (p<0.05)
### Table S8. Comparison of functional LV remodeling across groups in non-reperfused myocardial infarctions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Phase of MI</th>
<th>NR-PMO/T2*± (n = 15)</th>
<th>NR-PMO*/T2*± (n = 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acute (Median (Q1-Q3))</td>
<td>58.5 (55.2-69.3)</td>
<td>56.1</td>
</tr>
<tr>
<td></td>
<td>Chronic (Median (Q1-Q3))</td>
<td>74.1 (70.5-79.2)</td>
<td>67.4</td>
</tr>
<tr>
<td>% Change (Acute to Chronic)</td>
<td>19.1 (11.6-29.6)</td>
<td>14.3 (8.2-28.4)</td>
<td>20.1</td>
</tr>
<tr>
<td>p-value (Acute vs. Chronic)</td>
<td>0.001*</td>
<td>0.003*</td>
<td>--</td>
</tr>
</tbody>
</table>

*Statistically significant difference (p<0.05)
**Table S9. Summary of functional LV remodeling between reperfused and non-reperfused MI**

<table>
<thead>
<tr>
<th></th>
<th>vs. NR-PMO/T₂*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EDV</strong></td>
<td></td>
</tr>
<tr>
<td>p-value (Acute)</td>
<td>0.04*</td>
</tr>
<tr>
<td>p-value (Chronic)</td>
<td>0.01*</td>
</tr>
<tr>
<td>(ΔEDV between Acute and Chronic)</td>
<td>0.65</td>
</tr>
<tr>
<td><strong>ESV</strong></td>
<td></td>
</tr>
<tr>
<td>p-value (Acute)</td>
<td>0.005*</td>
</tr>
<tr>
<td>p-value (Chronic)</td>
<td>0.003*</td>
</tr>
<tr>
<td>(ΔESV between Acute and Chronic)</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>EF</strong></td>
<td></td>
</tr>
<tr>
<td>p-value (Acute)</td>
<td>0.005*</td>
</tr>
<tr>
<td>p-value (Chronic)</td>
<td>0.01*</td>
</tr>
<tr>
<td>(ΔEF between Acute and Chronic)</td>
<td>0.91</td>
</tr>
</tbody>
</table>

*Statistically significant difference (p<0.05)
<table>
<thead>
<tr>
<th>Phase of MI</th>
<th>Parameter</th>
<th>Ejection Fraction (%)</th>
<th>End-Diastolic Volume (mL/m²)</th>
<th>End-Systolic Volume (mL/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reperfused (n=17) (Median (Q1-Q3))</td>
<td>39.1 (30.4-48.1)</td>
<td>55.3 (49.8-62.9)</td>
<td>33.9 (27.8-44.6)</td>
</tr>
<tr>
<td>Acute</td>
<td>Non-Reperfused (n=16) (Median (Q1-Q3))</td>
<td>36.0 (30.7-40.3)</td>
<td>57.5 (55.6-69.6)</td>
<td>37.2 (32.1-46.0)</td>
</tr>
<tr>
<td></td>
<td>p-value (Reperfused vs. Non-Reperfused)</td>
<td>0.21</td>
<td>0.33</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>Reperfused (n=17) (Median (Q1-Q3))</td>
<td>39.4 (25.8-48.6)</td>
<td>68.1 (57.4-79.2)</td>
<td>35.5 (26.2-49.2)</td>
</tr>
<tr>
<td>Chronic</td>
<td>Non-Reperfused (n=16) (Median (Q1-Q3))</td>
<td>38.6 (32.4-45.0)</td>
<td>73.3 (69.1-78.0)</td>
<td>42.1 (39.1-53.2)</td>
</tr>
<tr>
<td></td>
<td>p-value (Reperfused vs. Non-Reperfused)</td>
<td>0.12</td>
<td>0.65</td>
<td>0.76</td>
</tr>
</tbody>
</table>

*Statistically significant difference (p<0.05)