Increased Release of Arachidonic Acid and Eicosanoids in Iron-Overloaded Cardiomyocytes

Rafael Mattera, PhD; Gregory P. Stone, BA; Nael Bahhur, BA; Yuri A. Kuryshchev, PhD

Background—Patients with transfusional iron overload may develop a life-limiting cardiomyopathy. The sensitivity of lipid-metabolizing enzymes to peroxidative injury, as well as the reported effects of arachidonic acid (AA) and metabolites on cardiac rhythm, led us to hypothesize that iron-overloaded cardiomyocytes display alterations in the release of AA and prostaglandins.

Methods and Results—Neonatal rat ventricular myocytes (NRVMs) cultured for 72 hours in the presence of 80 μg/mL ferric ammonium citrate displayed an increased rate of AA release, both under resting conditions and after stimulation with agonists such as [Sar1]Ang II. Although iron treatment did not affect overall incorporation of [3H]AA into NRVM phospholipids, it caused a 2-fold increase in the distribution of precursor in phosphatidylcholine species, with a proportional decrease in phosphatidylcholine, phosphatidylethanolamine, and phosphatidylethanolamine. Increased release of AA in iron-overloaded NRVMs was reduced by the diacylglycerol lipase inhibitor RHC80267 but was largely insensitive to inhibitors of phospholipases A2 and C. Iron-overloaded cardiomyocytes also displayed increased production of eicosanoids and induction of cyclooxygenase-2 after stimulation with interleukin-1α.

Conclusions—Iron overload enhances AA release and incorporation of AA into phosphatidylcholine, as well as cyclooxygenase-2 induction and eicosanoid production, in NRVMs. The effects of AA and metabolites on cardiomyocyte rhythmicity suggest a causal connection between these signals and electromechanical alterations in iron-overload-induced cardiomyopathy. (Circulation. 2001;103:2395-2401.)

Key Words: cardiomyopathy ■ prostaglandins ■ signal transduction ■ myocytes ■ iron
NRVM Preparation and Iron Treatment

Cell isolation was based on a previously reported procedure. The yield of the preparations was ~3 to 4 x 10^6 cells/heart. After isolation, NRVMs were resuspended at ~4 x 10^6 cells/mL in DMEM/F12 medium containing 50 μg/mL gentamicin (DMEM/F12/GENT) and 10% calf serum. Cells were plated at a density of 0.33 x 10^6 cells/well of a 12-well plate or 4 x 10^5 cells per 100-mm dish and cultured at 37°C under humidified atmosphere (95:5, air:CO2). After overnight incubation, the serum concentration was reduced to 0.4% by 2 consecutive 5-fold dilutions with serum-free DMEM/F12/GENT. Cells were subsequently cultured for 72 hours with or without 80 μg/mL elemental iron (supplied as 470 μg/mL ferric ammonium citrate, based on 17% iron content in this salt). Medium was partially renewed every 24 hours (removal of half volume, followed by addition of an equal volume of fresh DMEM/F12/GENT with or without iron). This resulted in serum concentrations ranging from 0.4% to 0.1% throughout the 72-hour culture. Cultured NRVMs displayed spontaneous contractility after 2 days in culture. Iron treatment decreased cardiomyocyte size, thinned its projections, reduced the number of spontaneously beating cells, and resulted in siderosome accumulation. LDH activity in extracellular medium of control and iron-treated cells (72-hour treatment) was 14±3% and 42±2%, respectively, of total activity in Triton X-100 cell lysates (mean±SD, n=4). Control and iron-treated NRVM cultures exhibited 13±5% and 13±1% Trypan blue–positive cells, respectively (mean±SD, n=4); the number of cells in the iron-treated cultures relative to the controls was 0.8±0.2 (mean±SD, n=4).

AA Release

Assays were adapted from a previous study. Briefly, NRVMs cultured in 12-well plates were labeled for 15 to 18 hours in 1.2 mL/well of DMEM/F12/GENT containing 0.7 μCi of [3H]AA and 0.1% BSA (≈90% of precursor was incorporated). Labeled cells were washed at 37°C with DMEM/F12/GENT plus 0.1% BSA. Assays were started by removal of wash media and addition of 1 mL of DMEM/F12/GENT supplemented with 0.1% BSA, 100 μg/mL unlabeled AA (unless otherwise indicated), and agonists and/or enzyme inhibitors. After incubation at 37°C for the indicated times, samples of media were collected, centrifuged at 14 000g for 2 minutes, and counted. [3H]AA release was normalized by measuring 3 H dpm in cell lysates (1 mol/L HONa) and expressed as a percentage of incorporated 3 H dpm.

Distribution of [3H]AA Into Individual Phospholipid Species

Control and iron-treated NRVMs were labeled with [3H]AA for 1 to 24 hours. Labeled cells were washed and extracted with chloroform-methanol-water (final ratio 2:1:0.8 by volume). Lower phases were dried under nitrogen, dissolved in chloroform/methanol/water (75:25:3 by volume), and applied onto silica gel plates previously dipped (up to 5 cm from origin) in 0.4 mol/L boric acid and air-dried. Samples were supplemented with phospholipid standards and subjected to ascending chromatography with chloroform/methanol/ ammonium hydroxide/water 65:35:2:3 by volume. Plates were developed with iodine, followed by liquid scintillation counting. Mobility of phospholipids in this system is as follows: origin; phosphatidylglycerol (PI); phosphatidylyserine (PS); phosphatidylcholine (PC); phosphatidylethanolamine (PE); front. Eicosanoid Production

NRVMs cultured for 72 hours in the presence or absence of 80 μg/mL iron were treated with or without 10 ng/mL IL-1α during the last 12 to 18 hours of culture. After treatment, extracellular medium was collected and centrifuged for 15 minutes at 1400 g and room temperature. Concentrations of PGE2, PGF2α, and 6-keto-PGF1α (stable metabolite of PGI2) in supernatants were determined by enzyme immunoassay.

Results

Alterations in AA Release

We studied NRVMs treated with ferric ammonium citrate and low serum concentrations (≈0.4% to 0.1% throughout the 72-hour culture). This presentation of iron to cardiomyocytes mimics the situation in patients with transfusional iron burden, who not only display transferrin saturation but also high levels of chelatable, low-molecular-weight, non-transferrin-bound plasmatric iron.7 Transferin-independent iron uptake involves participation of ferrieductases and low-affinity/high-capacity mechanisms.15 Unlike transferrin-dependent uptake, which desensitizes at high concentrations of iron, non-transferrin-bound iron uptake becomes 300-fold higher than the former in cultured cells.2,7 Treatment of NRVMs with ferric ammonium citrate results in intracellular accumulation comparable to levels in patients with significant iron burden.16 NRVMs treated with this ferric complex constitute a model of the iron-overloaded heart, given the observed metabolic alterations, ultrastructural pathology, and changes in the overshoot of the action potential and rhythm.2,4–6,13

We studied the effect of iron overload on AA release in resting NRVMs or after activation of angiotensin II (Ang II) receptors, a pathway relevant to cardiac pathophysiology. NRVMs cultured for 72 hours in the presence of 80 μg/mL ferric ammonium citrate and subjected to overnight labeling with [3H]AA displayed a significant increase in AA release, both under resting conditions and after stimulation with [Sar1]Ang II (a nonselective Ang II type 1 [AT1] and Ang II type 2 [AT2] receptor agonist with reduced susceptibility to amипептидases; Table). Similar increases in AA release in iron-overloaded NRVMs were observed after stimulation with thrombin or lysosphosphatidic acid (not shown). We routinely add 100 μmol/L unlabeled AA to the assay medium, to minimize reuptake of released [3H]AA. However, increased [3H]AA release in iron-overloaded NRVMs was not linked to this assay condition, because significant effects were also measured with medium containing 0 to 10 μmol/L unlabelled AA (Table). The effect of iron on [3H]AA release was concentration dependent: whereas no changes were detected in NRVMs cultured for 72 hours with 5 μg/mL iron, significant increases were observed after treatment with concentrations ≥20 μg/mL (not shown). All subsequent studies were performed with NRVMs cultured for 72 hours with or without 80 μg/mL iron. Time courses of [3H]AA release showed significantly higher rates in iron-treated cells either in presence or absence of agonist (Figure 1). As shown in Figure 2, increased response to [Sar1]Ang II in iron-overloaded NRVMs was characterized by a higher efficacy and unchanged potency compared with control cells (EC50 0.2±0.1 nmol/L and 0.16±0.03 nmol/L for control and iron-treated cultures, respectively).
Increased Release of $[^{3}H]$AA in Iron-Treated NRVMs

<table>
<thead>
<tr>
<th>AA $\mu$mol/L</th>
<th>[3H]AA Release (% of Incorporation)</th>
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<tbody>
<tr>
<td></td>
<td>Control</td>
</tr>
<tr>
<td>Resting 0</td>
<td>0.40±0.02</td>
</tr>
<tr>
<td>[Sar1]Ang II 0</td>
<td>0.51±0.01</td>
</tr>
<tr>
<td>Resting 10</td>
<td>1.10±0.004</td>
</tr>
<tr>
<td>[Sar1]Ang II 10</td>
<td>1.92±0.08</td>
</tr>
<tr>
<td>Resting 100</td>
<td>1.82±0.12</td>
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<tr>
<td>[Sar1]Ang II 100</td>
<td>3.72±0.12</td>
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$[^{3}H]$AA-labeled NRVMs were washed and assayed in 30-minute incubations, with or without 0.5 $\mu$mol/L [Sar1]Ang II, in the presence of the indicated concentrations of unlabeled AA. Values are means±SEM (n=3) and represent 3 independent experiments.

*P<0.05 and †P<0.01 vs controls (Student’s 2-tailed t test).

Iron-overload–dependent increases in AA release in iron-overloaded NRVMs were antagonized by candesartan (but insensitive to PD123319; Figure 3). The iron-overload–dependent increase in AA release was observed either in NRVMs cultured under standard conditions (low serum, maintaining nonmyocyte cardiac cells, and standard conditions: low serum, maintaining nonmyocyte cardiac cells) or with the antimitotic agent ara-c, to further minimize their contribution (Figure 4).

Predominant routes for production of AA in mammalian cells include hydrolysis of the sn-2 ester bond of glycerophospholipids by phospholipase A2 (PLA2) and the activity of diacylglycerol (DAG) lipase on DAG generated by phospholipase C (PLC) or phospholipase D/phosphatidic acid phosphohydrolase. Selective inhibitors were used to study the contribution of these pathways to increased AA release in iron-overloaded NRVMs. Whereas incubation with DAG lipase inhibitor RHC80267 inhibited $[^{3}H]$AA release in control cells, it also resulted in $\approx$65% inhibition of the enhancement in release triggered by iron treatment (Figure 5A). On the other hand, increased $[^{3}H]$AA release in iron-overloaded NRVMs was not blocked by various selective and nonselective PLA2 inhibitors, including aristolochic acid, AACOCF3, HELSS, and quinacrine (not shown). In contrast to the effects on AA release, iron-overloaded NRVMs showed no differences in PLC activity compared with control cells (Figure 5C, left panel). Consistent with this, the PLC inhibitor U73122 reduced production of inositol phosphates (Figure 5C) but did not normalize increased release of $[^{3}H]$AA in iron-loaded NRVMs (Figure 5B).

Phospholipid Labeling

Although iron treatment of NRVMs did not significantly affect overall incorporation of $[^{3}H]$AA into phospholipids (not shown), the distribution showed a 2-fold increase in the incorporation of $[^{3}H]$AA in PC species, together with a proportional decrease in labeling of PI, PE, and PS (Figure 6). Similar increases in PC labeling (2- to 2.2-fold) were detected in cells incubated with $[^{3}H]$AA for either 6.5 or 24 hours (Figure 6) or after shorter incubations (1 to 6 hours interval, not shown). We also observed a time-dependent shift in the PE/PC ratio in both experimental groups consistent with time-dependent remodeling of AA from PC to PE. How-
ever, increased labeling of PC in iron-overloaded NRVMs results in this being the predominantly labeled phospholipid class, as opposed to higher labeling of PE in controls (Figure 6).

Prostanoid Production
We also studied whether iron overload triggered changes in production of PGE$_2$, PGF$_{2\alpha}$, and PGI$_2$, the major eicosanoids secreted by cultured cardiomyocytes.\textsuperscript{18,19} Cells were stimulated with IL-1$\alpha$, which markedly increases prostanoid production in NRVMs compared with agonists such as Ang II or endothelins (not shown). Iron-overloaded cells stimulated with IL-1$\alpha$ displayed increased production of PGE$_2$, PGF$_{2\alpha}$, and 6-keto-PGF$_{1\alpha}$ (stable metabolite of PGI$_2$; Figure 7) compared with controls. The increase in IL-1$\alpha$-induced PGF$_{2\alpha}$ production driven by iron overload was sensitive to 30 $\mu$mol/L indomethacin, consistent with this effect representing cyclooxygenase (COX) activity; however, a fraction of the PGF$_{2\alpha}$ production in cytokine-stimulated control cells was insensitive to this treatment and may reflect isoprostanes (not shown). The higher resting levels of prostaglandin production in iron-overloaded cells seemed to originate from increased COX activity, as measured after 15-minute incubation with 50 $\mu$mol/L unlabeled AA (production of PGF$_{2\alpha}$ was $1.1 \pm 0.1$ and $2.1 \pm 0.1$ ng/mg in control and iron-treated NRVMs, respectively; $\text{mean} \pm \text{SEM}; n=4$). Iron treatment also enhanced IL-1$\alpha$-dependent COX-2 induction in NRVMs (bottom panel of Figure 7), whereas increased production of PGE$_2$ in cytokine-stimulated cells (either control or iron-overloaded) was blocked by the COX-2–selective inhibitor NS-398 (not shown).

Discussion
Ubiquitous iron-regulated RNA-binding proteins sense intracellular chelatable pools of iron and control expression of target genes by regulating either translation or stability of mRNAs containing 1 or more iron-responsive elements in their 5’ or 3’ regions, respectively.\textsuperscript{20} Genes regulated by this mechanism include H- and L-ferritin, erythrocYTE 5-aminolevulinic synthase, mitochondrial aconitase, transferrin receptor, and Nramp2/DCT1 intestinal iron transport-er.\textsuperscript{20} Although significant advances were made in understanding regulation of genes affecting iron homeostasis, limited information is available regarding signals altered by iron overload. Exceptions to this situation are the effects of iron on expression of protein kinase C-$\beta$\textsuperscript{21} and fibrogenic genes.\textsuperscript{22} This limitation hinders the treatment of transfusional iron-dependent cardiomyopathy, a life-limiting complication in inadequately chelated patients.\textsuperscript{1}

We showed that iron overload increases AA release and PE labeling, as well as COX activity, COX-2 induction, and eicosanoid production, in NRVMs. Release of AA is catalyzed by PLA$_2$ enzymes and/or DAG lipase. The PLA$_2$ superfamily includes at least 10 different groups displaying differences in primary structure, cellular localization, and activity in extracellular medium from 14%±2% to 23%±5% (means±SD; n=3) and LDH activity in extracellular medium from 14%±3% (mean±SD; n=3) to 36%±4% (average and range, n=2) of total LDL activity in cell extracts. Results are means±SEM of triplicate determinations and represent 2 independent experiments with different preparations of NRVMs. \textsuperscript{**}$P<0.01$, significant differences when responses in iron-treated NRVMs were compared with corresponding controls (Student’s 2-tailed t test). Ctrl indicates control; incor., incorporation.

Figure 4. Effect of ara-c on [3H]AA release in control and iron-treated NRVMs. The antimitotic agent ara-c, added after cell attachment and at onset of 72-hour incubation with or without iron, minimizes fibroblast proliferation. Treatment with 1 $\mu$mol/L ara-c for 72 hours increased proportion of Trypan blue–positive cells from 14%±2% to 23%±5% (means±SD; n=3) and LDH activity in extracellular medium from 14%±3% (mean±SD; n=3) to 36%±4% (average and range, n=2) of total LDL activity in cell extracts. Results are means±SEM of triplicate determinations and represent 2 independent experiments with different preparations of NRVMs. \textsuperscript{**}$P<0.01$, significant differences when responses in iron-treated NRVMs were compared with corresponding controls (Student’s 2-tailed t test). Ctrl indicates control; incor., incorporation.

Figure 5. Effects of inhibitors of DAG-lipase and PLC on AA release in control and iron-treated NRVMs. A and B, [3H]AA-labeled NRVMs were preincubated for 8 minutes with or without 150 $\mu$mol/L RHC80267 or 5 $\mu$mol/L U73122, followed by 30-minute assay. C, [3H]inositol-labeled NRVMs were washed and preincubated in HBSS containing 1.2 mmol/L CaCl$_2$, 1 mmol/L MgCl$_2$, 1.8 mg/mL glucose, and 1 mmol/L LiCl, in presence or absence of 5 $\mu$mol/L U73122, followed by 30-minute assay with or without agonist (U73122 was also present during incubation). When added, [Sar$^1$]Ang II was 10 nmol/L. \textsuperscript{*}$P<0.05$ and \textsuperscript{**}$P<0.01$, significant differences when corresponding responses in presence or absence of RHC or U73122 were compared (Student’s 2-tailed t tests of 2 groups). Ctrl indicates control; incor., incorporation; IP$_3$, inositol monophosphates; and PPI, phosphoinositides.
Ca\(^{2+}\) sensitivity. Most of the PLA\(_{2}\) activity in cardiomyocytes is Ca\(^{2+}\)-independent. The results obtained with the inhibitors AACOCF\(_3\) (selective for both group IV PLA\(_{2}\) and group VI-Ca\(^{2+}\)-independent PLA\(_{2}\)), HELSS (selective for group VI-Ca\(^{2+}\)-independent PLA\(_{2}\)), and RHC80267 (DAG lipase-selective) are consistent with an at least partial participation of the latter in increased AA release in iron-overloaded cells. However, 2 forms of Ca\(^{2+}\)-independent PLA\(_{2}\) (\(~82-\) and 40-kDa, respectively), exhibiting differences in intracellular localization and HELSS sensitivity, were evidenced in cardiomyocytes. The possibility that iron overload may affect a HELSS-insensitive Ca\(^{2+}\)-independent PLA\(_{2}\) deserves further exploration.

Interestingly, the distribution of labeled [\(^{3}\)H]AA incorporated in phospholipids of iron-overloaded NRVMs shows an increase in PC (Figure 6). Incorporation of [\(^{3}\)H]AA may predominantly reflect phospholipid remodeling through the deacylation-acylation Lands cycle, as opposed to de novo glycerophospholipid biosynthesis through the Kennedy cycle, whereas time-dependent remodeling of [\(^{3}\)H]AA from PC into PE may represent coenzyme A–independent transacylase activity. Iron treatment of NRVMs may increase availability of lysophospholipid acceptors for formation of PC and/or decrease AA remodeling into PE.

The association of changes in AA release and activity of AA-releasing enzymes with myocardial alterations is not unprecedented. Levels of unsterified fatty acids, particularly AA, increase in ischemic myocardium, preceding losses in total phospholipids. Similarly, translocation of Ca\(^{2+}\)-independent PLA\(_{2}\) from cytosol to membranes and protection by its selective inhibitor HELSS were reported in ischemic hearts.

The observation that iron overload sensitizes NRVMs to COX-2 induction (Figure 7) is also significant. Altered eicosanoid production in NRVMs may be responsible for either phenotypic protection or damage during iron overload. Cotreatment with 50 to 500 nmol/L PGF\(_{2\alpha}\) prevented morphological changes and the decreased beating in iron-overloaded NRVMs, whereas opposite effects were observed with the PGF\(_{1\alpha}\) analog beraprost (R.M. and Y.A.K., unpublished data, 2000). The observations with PGF\(_{2\alpha}\) are consistent with its hypertrophic effects in cardiomyocytes and with the compensatory role of COX-dependent signals during oxidative stress.
The reported effects of AA metabolites on myocardial rhythmicity suggest a causal connection between our observations and iron-overload-induced electromechanical changes. Indeed, PGD₂, PGE₂, and thromboxane A₂–mimetic compounds trigger reversible tachyarrhythmias, characterized by increased beating rate and contractures. Conversely, prostacyclin (PGI₁) reduces contraction rate in cardiomyocytes. Interestingly, iron overload not only potentiates IL-1α–induced eicosanoid release but also modified the relative ratio of eicosanoid production in cytokine-stimulated NRVMs. Although PGI₁ was the most abundant product in resting NRVMs (controls or iron-overloaded), a relatively higher increase in PGE₂ was observed after IL-1α treatment of iron-overloaded cells compared with smaller changes in either PGI₁ or the less abundant PGF₂₀ (30-fold versus 3- to 4-fold, respectively, in Figure 7). Consequently, PGE₂ was the predominant eicosanoid in cytokine-stimulated NRVMs. Although PGI₁ was the most abundant product in resting NRVMs (controls or iron-overloaded), a relatively higher increase in PGE₂ was observed after IL-1α treatment of iron-overloaded cells compared with smaller changes in either PGI₁ or the less abundant PGF₂₀ (30-fold versus 3- to 4-fold, respectively, in Figure 7). Consequently, PGE₂ was the predominant eicosanoid in cytokine-stimulated NRVMs. This is significant because the specific pattern of eicosanoid production in iron-overloaded cardiomyocytes may be ultimately responsible for the final balance of proarrhythmogenic or antiarrhythmogenic effects.

Reasonable targets for a role of altered production/metabolism of AA in the electromechanical derangement in iron-overloaded hearts include Na⁺ and K⁺ currents. Precedents supporting this possibility are the reduced Na⁺ currents and increased transient outward K⁺ current (Iₒ) in iron-overloaded gerbil cardiomyocytes, together with the inhibition of cardiac Na⁺ currents by acute treatment with exogenous AA and other polyunsaturated fatty acids. In support of this hypothesis, we observed that chronic treatment of NRVMs with AA (72 hours, 10 μmol/L) decreased Na⁺ currents and increased Iₒ density (Y.A.K. and R.M., unpublished data, 2000). Interestingly, iron-overloaded gerbil hearts exhibit decreased conduction velocity (K. Laurita, PhD, unpublished data, 2000), consistent with reduced Na⁺ currents in isolated cardiomyocytes. Whereas reduced cardiac Na⁺ currents may underlie antiarrhythmic effects of n-3 polyunsaturated fatty acids during delayed afterdepolarizations and triggered activity, a slowing in conduction velocity and the possible shortening of action potentials and refractoriness (due to increased Iₒ), combined with increased size of iron-overloaded hearts, may allow reentry arrhythmias in this cardiomyopathy.

The possible consequences of increased release of AA in Ang II–stimulated iron-overloaded NRVMs on cardiac phenotype deserve consideration. This peptide regulates contractility and growth of cardiomyocytes, as well as hyperplasia and matrix production in cardiac fibroblasts. Activation of AT₁ receptors is relevant to mechanical strain–dependent hypertrophy (through recruitment of mitogen-activated protein kinases) and stretch-mediated apoptosis in myocytes. Given the effects of AA on activation of mitogen-activated protein kinases and apoptosis, it is possible to speculate that increased Ang II–dependent AA release may contribute to progression from hypertension to heart failure in iron-overload–induced cardiomyopathy. The interaction between cardiac nonmyocyte cells and cardiomyocytes and the relative expression of Ang II receptors in these cell types received attention. The identification of different mechanisms responsible for activation of extracellular signal–regulated kinases by Ang II in rat neonatal cardiac fibroblasts and myocytes supports expression of receptors in both cell types. Using NRVMs cultured with ara-c (to minimize fibroblast proliferation), we observed similar iron overload–dependent increases in AA release and also increased production of PGE₂ and PGF₂₀ (albeit to a lower extent than in standard cultures; not shown), consistent with a significant role of cardiomyocytes in these responses. However, interactions between cardiomyocytes and nonmyocytes in the alterations driven by iron overload cannot be excluded.

Additional studies are required to determine whether the present observations extend to the animal model of cardiac overload and their incidence in human cardiomyopathy. Although the connection between altered production/metabolism of AA and electromechanical alterations in this cardiomyopathy requires additional investigation, the present observations represent an advance in the identification of pathways that either cause or represent adaptive responses to cardiac iron overload.

Acknowledgments

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References


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