Abstract: Atherosclerosis and its attendant clinical complications, such as myocardial infarction, stroke, and peripheral artery disease, are the leading cause of morbidity and mortality in Western societies. In response to biochemical and biomechanical stimuli, atherosclerotic lesion formation occurs from the participation of a range of cell types, inflammatory mediators, and shear stress. Over the past decade, microRNAs (miRNAs) have emerged as evolutionarily conserved, noncoding small RNAs that serve as important regulators and fine-tuners of a range of pathophysiological cellular effects and molecular signaling pathways involved in atherosclerosis. Accumulating studies reveal the importance of miRNAs in regulating key signaling and lipid homeostasis pathways that alter the balance of atherosclerotic plaque progression and regression. In this review, we highlight current paradigms of miRNA-mediated effects in atherosclerosis progression and regression. We provide an update on the potential use of miRNAs diagnostically for detecting increasing severity of coronary disease and clinical events. Finally, we provide a perspective on therapeutic opportunities and challenges for miRNA delivery in the field.
Atherosclerosis represents a chronic inflammatory disease of the arterial wall initiated by endothelial injury and subendothelial lipoprotein retention, particularly at sites of disturbed blood flow. The pathogenesis of atherosclerotic lesion formation is a multistage process involving both immune and nonimmune cellular constituents of the vessel wall. Research over the past 3 decades has uncovered key signaling and molecular regulatory pathways involved in the initiation and progression of atherosclerotic plaques. The recent emergence of microRNAs (miRNAs) as important regulators of pathophysiological processes, such as cellular adhesion, proliferation, lipid uptake and efflux, and generation of inflammatory mediators, has provided novel molecular insights into their impact on these pathways in atherosclerosis and identified new therapeutic targets. In addition, the appreciation that miRNAs can be detected extracellularly including in circulating blood raises the potential for their use as biomarkers for diagnosis, prognosis, or in response to cardiovascular therapeutics. This review highlights the role of miRNAs implicated in regulating critical aspects of atherosclerotic lesion formation and regression. We also review the potential use of miRNAs diagnostically for detecting in progression and by promoting mRNA degradation. It is estimated that >60% of all protein-coding genes are directly regulated by miRNAs. Furthermore, a given miRNA may bind to and regulate >1 target, sometimes as a part of the same signaling pathway. Conversely, a given miRNA may harbor several distinct miRNA-binding sites within its 3′-UTR, adding multiple levels of regulation. As such, miRNAs are fine-tuners of gene expression patterns in response to pathophysiological stimuli.

Intergenic miRNAs are located within the genome between gene-coding regions and are transcribed by their own promoters. By contrast, intronic miRNAs are found within intronic sequences of protein-coding genes and often share the same upstream promoters and transcriptional regulation with their host genes. MiRNA biogenesis proceeds in response to a well-defined series of cellular events. MiRNAs are transcribed primarily by RNA polymerase II (more rarely by polymerase III) to generate the primary miRNA transcript, termed pri-miRNAs that harbor a canonical hairpin structure including a 5′ cap and 3′ poly-A tail. The pri-miRNAs are converted to 70-nt-long hairpin precursor miRNAs (pre-miRNAs) by the Drosha/DGCR8 (Di George Syndrome Critical Region Gene 8) complex. Subsequently, the pre-miRNA is exported from the nucleus to the cytoplasm by Exportin 5, where it undergoes further processing by the RNase III enzyme complex Dicer (and other RNA-binding proteins) producing a mature miRNA duplex. This double-stranded product is composed of the mature miRNA guide strand and the miRNA passenger strand. The guide strand is typically incorporated in the RNA-induced silencing complex that contains Argonaute2, which facilitates the miRNA binding to the target mRNA leading to reduced protein expression by blocking mRNA translation and by promoting mRNA degradation. It is estimated that >60% of all protein-coding genes are directly regulated by miRNAs. Furthermore, a given miRNA may bind to and regulate >1 target, sometimes as a part of the same signaling pathway. Conversely, a given miRNA may harbor several distinct miRNA-binding sites within its 3′-UTR, adding multiple levels of regulation. As such, miRNAs are fine-tuners of gene expression patterns in response to pathophysiological stimuli.

### MiRNA Regulation of Lipoprotein Homeostasis

Cholesterol homeostasis is essential for cellular physiology, and altered levels of cellular or systemic cholesterol are associated with metabolic diseases. In the circulation, cholesterol is carried on lipoproteins, which can both deliver (eg, low-density lipoprotein [LDL]) and remove (eg, high-density lipoprotein [HDL]) cholesterol from cells and tissues to mediate cholesteryl homeostasis. Imbalances that favor the accumulation of cellular cholesterol, such as high levels of LDL-cholesterol (LDL-C) and low levels of HDL-cholesterol (HDL-C), promote atherosclerosis. The recent discoveries of miRNAs that control LDL and HDL abundance and function have greatly expanded our understanding of the regulatory circuits governing plasma lipoprotein levels.

### Nonstandard Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMI</td>
<td>acute myocardial infarction</td>
</tr>
<tr>
<td>cTn</td>
<td>cardiac troponin</td>
</tr>
<tr>
<td>CAD</td>
<td>coronary artery disease</td>
</tr>
<tr>
<td>D-flow</td>
<td>disturbed flow</td>
</tr>
<tr>
<td>DC</td>
<td>dendritic cell</td>
</tr>
<tr>
<td>ECs</td>
<td>endothelial cells</td>
</tr>
<tr>
<td>HDL-C</td>
<td>high-density lipoprotein cholesterol</td>
</tr>
<tr>
<td>IL</td>
<td>interleukin</td>
</tr>
<tr>
<td>KLF2</td>
<td>Krüppel-like factor 2</td>
</tr>
<tr>
<td>L-flow</td>
<td>laminar flow</td>
</tr>
<tr>
<td>LDL-C</td>
<td>low-density lipoprotein cholesterol</td>
</tr>
<tr>
<td>LDLR</td>
<td>LDL receptor</td>
</tr>
<tr>
<td>miRNA</td>
<td>microRNA</td>
</tr>
<tr>
<td>NF-κB</td>
<td>nuclear factor κB</td>
</tr>
<tr>
<td>PBMCs</td>
<td>peripheral blood mononuclear cells</td>
</tr>
<tr>
<td>SA</td>
<td>stable angina</td>
</tr>
<tr>
<td>siRNA</td>
<td>small interfering RNA</td>
</tr>
<tr>
<td>SOCS</td>
<td>suppressor of cytokine signaling</td>
</tr>
<tr>
<td>STEMI</td>
<td>ST-segment–elevation myocardial infarction</td>
</tr>
<tr>
<td>TNF</td>
<td>tumor necrosis factor</td>
</tr>
<tr>
<td>UA</td>
<td>unstable angina</td>
</tr>
<tr>
<td>UTR</td>
<td>untranslated region</td>
</tr>
<tr>
<td>VSMC</td>
<td>vascular smooth muscle cell</td>
</tr>
</tbody>
</table>
The liver plays a major role in both the production and the clearance of lipoproteins, and many hepatic-enriched miRNAs have been identified that functionally regulate lipoprotein metabolism. miR-122 was the first miRNA implicated in lipoprotein metabolism, and its expression is highly enriched in the liver. Loss-of-function experiments in both mice and non-human primates identified miR-122 as a crucial regulator of cholesterol and fatty acid synthesis, and thus lipoprotein homeostasis. Notably, miR-122 function seems to be broadly required for the expression of hepatocyte-specific genes, rather than the specific targeting of lipid metabolism pathways. By contrast, miR-223 and miR-27b act as key post-transcriptional regulatory hubs controlling networks of cholesterol and lipoprotein metabolism genes. miR-223 represses genes involved in cholesterol biosynthesis (HMGS1, SC4MOL) and HDL levels (SRBI), and Mir223-/- mice display increased LDL-C levels, as well as hepatic and plasma total cholesterol. miR-27b is a cholesterol-responsive hepatic miRNA that represses many targets (PPARG, glycerol-3-phosphate acyltransferase mitochondrial [GPAM], angiotensin like 3 [ANGPTL3], and N-deacetylase/N-sulfotransferase [NDS7]) involved in lipid metabolism and lipoprotein remodeling. In addition to these gene network-regulating miRNAs, miR-30c was shown to have a potent effect on the production of apoB-containing lipoproteins (very low-density lipoprotein and LDL). miR-30c targets the microsomal triglyceride transfer protein (MTP), a protein essential for the lipidation of nascent apoB, and also reduces de novo lipogenesis by targeting lysophosphatidylglycerol acyltransferase 1 (LPGAT1). Lentiviral overexpression of miR-30c in mice reduces the assembly and secretion of apoB lipoproteins, leading to decreased levels of plasma total cholesterol and LDL-C. Furthermore, studies in apoE-deficient mice (Apoe<sup>-/-</sup>) mice showed that miR-30c overexpression mitigated hyperlipidemia and atherosclerosis without inducing steatosis, an undesirable side effect associated with conventional MTP inhibitors.

MiRNA regulation of plasma levels of LDL-C through targeting of the LDL receptor (LDLR) has also been reported. LDLR expression in the liver promotes the clearance of circulating LDL particles and is a major determinant of plasma cholesterol levels. Two recent studies identified miR-148a as a negative regulator of LDLR expression and activity and showed that inhibition of miR-148a in mice could increase the clearance of circulating labeled LDL and decrease plasma LDL-C levels. Notably, single-nucleotide polymorphisms in the promoter region of miR-148A are associated with altered LDL-C in humans, suggesting that altered expression of this miRNA may contribute to dyslipidemias. Indeed, analysis of genome-wide association study data identified 3 other miRNAs predicted to target the LDLR (mir-128-1, miR-130b, and miR-301b) that lie in close proximity to human single-nucleotide polymorphisms associated with abnormal levels of plasma lipids. Like miR-148a, inhibition of miR-128-1 with locked nucleic acid antisense oligonucleotides increased hepatic LDLR expression and LDL clearance in mice. In addition to LDLR, miR-148a and miR-128-1 also target additional genes involved in lipid and energy metabolism (miR-148a: ATP-binding cassette [ABC] transporter A1 [ABCA1], 5' adenosine monophosphate-activated protein kinase a1 [AMPKα1], carnitine palmitoyltransferase 1a [CPT1a], and salt-inducible kinase 1 [SIK1]; miR-128-1: ABCA1, sirtuin 1 [SIRT1], and insulin receptor substrate 1), suggesting important roles for these miRNAs in regulating metabolic pathways.

MiRNAs have also been identified to act as critical regulators of HDL biogenesis and cholesterol efflux. These pathways control levels of plasma HDL-C and the reverse cholesterol transport pathway through which excess cholesterol is removed to the liver for excretion. The ATP-binding cassette transporter, ABCA1, plays a central role in these processes by controlling cholesterol efflux across the cell membrane onto lipid-poor apoA1 to mediate both hepatic HDL biogenesis and the removal of excess cholesterol from peripheral cells, particularly M<sub>0</sub> in atherosclerotic plaques. Many miRNAs have been identified that target ABCA1 to reduce cholesterol efflux to apoA1 in vitro, including miR-33, miR-758, miR-26, miR-106, miR-144, as well as the above-mentioned miR-128-1 and miR-148. Of these, inhibition of miR-33, miR-144, miR-128-1, and miR-148 has also been tested in vivo and shown to increase plasma levels of HDL-C in mice or monkeys. Circulating levels of HDL-C are also regulated by hepatic clearance via the scavenger receptor BI, which has been shown to be targeted by miR-223, miR-455-5p, miR-96, miR-185, and miR-125a. However, only miR-223 has been manipulated in vivo and shown to impact plasma HDL-C levels.

Epidemiological studies have shown an atheroprotective role for HDL, which is thought to be associated with its ability to mediate reverse cholesterol transport. Of the miRNAs targeting the LDL reverse cholesterol transport pathway, the miR-33 family has been the most extensively studied in vivo using preclinical animal models. MiR-33a and miR-33b are intronic miRNAs that are coexpressed with their host genes, SREBF2 and SREBF1, which code for transcription factors that regulate cholesterol and fatty acid synthesis/uptake. Thus, transcription of SREBF2 and SREBF1 also results in expression of miR-33a and b, which cooperate with their host genes to balance cellular lipid levels by repressing genes that oppose SREBP-regulated pathways, such those involved in cholesterol efflux (ABCA1 and ABCG1) and fatty acid oxidation (hydroxyacyl-CoA dehydrogenase/3-ketoacyl-CoA thiolase/enoyl-CoA hydratase [trifunctional protein], beta subunit [HADHB], carnitine O-octanoyltransferase [CROT], CPT1a, and AMPKα1). Inhibition of miR-33 using modified antisense or locked nucleic acid oligonucleotides increased hepatic ABCA1 expression and plasma HDL-C levels in both mice and monkeys by 40% to 50%, and enhanced cholesterol transport from macrophages to the plasma, liver, and feces by >80%. This increase in reverse cholesterol transport is likely the combined effects of derepression of ABCA1 and additional miR-33a/miR-33b targets such as Abcb11 and Atp8b1 that promote cholesterol excretion into bile. Importantly, HDL isolated from mice treated with anti-miR-33 was shown to retain its anti-inflammatory properties, particularly its ability to promote macrophage cholesterol efflux and to protect endothelial cells from cytokine-induced inflammation.

Multiple studies of miR-33 inhibition or deletion have now been conducted in mouse models of atherosclerosis. Targeted deletion of Mir33 increased plasma levels of HDL...
and reduced atherosclerotic plaque size in Apoe\textsuperscript{−/−} mice.\textsuperscript{38} Furthermore, treatment of Ldlr\textsuperscript{−/−} mice with established atherosclerosis with a miR-33 inhibitor for 4 weeks, in conjunction with a Chow diet, increased plasma levels of HDL-C and markedly regressed atherosclerosis.\textsuperscript{27} Notably, this intervention study was designed to simulate a clinical scenario, where plasma LDL-C levels were lowered in conjunction with anti-miR-33 treatment. However, 2 subsequent studies evaluating the effects of miR-33 inhibitors in Ldlr\textsuperscript{−/−} mice on a Western diet showed no effects on HDL-C levels, presumably because of decreased hepatic expression of SREBF2/miR-33 under these conditions.\textsuperscript{39,40} Despite this, Rotllan et al\textsuperscript{39} observed reductions in aortic atherosclerotic lesion area after 8 weeks of anti-miR-33 treatment, suggesting that miR-33 inhibition may have atheroprotective effects beyond raising HDL. This paradox may be explained by a recent report that miR-33 can also instruct macrophage inflammatory polarization by altering the balance of cellular aerobic glycolysis and mitochondrial oxidative phosphorylation.\textsuperscript{41} Targeted deletion or inhibition of miR-33 in macrophages increases oxidative respiration—a metabolic program characteristic of alternatively activated macrophages—and induces the expression of genes that define M2 macrophage polarization. Notably, inhibition of miR-33 also increased macrophage expression of the retinoic acid–producing enzyme Aldh1a2 and retinal dehydrogenase activity both in vitro and in vivo. Retinoic acid can foster the differentiation of atheroprotective regulatory T cells, and consistent with this, Ldlr\textsuperscript{−/−} mice treated with miR-33 inhibitors for 8 weeks on Western diet showed the accumulation of M2 macrophages and FoxP3\textsuperscript{+} T regulatory cells in plaques and reduced atherosclerosis progression in the absence of changes of plasma HDL.\textsuperscript{41} This study suggests that antagonism of miR-33 is atheroprotective, in part, by promoting M2 macrophage and regulatory T-cell polarization to suppress plaque inflammation.

Despite the beneficial effects of miR-33 inhibition on plasma levels of HDL-C and atherosclerosis, some studies of genetic deletion\textsuperscript{42} or antagonism of miR-33\textsuperscript{43} in conjunction with Western diet feeding have reported an increase in circulating triglycerides and hepatosteatosis. Not all studies have observed these effects of miR-33 inhibitors in mice,\textsuperscript{44} and increases in triglycerides or hepatic lipid levels have not been reported in studies of nonhuman primates treated with anti-miR-33 for >16 weeks.\textsuperscript{26,36} These conflicting findings suggest that more studies of miR-33 are warranted, particularly to understand whether effects on triglycerides and hepatosteatosis are species specific or because of potential differences of chemical modifications, delivery, or time of administration of anti-miR-33 oligonucleotides. Nonetheless, these studies highlight the potential utility of miRNA mimics and inhibitors in the treatment of dyslipidemias (Figure 1).

**MiRNA Regulation of Endothelial Cell Inflammation and Plaque Progression**

Sustained hyperlipidemia and altered shear stress predispose the vessel wall to atherosclerotic lesion formation. In response to biochemical and biomechanical stimuli, endothelial cells undergo a series of molecular and cellular conformational changes that promote atherogenesis. For example, early induction of adhesion molecule expression such as vascular adhesion molecule-1, intracellular adhesion molecule-1, and E-selectin facilitates leukocyte recruitment to the vessel wall and may be among the earliest hallmarks associated with nascent plaques.\textsuperscript{45} Several miRNAs have been implicated in atherogenesis by virtue of their ability to directly target the 3′-UTRs of these molecules such as miR-17-3p (targets intracellular adhesion molecule-1) and miR-31 (targets E-selectin).\textsuperscript{46} However, the functional role of both these miRNAs in experimental atherosclerosis remains unknown. Nuclear factor (NF)-κB signaling is a major pathway that activates not only these proadhesive molecules but also a range of other proinflammatory and prothrombotic factors. MiR-181b and miR-146a are 2 cytokine-responsive miRNAs that regulate distinct components of NF-κB signaling and are atheroprotective\textsuperscript{47} (Figure 2).

**Cytokine-Responsive MiRNAs That Regulate Atherosclerosis**

**MiR-181b**

Accumulating studies in mice and human subjects highlight a critical role for miR-181b as an inhibitor of endothelial inflammatory responses by targeting NF-κB signaling in both acute (eg, sepsis) and chronic (eg, atherosclerosis) vascular disease states.\textsuperscript{48,49} MiR-181b, an intergenic miRNA,\textsuperscript{46} inhibits NF-κB signaling uniquely in endothelial cells but not in leukocytes by targeting importin-α5, a protein important for NF-κB cytoplasmic-nuclear translocation. In leukocytes, the dominant isoform that mediates NF-κB nuclear import is importin-α5, which miR-181b does not target thereby leaving leukocyte NF-κB signaling intact. Nonetheless, on systemic intravenous delivery, miR-181b decreased endothelial NF-κB activation, an effect that was sufficient to markedly suppress leukocyte recruitment and atherosclerotic lesion formation in atherosclerotic-prone ApoE\textsuperscript{−/−} mice. Importantly, the miR-181b antiatherosclerotic effects were independent of any changes in lipid profiles. These findings are consistent with endothelial-specific NF-κB (I-kappaB kinase [IKKγ]) knockout and dominant-negative IkBα transgenic mice that also exhibit protection against atherosclerotic lesion formation.\textsuperscript{51} A range of proinflammatory stimuli (eg, tumor necrosis factor [TNF]-α, lipopolysaccharide) reduce miR-181b expression in endothelial cells in vitro. In vivo, miR-181b expression is reduced by 53% in the vascular endothelium and by ≈40% in plasma of mice after just 4 weeks of high cholesterol diet in ApoE\textsuperscript{−/−} mice, suggesting that loss of homeostatic control of miR-181b expression may predispose to inflammation in the vessel wall. In line with these observations, miR-181b expression is also reduced in plasma of human subjects with angiographically defined coronary artery disease (CAD) compared with those without CAD.\textsuperscript{49} Therapeutically, the cell-specific miR-181b inhibitory effects on NF-κB in the vascular endothelium, and not in myeloid cells, may be advantageous to maintain optimal protection in response to infectious pathogens. Indeed, miR-181b delivery also inhibits endothelial inflammation and confers protection against sepsis in mice.\textsuperscript{48} Collectively, these findings provide cogent evidence that miR-181b serves as an important regulator of NF-κB signaling in the vascular...
endothelium in response to diverse stimuli and provide new opportunities for anti-inflammatory replacement therapy.

**MiR-146a**

MiR-146a is another cytokine-responsive miRNAs that confers atheroprotective properties in the vessel wall. Cytokines such as TNF-α and interleukin (IL)-1β induced expression of miR-146a and miR-146b in a delayed kinetic manner in endothelial cells (ECs) that coincided with the resolution of inflammatory gene expression.52 MiR-146a overexpression inhibited cytokine responsiveness in ECs, suggesting that it may participate in a negative feedback mechanism to limit EC inflammatory signaling. Interestingly, miR-146a expression is also increased in human and mouse atherosclerotic plaques.33 Indeed, miR-146a repressed both NF-κB and mitogen activated kinase-like protein (MAPK) signaling pathways by directly targeting HuR, an RNA-binding protein that exerts inhibitory effects on endothelial nitric oxide synthase. In addition, miR-146a represses the induction of EC adhesion molecules by targeting upstream adaptor proteins TNF receptor–associated factor 6 and interleukin 1 receptor associated kinase 1 or 2 (IRAK1/2).35 In contrast to the more selective inhibitory role of miR-181b on EC NF-κB signaling, miR-146a inhibits NF-κB signaling in both ECs and macrophages.54 Indeed, overexpression of ApoE in ApoE−/− macrophages induced miR-146a expression to reduce macrophage proinflammatory responses and systemic delivery of miR-146a mimics markedly reduced atherosclerotic lesion progression. The specific cell subsets (eg, ECs or leukocytes) and mechanisms (eg, NF-κB dependent or NF-κB independent) by which miR-146a confers these favorable effects in experimental atherosclerosis will require additional study. However, given the anti-inflammatory role of miR-146a in regulating a range of immune cells (macrophages, dendritic cells [DCs], and T cells),55 it may participate more broadly to limit inflammatory stimuli. Nevertheless, miR-146 is another important cytokine-responsive miRNA that may serve to dampen EC inflammation in a negative feedback manner.

**Mechanosensitive EC MiRNAs That Regulate Atherosclerosis**

Atherosclerotic lesions preferentially develop at arterial branch points, bifurcations, and the lesser curvature of the
In response to biochemical and biomechanical stimuli, microRNAs (miRNAs) regulate vascular inflammation. MiRNAs regulate specific targets in endothelial cells (ECs) that alter the balance of pro- or anti-inflammatory signaling pathways. Biochemical stimuli such as tumor necrosis factor (TNF)-α reduce the expression of miR-181b, whereas it increases the expression of miR-146. MiR-181b targets importin-α3 in ECs, an effect that prevents cytoplasmic-to-nuclear translocation of nuclear factor-κB (NF-κB) family members, p50 and p65, thereby reducing NF-κB-responsive gene expression such as adhesion molecules vascular cell adhesion molecule 1 (VCAM-1), intercellular adhesion molecule 1 (ICAM-1), or E-selectin. Induction of miR-146 targets the 3′-untranslated region of tumor necrosis factor (TNF) receptor-associated factor 6 (TRAF6) and interleukin 1 receptor associated kinase 1 (IRAK1), to regulate upstream NF-κB signaling and targets HuR, which regulates endothelial nitric oxide synthase (eNOS) expression. The expression of miR-92a and miR-712 is increased in response to disturbed flow (d-flow), whereas miR-126-5p expression is reduced. MiR-92a targets the transcription factors Kruppel-like factor 2 (KLF2) and 4 (KLF4), and suppressor of cytokine signaling (SOCS5) expression, an effect that decreases anti-inflammatory pathways and increases monocyte chemoattractant protein-1 and IL-6 expression, which further promote EC activation. MiR-712 suppresses tissue inhibitor of metalloproteinase-3 (TIMP3), thereby increasing the expression of matrix metalloproteinases (MMPs) and a disintegrin and MMP (ADAMs). In contrast, d-flow reduces expression of miR-126-5p, thereby derepressing its target gene delta-like 1 homolog (Dlk-1), a negative regulator of endothelial cell proliferation. Laminar flow induces the expression of the miR-143/miR-145 cluster, which may be packaged and released extracellularly in microvesicles and taken up by neighboring vascular smooth muscle cells (VSMCs). Conversely, ECs may enable the passage of miR-143 and miR-145 released from VSMCs through specialized membrane protrusions known as tunneling nanotubes. HKII indicates hexokinase II; IKK, IκB kinase; and ITGβ3, integrin β3.

**MiR-92**

MiR-92a, a member of the miR-17 to miR-92 cluster, is expressed highly in endothelial cells and dynamically regulated by shear stress both in vitro and in vivo.\(^5\) On exposure of ECs to pulsatile l-flow in vitro, miR-92a expression is reduced, whereas d-flow increases its expression; in addition, miR-92a bound to the 3′-UTR of Kruppel-like factor 2 (KLF2), a flow-responsive transcription factor, suggesting a direct role for regulating l-flow.\(^6\) Similarly, in vivo miR-92a expression is highly induced in atheroprotective regions of the aortic arch when compared with atherosclerotic regions.\(^6\) In vitro studies suggest that miR-92a overexpression suppresses the 3′-UTRs of KLF2 and KLF4. In contrast, miR-92a–mediated inhibition of TNF-α–induced cytokines and leukocyte adhesion can be rescued, in part, by KLF4 small interfering RNA (siRNA), indicating partial KLF4 dependency.\(^6\) In a separate microarray profiling studies, Loyer et al\(^6\) identified that on exposure of ECs to oxidized LDL and low shear stress, expression of miR-92a and proinflammatory markers (monocyte chemoattractant protein-1 and IL-6) is increased in a STAT3-dependent manner. Overexpression of miR-92a in ECs reduced expression of KLF2 and KLF4, flow-responsive transcription factors, whereas miR-92a antagonism reduced EC inflammation as reflected by lower phospho-p65 expression. Mechanistically, miR-92a also targets suppressor of cytokine signaling (SOCS)-5 in ECs in the presence of oxidized LDL and low shear stress conditions.\(^6\) Although the in vivo role of SOCS5 in atherosclerosis remains unclear, siRNA-mediated knockdown of SOCS5 increased monocyte chemoattractant protein-1 and IL-6 expression in ECs without affecting the expression of endothelial nitric oxide synthase, KLF2, or KLF4. In addition, neutralization of miR-92a in LDLR−/− mice decreased EC inflammation and suppressed the progression of atherosclerotic lesion formation. Moreover, mice harboring a genetic deletion of miR-92a in Tie2-expressing endothelial cells were protected from neointimal formation after mechanical arterial injury.
attributed, in part, to enhanced re-endothelialization.66 Given the protective role of miR-92a-deficiency in other processes including re-endothelialization after mechanical arterial wire injury66,67 and angiogenesis after myocardial or peripheral ischemia,68,69 targeting this miR-92a may hold promise for a range of cardiovascular-relevant disease states.

**MiR-126**

MiR-126 is among the most abundantly expressed miRNAs in ECs and has been implicated in regulating both inflammation and angiogenesis in a flow-dependent manner. MiR-126 was initially described in vitro to bind to the 3′-UTR of vascular adhesion molecule-1 to limit leukocyte adhesion.70 Subsequent studies revealed that miR-126-deficient mice exhibit impaired vascular integrity and defects in EC proliferation and angiogenesis.71 Indeed, miR-126 may be induced by KLF2 to control flow-dependent angiogenesis.72 In the context of atherosclerosis, Zernecke et al73 demonstrated that miR-126 was the most abundant miRNA expressed in EC-derived apoptotic bodies where it induced CXCL12 expression by targeting KGF16, a negative regulator of stromal cell-derived factor 1/C-X-C chemokine receptor 4 (SDF-1/CXCR4) signaling and progenitor cell mobilization. Consistent with this pathway, intravenous delivery of endothelial apoptotic bodies mobilized progenitor cells in the circulation and enhanced their incorporation into aortic plaques, an effect that suppressed athero-protective progression in a miR-126–dependent manner. Within the vascular endothelium, Schober et al74 elegantly identified a functional role for the passenger strand, miR-126-5p, as a flow-responsive miRNA that is suppressed by d-flow, an effect that facilitates lesion formation through induction of a negative regulator of EC proliferation termed delta-like 1 homolog. Systemic delivery of miR-126-5p mimics rescued EC proliferation at vulnerable sites and inhibited lesion progression.74 Because the proinflammatory transcription factors Ets-1 and Ets-2 also induce miR-126 expression,75 the miR-126 duplex may mechanistically serve to limit proinflammatory factors such as TNF-α and angiotensin-II in a negative feedback manner in the vascular endothelium. However, ECs exposed to l-flow–induced KLF2-dependent expression of pri–miR-126 but not of miR-126-3p. Moreover, miR-126-5p expression, but not miR-126-3p expression, was lower at predilection sites of ApoE−/− aortas. In addition, delivery of miR-126-5p antago-miRs, but not of miR-126-3p antago-miRs, increased lesion formation after EC denudation in ApoE−/− mice, suggesting that miR-126-3p may not be implicated in flow-responsive vascular protection. Finally, athero-protective l-flow increases the release of miR-126 bound to Argonate2 into extracellular microvesicles that serves as a mediator to increase vascular smooth muscle cell turnover by targeting genes (eg, FOXO3, B-cell lymphoma 6, and insulin receptor substrate 1) implicated in maintaining an athero-protective VSMC contractile phenotype.76 In this study, miR-126 deficiency inhibited neointimal formation of mouse carotid arteries induced by cessation of blood flow, an effect rescued by miR-126 mimics or by conditioned media from static EC monolayers. These latter findings raise the possibility that despite its athero-protective in ECs, miR-126 may thin SMCs of the fibrous plaque leading to destabilization.

Future long-term studies will be required to assess the relative role of the miR-126-5p/miR-126-3p duplex in response to a range of important biochemical and biomechanical stimuli and in different phases of atherosclerosis.

**MiR-712/MiR-205**

Although miRNA biogenesis typically uses the canonical Drosha/DGCR8 and Dicer miRNA pathway, accumulating studies also highlight an important role for noncanonical pathways for miRNA maturation.77,78 miR-712 (human homologue miR-205) was identified as a d-flow responsive miRNA derived from noncanonical prerribosomal RNA (using the RN455 gene).79 Functionally, d-flow–induced miR-712 targets tissue inhibitor of metalloproteinase-3, an effect that increases matrix metalloproteinases and a disintegrin and MMPs to stimulate proinflammatory EC responses. Indeed, neutralization of miR-712 derepresses TIMP3 expression and ameliorates atherosclerotic progression in mice.79 Additional studies will be required to determine whether the in vivo neutralization of miR-712 directly affects other relevant cell types, such as immune subsets and vascular smooth muscle cells.

**MiR-143/MiR-145**

An emerging paradigm in cell-to-cell communication is the ability of miRNAs to be transferred from one cell to another within tissues. For example, in response to l-flow or KLF2 overexpression in ECs, extracellular microvesicles containing miR-143 and miR-145 are released that confer athero-protective properties in adjacent VSMCs. Intravenous delivery of these extracellular vesicles also blocked atherosclerotic lesion progression in a miR-143/145–dependent manner.80 Interestingly, miR-143/miR-145, which are expressed higher in VSMCs compared to ECs under basal conditions in vitro, may also participate in VSMC to EC communication via intercellular tubes called tunneling nanotubes in vitro.81 In support of this VSMC to EC passage, SMC-specific deletion of the miR-143/miR-145 cluster in mice effectively blocked the induction of miR-143/miR-145 expression in coronary artery endothelial cells in response to transaortic constriction–induced pressure overload, an effect that may be mediated by the activation of the transforming growth factor-β signaling pathway and the miR-143/miR-145 targets hexokinase II and integrin-β8.81 Collectively, although it remains to be determined whether bidirectional extracellular miRNA passage occurs between SMC and EC under athero-protective conditions, these findings raise the provocative question of skewed, preferential cell-to-cell miRNA shifts that may emerge under atherosclerotic progression or regression, or in response to pharmacological therapies.

**Others: MiR-10a, MiR-663, MiR-155, and MiR-30-5p**

Several other mechanosensitive miRNAs, such as miR-10a, miR-663, and miR-155, have been identified using a variety of profiling approaches. However, the functional role of these 3 miRNAs in regulating experimental atherosclerosis in vivo has not yet been validated (miR-10a and miR-663) or remains unclear (miR-155). Nonetheless, they may figure prominently at predilection sites in the macrovasculature. For example, miRNA microarray profiling of ECs from the
inner aortic arch of pig, an atherosusceptible region, and ECs from the descending thoracic aorta revealed that miR-10a expression was significantly reduced in the atherosusceptible regions. Mechanistically, miR-10a targets the 3′-UTRs of MAPK kinase kinase 7 and the β-transducin repeat-containing gene, 2 key regulators of IkBα degradation. Indeed, miR-10a overexpression inhibits canonical NF-κB signaling in ECs in vitro. Therapeutic manipulation of miR-10a in atherosclerotic-prone mice will be required to assess its relative contribution to EC function at predilection sites and lesion pathogenesis. Because miR-10a’s family member, miR-10b, which may also bind to similar consensus sites in target genes, has been implicated in promoting tumor invasion and metastasis, delivery of miR-10 mimetics may require close scrutiny for therapeutic gain. Another miRNA, miR-663, was identified by 2 groups as a d-flow–induced miRNA in ECs. Interestingly, human miR-663, such as miR-712, may also be derived from the same ribosomal RNA gene, RN45S. Because the XRN1 exonuclease can rapidly degrade the spacer regions from where this rRNA is derived, Son et al examined whether silencing XRN1 may affect miR-663 and miR-712 expression. Indeed, d-flow reduced XRN1 expression in predilection regions in the mouse carotid and aortic arch, and XRN1 deficiency in ECs in vitro significantly increased both miR-663 and miR-712 expression, suggesting another level of regulation and therapeutic modulation of atypical mechanosensitive miRNAs in the vascular endothelium. Finally, miR-155 is increased by d-flow in ECs and in the thoracic aorta when compared with the lower aortic arch. Mechanistic studies indicate that miR-155 may bind to both anti-inflammatory targets (eg, endothelial nitric oxide synthase) and proinflammatory targets (eg, myosin light chain kinase, RhoA, SOCS-1, and Bcl6).74,84–86 Studies examining the role for miR-155 in experimental atherosclerosis in mice highlight both pro- and antiatherosclerosis effects depending on the context. For example, LDLR−/− mice harboring bone marrow with miR-155 deficiency exhibited increased atherosclerosis with reduced plaque stability. In contrast, miR-155 deficiency in macrophages reduced atherosclerotic plaque size in ApoE−/− mice, an effect thought to be mediated by miR-155’s ability to target B-cell lymphoma 6 and, in turn, reduced C-C ligand 2 (CCL2)-mediated macrophage recruitment. Moreover, miR-155 delivery in vivo reduced atherosclerotic lesion formation, an effect that may be mediated by targeting MAP3K10. Because miR-155 also targets myosin light chain kinase in endothelial cells, and myosin light chain kinase deficiency in ApoE−/− mice reduces atherosclerosis by improving endothelial barrier dysfunction and monocyte migration, EC–derived miR-155 may be viewed as a potentially protective miRNA in the vessel wall. In line with this hypothesis, miR-155 expression is significantly higher in the thoracic aorta, an area associated with unidirectional shear stress, than in the lower curvature of the aortic arch, a region associated with low shear stress. These findings raise nuanced questions for miR-155 in vascular inflammation, and additional studies will be required to define the EC- and macrophage-specific roles of miR-155 in atherogenesis. Finally, l-flow shear stress or KLF2 overexpression in ECs induce members of the miR-30-5p family that, in turn, decrease anti-inflammatory markers such as vascular adhesion molecule-1 and intracellular adhesion molecule-1 by targeting angiopoietin-2. However, a role for miR-30-5p family members in regulating endothelial inflammation and atherosclerosis in mice will require future investigation.

MiRNAs Regulating Leukocyte Recruitment and Activation in Atherosclerosis

Immune responses critically shape atherogenesis. One of the earliest pathogenic events in atherosclerosis is the recruitment of monocytes from the circulation to the artery wall in areas of endothelial dysfunction and lipoprotein retention. On differentiation into macrophages, these cells play central roles in the pathophysiology of atherosclerosis by maintaining lipid homeostasis in the vessel wall and secreting inflammation-promoting mediators that act on both immune and nonimmune cell types in the artery wall. Lipoprotein uptake by macrophages in the nascent plaque results in the formation of lipid-laden macrophage foam cells that are hallmarks of atherosclerosis. For reasons that are poorly understood, these macrophage foam cells persist in the artery wall, setting off a maladaptive immune response that promotes the formation of plaques. These macrophages are a source of inflammatory mediators, including cytokines and chemokines, that mediate the recruitment and activation of other immune cells, thereby chronically sustaining the inflammation that fuels plaque progression. MiRNAs can impact each of these key macrophage processes to influence the progression of atherosclerosis.

Macrophage cholesterol homeostasis is maintained by the balance between cholesterol uptake, endogenous synthesis, esterification/hydrolysis, and efflux. Many miRNAs have been implicated in macrophage cholesterol metabolism. miR-27a/b, discussed above with regard to lipoprotein homeostasis, can regulate macrophage cholesterol homeostasis by targeting genes involved in cholesterol esterification (ACAT1), uptake (LDL and CD36), and efflux (ABCA1). miR-125a-5p and miR-146a decrease lipid uptake and cytokine release in oxidized LDL–stimulated macrophages, in part, by targeting the genes oxysterol binding protein-like 9 and TLR4, respectively. Addition of miR-155 may also regulate macrophage foam cell formation by targeting the transcriptional repressor HMG box-transcriptional protein 1, which negatively regulates macrophage inhibitory factor, a protein known to increase the uptake of oxidized LDL by macrophages. Furthermore, numerous miRNAs have now been identified that promote foam cell formation by inhibiting macrophage cholesterol efflux via ABCA1, including miR-26, miR-33, miR-106, miR-144, miR-128-1, miR-130b, miR-148a, miR-301b, miR-302a, and miR-758. This high degree of miRNA targeting of ABCA1 points to the need for careful fine-tuning of macrophage cholesterol efflux to maintain cholesterol homeostasis.

In response to microenvironmental signals, macrophages can initiate different activation programs, including the classical proinflammatory phenotype (also called M1) and the alternatively activated M2 phenotype associated with an anti-inflammatory profile. Atherosclerosis progression is
associated with the predominance of an M1 macrophage phenotype in the plaque, whereas plaques undergoing regression are enriched in M2 macrophages. A growing list of miRNAs is implicated in regulating the balance between the M1 and M2 phenotypes, including miR-let7a, miR-19a, miR-21, miR-27a, miR-33, miR-124, miR-125a, miR-146a, miR-155, miR-214, and miR-223. However, few of these have been investigated in the context of atherosclerosis. Of note, miR-33, which plays a central role in regulating cholesterol efflux, also regulates macrophage cellular metabolism to alter the cell’s inflammatory phenotype. miR-33 reduces fatty acid oxidation, the metabolic program that fuels M2 macrophages, and promotes aerobic glycolysis, which in turn sustains the inflammatory M1-like macrophage phenotype. Inhibition of miR-33 metabolically reprograms plaque macrophages to the M2 phenotype involved in resolving inflammation and tissue repair, which in turn promotes the accumulation of atheroprotective T-regulatory cells. miR-155, which as described above has a controversial role in atherosclerosis, can also reprogram macrophages from the M2 to M1 phenotype, and thus may play a role in the accumulation of M1 macrophages. miR-155 expression is significantly higher in CD14+ monocytes from patients with CAD than from healthy controls and is induced by oxidized forms of LDL in macrophages. miR-155 acts to repress negative regulators of inflammatory cytokine signaling, such as SOCS1, Src homology 2 domain-containing inositol-5-phosphatase-1, or B-cell lymphoma 6, and thereby promoting the release of proinflammatory mediators. Conversely, miR-223, which regulates lipid metabolism-related genes in the liver, can suppress M1 proinflammatory pathways and enhance alternative activation, in part, by targeting Pknox1. Finally, miR-27a, which also plays a role in macrophage foam cell formation, can promote markers of M2 macrophages (eg, CD206 and DC-SIGN) and secretion of IL-10.

Other miRNAs have been implicated in enhancing or reducing macrophage responses to inflammatory stimuli. For example, miR-147 and miR-21 attenuate TLR-associated signaling events in macrophages to limit inflammation. Likewise, miR-146a/b is induced in macrophages in an NF-kB–dependent manner and are involved in inflammation resolution by limiting Toll-like receptor and cytokine signaling. Recently, the expression of miR-146a was shown to be induced in macrophages by apoE, a protein with antiatherosclerotic properties, and to suppress macrophage inflammatory responses in vitro and in vivo. Furthermore, the transcription factor KLF2, whose expression in macrophages protects from atherosclerosis, downregulates expression of proatherosclerotic chemokines (eg, CCL2 and C-X-C ligand 1 [CXCL1]) by increasing expression of miR-124a and miR-150. During early atherogenesis, one of the most prominently induced miRNAs in lesional macrophages is miR-342-5p. This miRNA enhances the production of macrophage inflammatory mediators such as iNOS and IL-6 by suppressing Akt1-mediated suppression of miR-155. Accordingly, inhibition of miR-342-5p in Apoe−/− mice reduces atherosclerosis progression.

Other immune cells, such as DCs and T cells, also participate in atherogenesis and the regulation of plaque inflammation. By sensing and presenting antigens in the plaque, DCs are positioned at the crossroad of innate and adaptive immune responses.

Furthermore, T-cell (Th1, Th2, Th17, and Treg) and B-cell subpopulations can modulate atherosclerosis development. Thus, miRNAs that regulate immune cell differentiation and function would be expected to have wide-ranging effects on plaque evolution. An atlas of miRNA expression patterns in human T- and B-cell subsets was recently completed, and their roles in regulating T- and B-cell differentiation, activation, and function were recently reviewed. However to date, miRNA regulation of these immune cell subsets in atherosclerosis has been underexplored when compared with macrophages.

Notably, several miRNAs shown to regulate atherogenic processes in macrophages have also been implicated in DC function. For example, miR-155 is required for efficient DC maturation by targeting the transcription factor c-Fos, and its expression increases TLR/IL-1 and type I interferon signaling pathways in human monocyte-derived DCs required to promote antigen-specific T-cell activation. Furthermore, like its role in macrophages, miR-146a reduces TLR signaling and cytokine production in DCs, thereby regulating DC activation. Moreover, miR-148/miR-152 inhibits the production of proinflammatory cytokines (eg, IL-12, IL-6, and TNF-α) by targeting calcium/calmodulin-dependent protein kinase II alpha (CaMKIIα), consequently reducing DC-triggered antigen-specific T-cell proliferation. By regulating activation of DCs and their interactions with T and B cells in plaques, these miRNAs are likely to impact the inflammatory milieu of the plaque and atherosclerosis progression.

**MiRNAs Implicated in Vascular Smooth Muscle Function and Atherosclerosis**

VSMCs contribute to the maintenance of vascular wall function by assuming a differentiated, contractile phenotype. In response to vascular injury, VSMCs undergo a switch to a synthetic phenotype, an effect that induces signals that promote migration, proliferation, and inflammation. Several miRNAs have been implicated in regulating important VSMC nodal regulators such as the transcription factors (serum-response factor [eg, serum response factor/KLF4], coactivators [eg, myocardin], transforming growth factor-β signaling effectors [eg, Smads], or cytokines/growth factors [eg, platelet-derived growth factor (PDGF)]). Although the traditional view of VSMCs in vascular injury states is that they dedifferentiate to assume a synthetic, proliferative state, recent studies have broadened this concept to suggest that VSMCs may adopt a reprogrammed transdifferentiated macrophage phenotype. Although the role of miRNAs has emerged as important players in the former, their role in VSMC-to-macrophage transdifferentiation in vivo remains relatively unexplored. We summarize below major miRNA regulators implicated in VSMC and atherosclerotic lesion formation (Figure 3).

**MiR-143/MiR-145**

The miRNAs miR-143 and miR-145 are co-transcribed as a single primary-miR transcript because of their close proximity and are among the highest expressed miRNAs in VSMCs and
Because upstream control of miR-143/miR-145 expression is governed, in part, by serum response factor, Nkx2.5, and myocardin, miR-143/miR-145 may contribute to fine-tuning a SMC-specific transcriptional program important in regulating the contractile VSMC state.

**MiR-221/MiR-222**

In contrast to miR-143/miR-145, the miRNAs, miR-221 and miR-222, are increased in response to injury in neointimal lesions. In vitro studies have implicated miR-221/miR-222 in regulating PDGF-mediated VSMC proliferation. PDGF induced miR-221/miR-222 in VSMCs, an effect leading to reduced expression of its target genes c-Kit and p27Kip1 and decreased SMC-specific contractile gene expression. Using miR-221/miR-222 knockdown approaches, in vivo studies demonstrated that miR-221 and miR-222 deficiency reduced VSMC proliferation and neointimal lesion formation after mechanical injury by targeting p27(Kip1) and p57(Kip2). In human atherosclerotic lesions, reduced expression of miR-221 and miR-222 was noted in the shoulder of plaques from patients undergoing carotid endarterectomy caused by an acute neurological event occurring within 5 days of the carotid endarterectomy. Although this study demonstrated a compelling association of reduced miR-221/miR-222 with unstable lesions, it also revealed that the target gene p27(Kip1) was significantly increased. Interestingly, miR-222 expression in isolated human ECs decreased from early lesions to advanced plaques. Collectively, these studies provide accumulating evidence that miR-221/miR-222 may play a destabilizing role in atherosclerotic lesions.
Although miR-21 has been implicated in promoting VSMC proliferation in response to a range of vascular mechanical injury models, its role remains to be defined in atherosclerotic lesion formation. Neutralization of miR-21 reduced neointimal lesion formation in response to mechanical balloon injury. In keeping with its role in regulating VSMC contractile phenotype, miR-21 expression increased significantly in isolated dedifferentiated VSMCs when compared with mature differentiated VSMCs. Consistent with these findings for miR-21 in rodent vascular injury, delivery of an anti–miR-21-coated stent into balloon-injured human internal mammary arteries using a humanized rat model also revealed protective effects on neointimal lesion formation. Mechanistically, miR-21’s proliferative properties may be because of its ability to target phosphatase and tensin homolog in VSMCs and indirectly increase the antiapoptotic gene Bcl-2. Furthermore, miR-21 mediates the induction of the VSMC contractile phenotype by transforming growth factor-β and BMP signaling in a unique post-transcriptional processing step implicating that Smad proteins may control DROSHA-regulated maturation of miRNAs. Additional studies will be required to assess whether the antiproliferative effects of miR-21 neutralization also reduce atherosclerotic progression in nonmechanically injured vessels.

MiRNAs as Diagnostic Markers of Atherosclerotic Disease Severity

Accumulating studies implicate miRNAs as potential diagnostic or prognostic markers in a range of disease states. Because circulating miRNAs can be detected in peripheral blood, saliva, and urine, their expression may be harbingers of various stages of CAD from subclinical atherosclerotic disease to acute coronary syndromes. Herein, we summarize the profiling of several studies linking specific miRNAs to atherosclerotic disease burden as primarily diagnostic markers. Additional studies will be required to further define these miRNAs for their prognostic significance in CAD.

Stable CAD

One of the earliest studies that analyzed miRNAs from plasma of 8 stable CAD subjects and healthy controls examined candidate miRNAs based on their putative cell-selective expression patterns. In the CAD group, expression of EC-enriched miRNAs (miR-126, miR-17, and miR-92a), VSMC-enriched miRNAs (miR-145), and inflammatory cell enriched miRNAs (miR-155) were all reduced. In contrast, cardiomyocyte-enriched miRNAs (miR-133 and miR-208a) were increased. Other groups have identified reduced expression of miRNAs (miR-19a, miR-484, miR-155, miR-222, miR-145, miR-29a, miR-378, miR-342, miR-181d, miR-150, miR-30e-5p) from whole blood of patients with angiographically defined stable CAD (at least 1 epicardial vessel with >50% stenosis) compared with healthy subjects. Interestingly, when this cassette of 11 miRNAs were compared with another group of subjects with at least 2 cardiac risk factors, but without angiographically defined CAD, there were no differences observed, suggesting that this cassette of miRNAs may also be associated with subclinical atherosclerosis. Surprisingly, reduced expression of 9 miRNAs of this cassette was also associated with reduced expression in CAD or at-risk CAD patients taking angiotensin-converting enzyme inhibitors or angiotensin receptor blocker antagonists compared with CAD/at-risk CAD patients not taking angiotensin-converting enzyme inhibitor/angiotensin receptor blockers. No associations were observed in this same cohort for treatment of statins versus no statins. Another study by Zhu et al identified miR-155 expression in peripheral blood mononuclear cells (PBMCs) or plasma in patients with increasing severity of coronary syndrome and found that miR-155 was lower in patients with unstable angina (UA) or acute myocardial infarction (AMI) than in patients with chest pain syndrome. MiR-155 expression was further reduced in patients with 2 or 3 diseased vessels when compared with patients with 0 or 1 diseased vessels. However, miR-155 also negatively correlated with a range of traditional cardiac risk factors. In addition, D’Alessandra et al identified increased expression of miR-337-5p, miR-433, and miR-485-3p of 178 miRNAs profiled in patients with CAD. Specifically, miR-1, miR-122, miR-126, miR-133a/miR-133b, miR-199a, miR-485-3p, and miR-377-5p were increased in subjects with stable angina (SA) or UA. Using only miR-1, miR-126, and miR-485-3p, this classified correctly subjects with SA compared with controls, whereas miR-1, miR-126, and miR-133a classified correctly with UA versus controls in >87% of cases. However, no combination could correctly discriminate between UA and SA, suggesting that these markers likely reflect atherosclerotic burden present in both UA and SA patients. Moreover, using PBMCs, a higher ratio of miR-135a:miR-147 was used to help discriminate patients with or without CAD. In addition, reduced expression of miR-181a in PBMCs of obese patients is associated with prevalence of CAD. In contrast, increased expression of miR-146a or miR-146b in patients with CAD was associated with an increased risk of atherosclerosis. Interestingly, the rs2910164 polymorphism in the miR-146a locus is associated with an increased risk of CAD in a Chinese Han population. Finally, miR-146a expression was significantly increased in a Japanese cohort of 66 patients with CAD when compared with patients with no CAD. Furthermore, 12 months of statin therapy with an angiotensin-converting enzyme inhibitor or angiotensin receptor blocker indicated that miR-146a/b and its regulated targets (IRAK, TNF receptor–associated factor 6, and TLR4) were significantly decreased.

Unstable Angina

Although the diagnosis of AMI can be facilitated using myocardial injury biomarkers such as cardiac troponin (cTn) I or T, the diagnosis of UA in patients with normal troponin values can be elusive. Because UA is associated with a higher risk of cardiovascular events, identification of a set of ischemic biomarkers may be useful for diagnosis, risk stratification, and therapeutic decision-making. Only a few miRNAs have been uniquely linked to UA when compared with stable CAD. However, these findings have not been replicated in larger clinical data sets. For example, the expression of miR-134, miR-198, and miR-370 from PBMCs was enriched higher in 25 patients with UA than in 25 with SA. However, these findings were not verified in a separate cohort of 19 UA and 34
SA patients.\textsuperscript{139} When the comparator group was noncoronary chest pain patients (instead of SA patients), a different cassette of miRNAs (miR-132, miR-150, and miR-186) was found to be increased in UA patients.\textsuperscript{145} Collectively, these findings suggest that rigorous phenotyping of patients with UA when compared with other distinct patient subgroups (eg, AMI, SA, and noncoronary chest pain) will be required for appropriate discrimination of this unique and important UA group with elevated cardiac risk.

**Acute Myocardial Infarction**

Although cTn is used to assist with the diagnosis of AMI, it may serve as a poor discriminator between AMI subtypes.\textsuperscript{144} In particular, additional biomarkers are desperately needed to further define type I MI (ischemic myocardial necrosis caused by atherosclerotic plaque rupture) versus type II (ischemic myocardial necrosis not caused by atherosclerotic plaque rupture, but typically because of supply/demand mismatch).\textsuperscript{144} Emerging studies indicate that different miRNAs may be released into the peripheral circulation in response to distinct pathophysiological stimuli, suggesting that identification of a cassette of miRNAs may possess improved discriminatory power to diagnose MI subtype or possibly lead to an earlier diagnosis. For example, the cardiac-specific miRNA, miR-208b, is detected in circulation by 3 hours after AMI and may persist with an elevated expression >90 days.\textsuperscript{146,147} Several other groups validated the potential clinical usefulness of miR-208b as an early biomarker for AMI. Interestingly, miR-208 expression levels were increased in all (n=33) patients 4 hours post MI when compared with 85% for cTnI. When compared with other cardiac-enriched miRNAs (miR-1, miR-133a, and miR-499), the use of miR-208b conferred more favorable receiver operating characteristic curve with higher sensitivity and specificity to diagnose AMI than noncoronary heart disease patients.\textsuperscript{148} Similarly, miR-208b and miR-499 were significantly increased in AMI (n=32) when compared with controls (n=36) that correlated with plasma cTnT.\textsuperscript{149} However, in another study that used a larger number of patients with AMI (n=224), the diagnostic value for miR-208b (as well as miR-499 and miR-320a) in AMI was significantly lower than that of cTnI or cTnT.\textsuperscript{150}

Furthermore, although miR-208b and miR-499 expressions were increased higher in patients with ST-segment–elevation myocardial infarction (STEMI) than in those with non-STEMI and correlated with high-sensitivity cardiac troponin T (hs-cTnT) and creatine kinase-MB (CK-MB) in the plasma 1 hour after onset of chest pain, their diagnostic value was comparable with hs-cTnT.\textsuperscript{151} Nonetheless, in a more focused patient cohort of non-STEMI geriatric subjects (mean age, 82.6 years), Olivieri et al \textsuperscript{152} examined plasma levels of miR-1, miR-21, miR-133a, miR-208a, miR-423-5p, and miR-499-5p. Remarkably, miR-499-5p was equivalent to cTnT in discriminating non-STEMI patients when compared with healthy controls or those with acute congestive heart failure. Furthermore, the diagnostic accuracy of miR-499-5p was higher than either conventional or high-sensitivity-troponin T in discriminating non-STEMI and acute CHF (area under the curve, 0.86 for miR-499-5p versus cTnT area under the curve, 0.68 or high-sensitivity cTNT area under the curve, 0.70). Finally, the bicistronic miRNA cluster of miR-1/miR-133 has also been implicated in AMI.\textsuperscript{153–155} Despite detection of these 4 miRNAs, miR-208b, miR-499-5p, miR-1, and miR-133a, in the plasma after AMI, these cardiac-enriched miRNAs did not improve diagnostic accuracy of AMI when compared with cTnT.\textsuperscript{156} These findings may reflect the well-established ability of high-sensitivity troponins to be released into circulation after generalized myocardial injury.

Atherosclerotic-based biomarkers that may reflect AMI or increased predisposition to plaque rupture or erosion would help discriminate MI subtype. In keeping with this notion, noncardiomyocyte specific miRNAs may provide further refinement. For example, increased circulating levels of the miR-663 family member, miR-663b (a potential endothelial-enriched and flow-sensitive miRNA implicated in atherosclerosis [see Mechanosensitive EC miRNAs That Regulate Atherosclerosis section of this article] exhibited a high sensitivity (95%), specificity (90%), and accuracy (92.5%) to discriminate AMI (n=20 subjects) when compared with controls (n=20 subjects).\textsuperscript{157} Examination of different subtypes of ischemic injury may also be informative for the use of miRNA to assist in diagnostic discrimination of related disease conditions. For instance, plasma levels of miR-21-5p and miR-361-5p were significantly increased in patients with AMI (n=17), whereas miR-519e-5p was reduced with comparable diagnostic accuracy to cTnI. In contrast, these 3 miRNAs were all increased in patients with ischemic stroke (n=9) or pulmonary embolism (n=8), whereas decreased miR-519e-5p was only detected in AMI.\textsuperscript{158} Collectively, these findings indicate that miRNAs may be useful to discriminate AMI subtype and raise the possibility of incorporating miRNAs as a tool for linking pathophysiological events, prognosis, and stage-specific therapy.\textsuperscript{159}

Taken together, these findings indicate that miRNAs may be associated with subclinical atherosclerosis. Furthermore, caution should be required for interpretation of similar miRNA profiling studies based on baseline characteristics of medical treatment.

**Therapeutic Opportunities and Challenges**

Nucleic acid–based therapies represent a new frontier in the treatment of human diseases. Several classes of RNA therapeutics are currently under clinical development, including antisense oligonucleotide, siRNA and miRNA mimetics and inhibitors. The field of RNA therapeutics saw a huge leap forward with the recent Food and Drug Administration approval of the first antisense oligonucleotide drug, Mipomersen, an antisense oligonucleotide drug targeting apoB to treat homozygous familial hypercholesterolemia.\textsuperscript{160–163} This will likely pave the way for other oligonucleotide-based drugs, including miRNA replacement and inhibitor therapies. Notably, pharmacological targeting of miRNAs in disease moves beyond the one-drug-one-target mode of treatment offered by siRNAs, and this has both benefits and drawbacks. The ability of miRNAs to target gene networks not only provides a unique approach for the treatment of disease by modulating gene pathways but also opens the door to potential unwanted effects on additional target genes. Yet, this type of approach...
may prove to be more effective at improving complex diseases like atherosclerosis, which involve many pathways and would benefit from a multimodal therapeutic.

Antisense oligonucleotides offer the ability to silence miRNAs to fine-tune specific pathways or to reduce miRNAs expression dysregulated by disease. Several approaches have been used to chemically modify anti-miR oligonucleotides to enhance target affinity, stability, and tissue uptake. These include (1) locked nucleic acids which have high binding efficiencies and improved stability with the addition of a methylene link between the 2′-oxygen and the 4′-carbon resulting in a locked position and reducing the flexibility of the ribose ring, (2) ribose 2′-OH group modifications such as 2′methoxyethyl and 2′4′-constrained 2′O-ethyl, and (3) phosphorothioate modification. Careful evaluation of these chemical modifications will be required to minimize potential side effects and unanticipated toxicities. For example, phosphorothioate modification may facilitate nucleotide-based drugs to bind and activate platelets eliciting thrombus formation in response to carotid injury, pulmonary thromboembolism, and mesenteric artery injury in mice. Unlike their double-stranded counterparts, single-stranded anti-miR oligonucleotides can be formulated in saline for subcutaneous or intravenous delivery and do not require lipid-based delivery systems. On systemic delivery, these compounds rapidly leave the plasma and are taken up by multiple tissues, most prominently liver, spleen, kidney, adipose tissue, and bone marrow. Once taken up by cells, the anti-miR forms a stable, high-affinity bond with the miRNA reducing the availability of the endogenous miRNA for binding to the 3′-UTR of the miRNA target. Preclinical studies in nonhuman primates using naked anti-miR oligonucleotides have shown promise, particularly in targeting miRNA expression in the liver (eg, miR-122 and miR-33). Cholesterol analogs have been added to anti-miRs in an attempt increase cellular uptake, and this promotes their incorporation into LDL and HDL. Another approach for miRNA inhibition involves the use of miRNA sponges or decoy transcripts, which act as competitive inhibitors of the miRNA of interest. MiRNA sponges contain multiple binding sites that are complementary to the seed sequence of a miRNA of interest, which mops up the miRNA and inhibits its function. MiRNA sponges can be delivered using viral vectors, and their expression can be made to be inducible in a specific cell type or developmental stage by using specific promoters. Notably, when vectors containing miRNA sponges were transfected into cells, miRNA target genes were derepressed as when anti-miR oligonucleotides were used.

MiRNA mimic therapy using synthetic miRNAs (miRNA mimics) offers the ability to reconstitute a miRNA that is downregulated during disease or to decrease gene pathways involved in disease pathology. For example, patients with CAD exhibit decreased plasma levels of miR-181b, which is also expressed in ECs, and miRNA mimics could be used to restore its expression. The delivery of therapeutic miRNA molecules in vivo faces many of the same challenges as siRNAs because of their double-stranded nature. Drug delivery vehicles such as liposomes, polymeric micelles, and lipoprotein-based drug carriers are being developed to deliver these oligonucleotides to cells. Notably, miRNAs were recently shown to be associated with endogenous HDL particles and to deliver their miRNA cargo to other cells, offering the potential to use HDL infusion as a miRNA delivery vehicle. Some of the current challenges associated with miRNA replacement technology include the ability to target miRNAs to a specific tissue, and the potential requirement of multiple doses of a miRNA mimic to achieve sustained target repression. Viral vectors can be used as gene delivery carriers for miRNAs, including short hairpin RNAs that can be processed in the target cell into the mature miRNA, a approach that has been used in multiple preclinical studies. However, viral delivery systems will require careful scrutiny for clinical use.

Although miRNA mimics and oligonucleotide inhibitors are taken up more efficiently in the liver, we and others have demonstrated success at penetrating the vascular endothelium of the vessel wall and PBMCs. Because only a minority of miRNAs are tissue specific, delivery of miRNA mimics or inhibitors in a targeted cell- or tissue-specific rather than a systemic manner may represent a novel opportunity to prevent the development or progression of atherosclerosis. Recent approaches to tailor miRNA delivery to specific tissues include incorporating target sites for tissue-specific miRNAs, such as liver-specific miR-122 and miR-192, which would silence the vector in the liver, but allow it to be functional in other tissues.

Many miRNA-based therapeutics are currently in preclinical development, and 2 have reached clinical trials. The first is a locked nucleic acid directed against miR-122 (Miravirsen), which targets hepatitis C virus RNA. Studies in nonhuman primates showed that miR-122 inhibition resulted in lasting suppression of hepatitis C virus viremia with no evidence of viral resistance or side effects. In a human phase 2 study, Miravirsen demonstrated dose-dependent antiviral activity when given as a 4-week monotherapy that was maintained for >4 weeks after the end of therapy. Notably, hepatitis C virus RNAs in 4 of 9 patients treated with the highest doses of Miravirsen became undetectable during the study, demonstrating the potential of anti-miR therapeutics. The second miRNA therapeutic in clinical trial is a double-stranded miRNA mimic of miR-34, which acts as a tumor suppressor by inhibiting multiple oncogenic pathways and stimulating antitumor immune responses. MRX34 is a miR-34 mimic encapsulated in a liposomal nanoparticle formulation that is being tested in patients in a range of advanced solid tumors and hematologic malignancies. The results of these first clinical trials of a miRNA mimic and inhibitor are eagerly awaited.

During the past several decades, significant progress has been achieved to treat atherosclerosis. Most notably, 3-hydroxy-3-methyl-glutaryl-coenzyme A reductase inhibitors (statins) have been widely used to treat patients in the primary and secondary prevention of CAD. Although statins effectively reduce LDL levels and cardiovascular events, a considerable residual burden of CAD remains even in patients treated with statins. Novel complementary therapeutic approaches will likely be necessary for treating disease states such as atherosclerosis involving complex signaling networks.
In this regard, because miRNAs target multiple genes often in the same regulatory network, miRNAs may have tremendous effects on biological pathways, cell function, and homeostasis in the vessel wall, liver, and periphery. Delivery of a cassette of miRNA mimics or inhibitors may thereby offer an attractive therapeutic approach to facilitate fine-tuning specific stages of atherosclerotic disease and in the management of its complications.

**Sources of Funding**

This work was supported by the National Institutes of Health (HL115141, HL117994, and GM115605 to M.W. Feinberg and HL108182 and HL119047 to K.J. Moore), the Arthur K. Watson Charitable Trust (to M.W. Feinberg), and the Dr. Ralph & Marian Falk Medical Research Trust (to M.W. Feinberg).

**Disclosures**

None.

**References**


MicroRNA Regulation of Atherosclerosis


MicroRNA Regulation of Atherosclerosis

Feinberg and Moore


MicroRNA Regulation of Atherosclerosis
Mark W. Feinberg and Kathryn J. Moore

Circ Res. 2016;118:703-720
doi: 10.1161/CIRCRESAHA.115.306300
Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2016 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/118/4/703

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation Research can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation Research is online at:
http://circres.ahajournals.org/subscriptions/