Inhibition of MicroRNA-29 Enhances Elastin Levels in Cells Haploinsufficient for Elastin and in Bioengineered Vessels—Brief Report

Pei Zhang, Angela Huang, Jacopo Ferruzzi, Robert P. Mecham, Barry C. Starcher, George Tellides, Jay D. Humphrey, Frank J. Giordano, Laura E. Niklason, William C. Sessa

Objective—The goal of this study was to determine whether antagonizing microRNA (miR)-29 enhances elastin (ELN) levels in cells and tissues lacking ELN.

Methods and Results—miR-29 mimics reduced ELN levels in fibroblasts and smooth muscle cells, whereas miR-29 inhibition increased ELN levels. Antagonism of miR-29 also increased ELN levels in cells from patients haploinsufficient for ELN and in bioengineered human vessels.

Conclusion—miR-29 antagonism may promote increased ELN levels during conditions of ELN deficiencies. (Arterioscler Thromb Vasc Biol. 2012;32:756-759.)

Key Words: aneurysms ■ extracellular matrix ■ microRNA

Elastin (ELN) is a major component of the extracellular matrix in arteries that is essential for normal structural integrity and function. In humans, a single ELN gene is found on chromosome 7, and mutations in 1 allele can lead to several elastinopathies, including supravalvular aortic stenosis (SVAS) and a congenital narrowing of the ascending aorta or other vessels. SVAS is also a prominent component of Williams-Beuren syndrome (WBS), a frequent heterozygous deletion of a 1.5-Mb segment at chromosome 7q11.23 that includes ELN. Despite having 1 intact allele, the expression of ELN is less than 50% of normal in WBS, thus suggesting posttranscriptional modulation of the mRNA. In the past decade, microRNAs (miRNAs) have emerged as important regulators of gene expression robustness. miRNAs predominantly target the 3′-untranslated region of mRNAs, either destabilizing the mRNA transcript or interfering with its translation into protein. Previous work has shown that microRNA (miR)-29 mimics downregulate the expression of ELN, COL1A1, and COL3A1. Here, we show that inhibition of miR-29a can dramatically increase ELN expression in human cells and miR-29 inhibition upregulates ELN levels in cells from patients with ELN haploinsufficiencies and in bioengineered human blood vessels. Thus, antagonizing the actions of miR-29 may promote increased ELN levels during conditions of enhanced elastinolysis or deficiencies.

Materials and Methods

Cell Culture and miRNA Treatment

Human dermal fibroblasts, isolated from human foreskin or adult skin, were purchased from Coriell. WBS and age-matched normal human dermal fibroblasts were purchased from the National Institute of Child Health and Human Development Brain and Tissue Bank for Developmental Disorders (University of Maryland, Baltimore, MD). Human vascular smooth muscle (VSM) cells and SVAS pulmonary VSM cell were explanted by outgrowth as described. Cells were treated with miRIDIAN miR-29 mimic, hairpin inhibitors or corresponding controls (Dharmacon, Chicago, IL) at 60 nmol/L for 15
hours unless specified otherwise and then were grown in complete media for 48 hours before harvest for RNA or protein studies.

**Western Blot**

To measure tropoelastin expression in the media, cells were grown in 0.5% FBS Dulbecco’s modified Eagle’s medium for the final 24 hours and media proteins were precipitated by 10% trichloroacetic acid and resolved on 10% SDS-PAGE gels. To measure ELN protein associated with cell membrane, equal number of cells were lysed in 6 mol/L urea-containing sample loading buffer and loaded onto 10% SDS-PAGE. Western membranes were probed with a polyclonal antibody recognizing human ELN. Ponceau red staining (for media proteins) or β-actin levels (in cell lysates) were used to normalize protein loading.

**Culture and Analyses of Tissue Engineered Vessels**

Engineered arteries 1 mm in diameter and 3 cm in length were grown as previously described.9 Biaxial tests were performed using a custom device as previously described.10

**Desmosine and Hydroxyproline Analysis**

Desmosine and hydroxyproline, demonstrating cross-linked ELN and collagen respectively, were measured as described.11

**Results and Discussion**

Human dermal fibroblasts were transfected with miRNA mimics for miR-29a, -29b, and -29c or inhibitors (60 nmol/L of each) for 48 hours, and the levels of ELN mRNA were quantified using quantitative reverse transcription–polymerase chain reaction. Figure 1A shows that miR-29a, -29b, and -29c mimics significantly reduced ELN mRNA levels (to 2%–3% of control), whereas transfection with miR-29 inhibitors increased ELN mRNA levels (4–6-fold). Because of homology within the seed sequence of miR-29 family members,7 miR-29 inhibitors also reduced the levels of other miR-29 miRNAs (Figure I in the
Online-only Data Supplement). Computational analyses have predicted 3 seed sequences (38–44, 297–303, 310–316) for miR-29 binding in the 3’/H11032-untranslated region of the human ELN mRNA and these sequences are highly conserved among mammals. As seen in Figure 1B, treatment of human dermal fibroblasts with mimics reduced tropoelastin protein levels, whereas miR-29a, -29b, and -29c inhibitors increased levels compared with controls. To further test whether the miR-29 inhibitor increases major ELN isoforms, we used exon-specific primers to detect the existence of major ELN exons. As seen in Figure 1C, ELN miRNAs containing the known exons 3, 10, 13, 23, and 25 were upregulated to a similar degree with the miR-29a inhibitor.

Because all miR-29 members are abundantly present in the cell types in this study and can potentially regulate ELN levels, we performed additional experiments using only miR-29a. To test the specificity of the miR-29a inhibitor, it was titrated (0–100 nmol/L) in the presence or absence of 60 nmol/L of the miR-29a mimic. As seen in Figure 1D, miR-29a inhibitor (29a-I) dose dependently increases ELN mRNA levels. In the presence of miR-29a mimic (60 nmol/L), more miR-29a inhibitor was needed to achieve the same fold increase of ELN mRNA, but this difference disappeared between 30 and 100 nmol/L of the inhibitor. These data together with data in Figure 1A suggested that (1) the miR-29a inhibitor specifically antagonizes endogenous miR-29, as well as the miR-29a mimic, in a dose-dependent manner, and (2) the miR-29a inhibitor specifically protects ELN mRNA from endogenous miR-29a dependent decay.

Computer analyses also predict several other genes with miR-29 seed sequences, including COL1A1, COL3A1, and VEGF. Overexpression of miR-29 can decrease the activity of luciferase reporter plasmids containing 3’-untranslated regions of COL1A1, COL3A1, and ELN1, and inhibiting miR-29 in vivo can modestly upregulate COL1A1 and COL3A1 mRNA levels in the heart. Indeed, miR-29a mimic (60 nmol/L) reduced ELN, COL1A1, COL3A1, and VEGF-A (not shown) mRNA levels in human VSM (Figure 1E). In contrast, the miR-29a inhibitor enhanced ELN expression but did...
not significantly change the levels of COL1A or COL3A. Additional genes involved in matrix assembly, fibrillin-1 to -3, emilin1, lysyl oxidase 1, and lysyl oxidase-like 1/2, were also tested in VSM and fibroblasts, and miR-29a-I did not increase their expression levels (Figure II in the online-only Data Supplement). The miR-29a inhibitor increased soluble and cell-associated ELN levels in VSM (Figure 1F, left and right). This suggests that miR mimics may achieve concentrations that destabilize multiple transcripts having seed sequences, whereas miR inhibition may selectively upregulate physiological mRNA partners regulated by the endogenous miRNA levels.

Next, we tested the ability of miR-29a inhibitor to upregulate ELN expression in pulmonary VSM cells isolated from a patient with SVAS. A GTAT insertion in exon 9 of the ELN gene caused a frame shift and a premature stop codon in exon 10. Quantitative polymerase chain reaction experiments using primers recognizing ELN exon 18 showed that SVAS cells had low levels of ELN mRNA (~10% of normal VSM) but equal amounts of endogenous miR-29a compared with normal VSM (Figure IIIA, left, in the online-only Data Supplement). Transfection of SVAS cells with miR-29a inhibitor upregulated ELN expression 3.5-fold (Figure 2A). The expression of COL1A1 and COL3A1 mRNAs were moderately higher in SVAS compared with normal cells (0.68±0.24 versus 0.23±0.09 for COL1A1; 17.5±2.2 versus 9.6±4.6 for COL3A1), and miR-29a inhibitor (60 nmol/L) increased COL1A1 (1.7-fold) but not COL3A1 mRNA levels. miR-29a inhibition increased tropoelastin levels in SVAS cells dose dependently, and in contrast, miR-29 mimic decreased tropoelastin (Figure 2B).

Next, we examined whether miR-29 regulates ELN in dermal fibroblasts isolated from 2 donors with WBS. Comparative genomic hybridization verified that these cells had a typical ~1.5-Mb microdeletion at 7q11.23 encoding 25 genes, including ELN (Figure IV in the online-only Data Supplement). These ELN-haplodeficient cells expressed only 26% to 36% of ELN mRNA levels but comparable levels of miR-29a (Figure IIIA, right, and IIIB, left, in the online-only Data Supplement) compared with age-matched normal fibroblasts from the same bank. Treatment of WBS cells with miR-29 inhibitor upregulated ELN mRNA levels close to those seen in normal cells (Figure 2C and Figure IIIB, middle, in the online-only Data Supplement). In contrast, the levels of COL1A1 were comparable in WBS cells, and miR-29 inhibition increased COL1A1 levels. Western blot analysis showed ELN protein was increased by 40% in WBS cells 48 hours after miR-29 inhibitor treatment (Figure 2D).

Bioengineered human blood vessels are collagen replete but ELN deficient, and this paucity of ELN may compromise their mechanical properties. To examine whether miR-29a inhibition can enhance ELN levels and therefore improve vascular mechanics, polyglycolic acid scaffolds were seeded with early passage human VSM as described, and vessels were grown in a bioreactor for 6 weeks in the absence or presence of miR-29a inhibitor. As seen in Figure 2E (left), there was little ELN (via transmission electron microscopy) in the control vessels, whereas miR-29a inhibition increased the appearance of ELN “islands” (Figure 2E, right) and its detection by Western blotting (Figure 2F). This ELN was cross-linked as quantified by desmosine content (Figure 2G), and levels of hydroxyproline were comparable between the vessels (Figure 2H). The number of VSM in the vessels were not different between groups (143±437 versus 1797±453 4’,6-diamidino-2-phenylindole–positive/mm² for treated versus control vessels, respectively). Finally, biaxial mechanical tests revealed that miR-29a inhibition increased the distensibility of the bioengineered vessels at low pressures (Figure 2I); this response is similar to that of native vessels and suggests that the ELN conferred some structural benefit to the vessel.

Collectively, these data suggest that antagonizing miR-29 may increase functional ELN levels in conditions of ELN haploinsufficiency or during enhanced elastinolysis secondary to aneurysms, emphysema, or aging.

While this work was in review, a new study documented that anti-miR-29a reduces the extent of aneurysms.13

Statistical Analysis
Comparisons between 2 groups were made by unpaired Student t test. Statistical analyses were performed using Prism 4 software (GraphPad). Probability values were 2-tailed, and values <0.05 were considered statistically significant.

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Disclosures
None.

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Supplementary figure legends

Figure I: HDF cells were treated with miR-29a-b or-c inhibitor (90nM) and RNAs were isolated 48 h post-treatment. qPCR values of miR-29abc were normalized to 5S and then compared to those in a control group, which were set as 1. Data are mean ± SEM.

Figure II: VSM or human dermal fibroblast (HDF) were treated with control mimic/inhibitor, miR-29a mimic (29a-M) or miR-29a inhibitor (29a-I) and the levels of several genes implaicted in elastic matrix biogenesis assessed by qPCR. Data are mean ± SEM, n= 3.

Figure III: In A, the levels of miR-29a were measured in VSM, SVAS (left panel), or WBS (donor 1, right panel). In B, the levels of miR-29a (left panel), ELN (center panel) and COL1A1 (right panel) were measured in normal fibroblasts (NF) and an additional WBS donor.

Figure IV. Genotyping of two WBS donors.
Supplemental Figure III

A

B
Method and outcome of genetic sequence of WBS specimens:

A Chromosome Microarray Comparative Genomic Hybridization (CM-CGH) test was performed on a slide with an array of 180,000 60-mer oligonucleotide probes (Agilent 180K) in Yale cytogenetics laboratory.

WBS donor 1
The analysis of signal patterns revealed an XY male with a 822 Kb microduplication at 5q12.3 (chr5:65,489,514-66,312,145, involving genes SFRS12 and MAST4) and 1.413 Mb microdeletion at 7q11.23 (chr7:72,364,314-73,777,467.NCBI36/hg18, including genes from TRIM50 to GTF2I). The 7q11.23 microdeletion is pathognomonic for Williams-Beuren syndrome (OMIM #194050).

WBS donor 2
The analysis of signal patterns revealed an XY male with a 1.413 Mb microdeletion at 7q11.23 (chr7:72,364,314-73,777,467.NCBI36/hg18, including genes from TRIM50 to GTF2I). The 7q11.23 microdeletion is pathognomonic for Williams-Beuren syndrome (OMIM #194050).