The Tissue-Specific IncRNA Fendrr Is an Essential Regulator of Heart and Body Wall Development in the Mouse

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1016/j.devcel.2012.12.012">http://dx.doi.org/10.1016/j.devcel.2012.12.012</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>Elsevier</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
</tr>
<tr>
<td>Accessed</td>
<td>Fri Jun 23 23:11:08 EDT 2017</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/87007">http://hdl.handle.net/1721.1/87007</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.</td>
</tr>
<tr>
<td>Detailed Terms</td>
<td></td>
</tr>
</tbody>
</table>
The Tissue-Specific IncRNA Fendrr Is an Essential Regulator of Heart and Body Wall Development in the Mouse

Phillip Grote, Lars Wittler, David Hendrix, Frederic Koch, Sandra Währisch, Arica Beisaw, Karol Macura, Gaby Bläss, Manolis Kellis, Martin Werber, and Bernhard G. Herrmann

INTRODUCTION

Embryonic development commences with the formation of a group of pluripotent stem cells, which give rise to all cell types of the body. Development then proceeds through the coordinated action of cellular proliferation, patterning, lineage commitment, and differentiation, which are controlled by transcriptional regulators acting in a cell type-specific manner. The activity of genes encoding such regulatory proteins depends largely on the chromatin structure at their promoters and the associated regulatory elements. The histone-modifying Polycumb repressive complexes (PRC1/PRC2) and the Trithorax group/MLL protein complexes (TrxG/MLL) play pivotal roles in the control of chromatin structure and, hence, gene activity of a subset of developmentally important regulators (Schuettengruber et al., 2007). In particular, PRC2 catalyzes the methylation of histone H3 at lysine 27 (H3K27me3), which is repressive to gene activity, while the TrxG/MLL complex catalyzes the methylation of histone H3 at lysine 4 (H3K4me3), which acts as an activating mark (Margueron and Reinberg, 2011; Schuettengruber et al., 2011). Thus, PRC2 and TrxG/MLL have opposing activities, and both are essential for embryonic development (O’Carroll et al., 2001; Yu et al., 1995).

It has been shown that components of both the PRC2 and TrxG/MLL complexes are able to interact with long noncoding RNAs (lncRNAs) (Zhao et al., 2008, 2010; Wang et al., 2011). Recent reports have suggested that lncRNAs may target PRC2 or TrxG/MLL to specific genomic loci, and thus contribute to the histone modification status and activity level of target genes (Rinn et al., 2007; Khalil et al., 2009; Bertani et al., 2011; Guttman and Rinn, 2012). In vitro knockdown experiments have revealed the involvement of lncRNAs in gene regulatory networks controlling embryonic stem (ES) cell differentiation (Guttman and Rinn, 2012), and functional studies have provided evidence for the roles of several lncRNAs (Wang et al., 2011; Hu et al., 2011; Kretz et al., 2012; Rinn et al., 2007; Gupta et al., 2010; Ullitsky et al., 2011). For instance, the knockdown of HOTTIP by an RCAS-shRNA in the developing chick limb resulted in a shortening of the distal bony elements of the limb, and morpholin-mediated knockdown of megamin and cyrano in zebrafish embryos revealed important roles for these IncRNAs in organogenesis (Wang et al., 2011; Ullitsky et al., 2011). However, stringent genetic approaches for probing the role of IncRNAs in mouse embryogenesis using loss-of-function analyses have not yet been reported.

Here we have identified an IncRNA, which we have termed Fendrr, that is specifically expressed in nascent lateral plate mesoderm. We inactivated Fendrr by gene targeting in ES cells and show that Fendrr is essential for proper development of tissues derived from lateral mesoderm, specifically the heart and the body wall. We illustrate that Fendrr acts by modifying the chromatin signatures of genes involved in the formation and differentiation of the lateral mesoderm lineage through binding to both the PRC2 and TrxG/MLL complexes. Furthermore, we provide evidence that an oligonucleotide corresponding to part of the Fendrr transcript can bind to dsDNA in target promoters.

SUMMARY

The histone-modifying complexes PRC2 and TrxG/MLL play pivotal roles in determining the activation state of genes controlling pluripotency, lineage commitment, and cell differentiation. Long noncoding RNAs (lncRNAs) can bind to either complex, and some have been shown to act as modulators of PRC2 or TrxG/MLL activity. Here we show that the lateral mesoderm-specific IncRNA Fendrr is essential for proper heart and body wall development in the mouse. Embryos lacking Fendrr displayed upregulation of several transcription factors controlling lateral plate or cardiac mesoderm differentiation, accompanied by a drastic reduction in PRC2 occupancy along with decreased H3K27 trimethylation and/or an increase in H3K4 trimethylation at their promoters. Fendrr binds to both the PRC2 and TrxG/MLL complexes, suggesting that it acts as modulator of chromatin signatures that define gene activity. Thus, we identified an IncRNA that plays an essential role in the regulatory networks controlling the fate of lateral mesoderm derivatives.

http://dx.doi.org/10.1016/j.devcel.2012.12.012

206

RESULTS

Fendrr Expression Is Restricted to Nascent Lateral Plate Mesoderm

We searched for differentially expressed IncRNAs in six different tissues dissected from early somite-stage mouse embryos (TS12, E8.25, three to six somites) using RNA-seq and ChIP-seq analyses. From this data set, we identified a gene that is specifically transcribed in the posterior mesoderm. We isolated it by RACE-PCR from embryonic cDNA and determined its 2,397 base pair (bp) sequence and gene structure (Figure 1A). The gene consists of seven exons and is transcribed divergently from the transcription factor-coding gene Foxf1. Its transcriptional start site is located 1,250 bp upstream of the 5’-end of Foxf1. We termed this IncRNA Fendrr (Fetal-lethal noncoding developmental regulatory RNA).

Whole-mount in situ hybridization showed that Fendrr is confined to the caudal end of the lateral plate mesoderm (LPM) of midgestation embryos, which gives rise to ventral structures such as the heart and body wall (Figures 1B and 1C). We could not detect Fendrr expression in other tissues or in organs of later stage embryos using qPCR analysis (data not shown). In the caudal LPM it is coexpressed with Foxf1, while in more anterior LPM cells that are undergoing differentiation, Fendrr is downregulated, whereas Foxf1 expression is maintained in the splanchnic mesoderm (Peterson et al., 1997; Mahlapuu et al., 2001a). Quantitative PCR analysis of RNA extracted from the nuclear or cytosolic faction of E9.5 embryo caudal ends showed that Fendrr RNA is predominantly localized in the nucleus, consistent with its human ortholog in cultured cells (Figure 1D) (Khall et al., 2009).

Loss of Fendrr Causes Embryonic Lethality

To investigate the function of Fendrr in mouse development, we first knocked down Fendrr transcripts using a method for shRNAmir-mediated RNA interference in vivo (Vidigal et al., 2010). A reduction in Fendrr transcripts to 40% of the wild-type level caused no phenotype (data not shown). Therefore, we consecutively replaced the first exon of Fendrr on both chromosomes in ES cells with a strong transcriptional stop signal.
by homologous recombination (Friedrich and Soriano, 1991), thereby generating a Fendrr null mutant (Figure 2A). Successful targeting of both alleles in ES cells was confirmed by Southern blot analysis (Figure S1A available online). We confirmed loss of Fendrr transcripts in the caudal ends of Fendrr null embryos generated by tetraploid complementation (Gertsenstein, 2011) using whole-mount in situ hybridization (Figure S1B).

Homologous mutants (Fendrr3xpA[N]/3xpA[H]) were found to be embryonic lethal around E13.75 (Figures 2B and S1C). At this stage they appeared pale and displayed a prominent omphalocele, wherein parts of the developing liver and all umbilical...
vessels protruded from the ventral body (88.9%, n = 9) (Figures 2B and 2C). Omphalocele and embryonic death persisted after removal of the PKG-Neo and PKG-Hygro selection cassettes (genotype Fendrr<sup>2xpA/3xpA</sup>; Figures S1C and S1D).

To rule out that the phenotype of Fendrr<sup>2xpA/3xpA</sup> mutant embryos was due to compromised genetic integrity of the ES cells we performed a rescue experiment. We introduced a BAC clone containing a functional Fendrr gene next to an inactivated Foxf1 locus into Fendrr<sup>3xpA/3xpA</sup> mutant ES cells and generated embryos by tetraploid complementation. These Fendrr<sup>2xpA/3xpA;Tg(RP23-455G4)Bgh</sup> embryos showed a normal expression pattern of Fendrr at E9.5 (Figure S1B) and expressed approximately half of the wild-type level of Fendrr RNA, as expected from a single functional allele (Figure S1E). The Foxf1 expression level was unchanged in rescued embryos in E9.5 caudal ends as compared to wild-type embryos (Figure S1F).

They appeared phenotypically normal until E17.5, while at E18.5 rescue was observed in the majority of embryos (Figures 2B, 2C, and 2D). Thus, the embryonic rescue confirmed the genetic integrity of the mutant ES cells used in the following experiments, and we conclude that the lethal phenotype of Fendrr<sup>2xpA/3xpA</sup> embryos is entirely due to loss of Fendrr transcripts.

To determine the etiology of the mutant phenotype, we examined the morphology of embryos at stage E12.5, when mutants still appeared phenotypically normal. Measurements of the thickness of the ventral body wall, a derivative of the somatic LPM lineage, showed a severe reduction in homozygous mutant as compared to wild-type embryos (Figure 2G). Measurements of the thickness of the ventral body wall revealed a severe reduction in mutant as compared to wild-type hearts (Figure S1H). The Foxf1 expression level was unchanged in rescued embryos in E9.5 caudal ends as compared to wild-type embryos (Figure S1F). They appeared phenotypically normal until E17.5, while at E18.5 rescue was observed in the majority of embryos (Figures 2B, 2C, and 2D).

Besides an omphalocele, mutant embryos also displayed blood accumulation in the right heart chamber (Figure S1H). To assess functioning of the heart, which is a derivative of the somatic LPM lineage, we performed a rescue experiment. We introduced a BAC clone containing a functional Fendrr gene next to an inactivated Foxf1 locus into Fendrr<sup>3xpA/3xpA</sup> mutant ES cells and generated embryos by tetraploid complementation. These Fendrr<sup>2xpA/3xpA;Tg(RP23-455G4)Bgh</sup> embryos showed a normal expression pattern of Fendrr at E9.5 (Figure S1B) and expressed approximately half of the wild-type level of Fendrr RNA, as expected from a single functional allele (Figure S1E). The Foxf1 expression level was unchanged in rescued embryos in E9.5 caudal ends as compared to wild-type embryos (Figures 2B and 2D).

They appeared phenotypically normal until E17.5, while at E18.5 rescue was observed in the majority of embryos (Figures 2B, 2C, and 2D). Thus, the embryonic rescue confirmed the genetic integrity of the mutant ES cells used in the following experiments, and we conclude that the lethal phenotype of Fendrr<sup>2xpA/3xpA</sup> embryos is entirely due to loss of Fendrr transcripts.

To determine the etiology of the mutant phenotype, we examined the morphology of embryos at stage E12.5, when mutants still appeared phenotypically normal. Measurements of the thickness of the ventral body wall, a derivative of the somatic LPM lineage, showed a severe reduction in homozygous mutant as compared to wild-type embryos (Figures 2B and 2D). Omphalocele and embryonic death persisted after removal of the PKG-Neo and PKG-Hygro selection cassettes (genotype Fendrr<sup>2xpA/3xpA</sup>; Figures S1C and S1D).
Because Gata6 is widely expressed in the LPM, including nascent LPM and heart progenitor cells, we wanted to determine whether changes in Gata6 expression and promoter histone modifications were already present in nascent LPM. In addition, we analyzed the expression of the LPM control genes Foxf1, Pitx2, and Irx3, which play important roles in determining the splanchnic and somatic LPM lineages, along with Tbx3 (Mahlapuu et al., 2001b; Rallis et al., 2005; Kitamura et al., 1999). The presomitic mesoderm (PSM) marker genes Dll1 and Tcf15 were included as controls.

The expression levels of Gata6 and Foxf1 were significantly increased in the caudal ends of E8.5 mutant embryos, while Irx3, Tbx3, and the PSM marker genes were not affected at this stage (Figure 3C). This increase in Gata6 and Foxf1 expression persisted in the nascent LPM of E9.5 mutant embryos. In addition, Irx3 and Pitx2 expression was also increased at this later stage, during which the progenitors of the ventral body wall are generated (Figure 3C). The expression of Foxc2, Fox1, and Mthfsd, located in close vicinity to Foxf1 and Fendrr, was unchanged, excluding unspecific effects of Fendrr gene locus alterations on neighboring genes in the knockout allele (Figure S2A).

Similarly to what was observed in the heart, changes in gene expression were accompanied by changes in the methylation status of the promoters. The Gata6 and Foxf1 promoters of mutant embryos showed a strong increase in H3K4me3, and the Irx3 and Pitx2 promoters a slight increase in H3K4me3 (Figure 3D). In contrast to Gata6, which showed no difference in the repressive mark, the H3K27me3 levels at the Foxf1, Irx3, and Pitx2 promoters of mutant embryos were strongly reduced as compared to wild-type (Figure 3D). The methylation status of the control PSM marker gene promoters was not altered for either the H3K4me3 or the H3K27me3 marks.

Next we asked whether the changes in histone modifications observed correlated with altered occupancy of the PRC2
and/or TrxG/MLL complexes at the respective promoters. We analyzed the presence of PRC2 or TrxG/MLL by ChIP with antibodies against EZH2, SUZ12 (PRC2 components), or WDR5 (TrxG/MLL component), followed by qPCR analysis of the promoter regions. Immunoprecipitation of the Foxf1, Irx3, and Pitx2 promoter regions with EZH2 or SUZ12 antibodies from mutant caudal end tissue was drastically reduced compared to wild-type tissue, whereas all other promoters were not affected (Figures 3 E and S2B). In contrast, promoter occupancy of WDR5 in caudal end tissue was unchanged for all of the promoters tested (Figure 3 E). In addition, no changes in EZH2, SUZ12, or WDR5 occupancy were observed in heart tissue for any of the promoters tested (Figure S2 C).

These combined data show that Fendrr has differential effects on the histone modification of promoters for transcriptional regulators in the lateral mesoderm and at least one of its derivatives, the cardiac mesoderm. The data suggest that the primary role of Fendrr is to promote occupancy of the PRC2 complex on particular promoters for LPM control genes, resulting in an increase of the repressive H3K27me3 mark, accompanied by a reduction in gene expression. In addition, probably via a different mechanism, Fendrr is involved in controlling the level of the activating H3K4me3 mark on a subset of promoters, thereby modifying the expression level of those genes.

We asked if the epigenetic changes caused by loss of Fendrr at the Foxf1, Pitx2, and Irx3 promoters, which caused upregulation of these genes in lateral mesoderm, had an effect on the expression of these genes in E12.5 cardiac tissue. RNA-seq data showed a moderate, ectopic expression of Foxf1 in E12.5 mutant hearts, whereas no Foxf1 transcripts were detected in wild-type tissue (Figure 2 I). Irx3 and Pitx2 expression, which is active in the wild-type E12.5 heart, was not altered in the mutant organ. These data suggest that the epigenetic changes caused by Fendrr at its target promoters in lateral mesoderm may persist through consecutive stages of differentiation and thus also take effect in the descendants of the cells exposed to Fendrr activity.

**Fendrr Binds In Vivo to the PRC2 and TrxG/MLL Complexes and to Target Promoters**

(A and B) RNA coimmunoprecipitation (RIP) from forebrain (upper panels) and caudal end (lower panels) lysates from wild-type embryos using antibodies directed against EZH2 and SUZ12 (A) or WDR5 (B); normal rabbit IgG was used as control. Fold enrichment has been normalized to nonenriched input sample and U1 rRNA. Foxf1 and Hmbs RNA served as negative control. Mean ± SD are shown (n = 3).

(C) Binding potential between Fendrr and genomic regions. The red curve shows the average probability of single-stranded RNA (Ding et al., 2004). The heat map represents the base-pairing energy for an RNA/RNA duplex model for 40-bp regions along the Fendrr transcript and 2,000 bp around the TSS of Foxf1 (top) and Pitx2 (bottom).

(D) Representation of the predicted interaction of the Fendrr RNA region and the promoter DNA region exhibiting the lowest free energy of approximately −70 kcal/mol (see yellow spot in C).

(E) In vitro RNA/dsDNA binding assay utilizing biotin tagged RNA oligos as bait. Bars represent normalized enrichment of indicated 2,000-bp promoter fragment over background using a control RNA oligonucleotide (Mean ± SD, n = 3).

See also Figure S3.

**Fendrr Binds In Vivo to the PRC2 and TrxG/MLL Histone-Modifying Complexes**

The ChIP data prompted us to investigate whether Fendrr interacts directly with the PRC2 and/or TrxG/MLL complexes in mouse embryos. We immunoprecipitated the PRC2 complex with specific antibodies directed against EZH2 and SUZ12 from lysates of wild-type E9.5 embryonic caudal ends, resulting in an increase of the repressive H3K27me3 mark, accompanied by a reduction in gene expression. In addition, probably via a different mechanism, Fendrr is involved in controlling the level of the activating H3K4me3 mark on a subset of promoters, thereby modifying the expression level of those genes.

We asked if the epigenetic changes caused by loss of Fendrr at the Foxf1, Pitx2, and Irx3 promoters, which caused upregulation of these genes in lateral mesoderm, had an effect on the expression of these genes in E12.5 cardiac tissue. RNA-seq data showed a moderate, ectopic expression of Foxf1 in E12.5 mutant hearts, whereas no Foxf1 transcripts were detected in wild-type tissue (Figure 2 I). Irx3 and Pitx2 expression, which is active in the wild-type E12.5 heart, was not altered in the mutant organ. These data suggest that the epigenetic changes caused by Fendrr at its target promoters in lateral mesoderm may persist through consecutive stages of differentiation and thus also take effect in the descendants of the cells exposed to Fendrr activity.
in the mouse embryo, confirming data previously obtained in cultured human foreskin fibroblasts for the human orthologous lncRNA (Khalil et al., 2009). Next, we tested whether Fendrr transcripts could interact with the TrxG/MLL component WDR5. The lncRNA HOTTIP served as positive control (Wang et al., 2011). Again, both Fendrr and HOTTIP transcripts were coimmunoprecipitated with WDR5 from the caudal end, but not from forebrain tissue (Figure 4B). In contrast, Fendrr RNA was not coprecipitated with the PRC1 component RING1B, the NuRD complex component LSD1, or SIRT6 (Figure S3A). Thus, Fendrr RNA binds to PRC2 and TrxG/MLL and discriminates between various histone-modifying complexes.

Fendrr Binds to the Foxf1 and Pitx2 Promoters In Vitro
Because Fendrr binds to the PRC2 complex and loss of Fendrr resulted in a strong reduction of PRC2 occupancy at the Foxf1, Pitx2, and Irx3 promoters, we asked whether Fendrr is able to bind directly to any of these promoters. We calculated the binding potential of Fendrr to fragments covering 1 kb upstream to 1 kb downstream of the transcriptional start site of each of the three genes. The heat map revealed a short stretch in the Fendrr RNA predicted to bind to a complementary region in the Foxf1 and Pitx2 promoters (Figures 4C and 4D). The Irx3 promoter was negative within the region analyzed, just as the promoters of Dll1 and Tcf15, which served as negative controls (Figure S3B). We used a synthetic RNA oligonucleotide coupled to psoralen and biotin at either end and performed an in vitro binding assay (Besch et al., 2004; Schnitz et al., 2010). The promoter fragments of both Foxf1 and Pitx2, but not of Dll1, co-precipitated with this RNA oligomer (Figure 4E). Coprecipitation occurred in the presence of RNaseH, but was prevented by RNaseV1 treatment. The former enzyme specifically cuts RNA in DNA/RNA heteroduplexes, while the latter cleaves base-paired nucleotides. The data show that Fendrr can bind to double-stranded Foxf1 and Pitx2 promoter fragments, and suggest triplex formation at the complementary region (Buske et al., 2012). The data in combination with findings discussed above confirm that Fendrr acts in cis (at the Foxf1) and in trans (at the Pitx2 and possibly other promoters).

The combined data suggest that Fendrr anchors PRC2 at its target promoters, thereby increasing PRC2 occupancy and H3K27 trimethylation, which consequently leads to attenuation of target gene expression. Moreover, the coexpression of the transcriptional regulator Foxf1 and the IncRNA Fendrr in lateral mesoderm links the transcriptional regulatory network with the epigenetic regulatory network acting in this tissue.

DISCUSSION

Fendrr is a regulatory RNA, which mediates the modification of the epigenetic landscape of target promoters thereby causing attenuation of the expression of transcription factors that are important in lateral mesoderm differentiation.

Our data suggest that changes in epigenetic modifications within promoters of genes involved in a gene regulatory network (GRN) can cause deleterious effects, which are similar to those seen following the loss of a single crucial transcription factor. For instance, Foxf1 is essential for the separation of splanchnic and somatic mesoderm (Mahlapuu et al., 2001b), where it is required to inhibit Irx3 expression in the splanchnic mesoderm and direct it to the somatic mesoderm lineage (Mahlapuu et al., 2001b). Pitx2 is required for heart and ventral body wall development (Kitamura et al., 1999). However, at this point we cannot conclude that the mutant phenotype observed is indeed caused by increased expression of several transcriptional regulators, nor can we exclude that failure of Fendrr binding to TrxG/MLL at presently unidentified promoters leading to downregulation of target genes may contribute to the mutant phenotype.

Compound heterozygosity of Gata4 and Gata6 has been shown to result in embryonic lethality demonstrating that a threshold of both genes is required to support cardiovascular development (Xin et al., 2006). Moreover, heterozygosity for Foxf1 or Pitx2 results in haplo-insufficiency phenotypes, indicating that a threshold level of each of these regulators is critical for proper embryonic development (Mahlapuu et al., 2001a; Liu et al., 2003). While on the basis of current knowledge this is well conceivable, it is harder to envisage how an excess of transcriptional regulators might perturb embryonic processes.

An important feature of Fendrr is its long-term effect. In general, the action of transcription factors is restricted to the cells in which they are expressed. In contrast, the epigenetic signatures of regulatory elements set early in a differentiation process can persist through several stages of differentiation. The ectopic upregulation of Foxf1 in E12.5 Fendrr mutant hearts indicates that Fendrr is involved in epigenetic modifications affecting activation or repression of its target genes in descendants of the cells in which Fendrr was, but no longer is, active. Thus, disturbances in the epigenetic prepattern within the early precursor cells of organs and tissues may have far-reaching consequences on subsequent cell proliferation, patterning or differentiation processes in the descendants of those cells. Cardiac myocyte proliferation in Fendrr mutant hearts is not affected before E12.5, 6 days after Fendrr expression in the cardiac progenitor cells of the lateral mesoderm has been lacking. Future work has to address how this late effect in cardiac tissue is triggered by Fendrr loss in cardiac progenitor cells.

The gene pairing of Fendrr and Foxf1 highlights the intriguing transcriptional and functional coupling of a divergent IncRNA with an adjacent regulatory protein, both of which are essential for development of the same embryonic tissue. Such IncRNA: protein-coding gene neighbors are found throughout the genome (Cabili et al., 2011) and this functional link may reveal a more general mechanism for the control of patterning and lineage commitment (Cabili et al., 2011; Ulltisky et al., 2011; Mar-gueron and Reinberg, 2011; Ørom et al., 2010).

EXPERIMENTAL PROCEDURES

Fluorescent Imaging
All animal procedures were conducted as approved by the local authorities (LAGeSo Berlin) under the license number G0368/08. Embryos were dissected at E12.5 into warm M2 medium, and kept at 37°C. Embryos were fixed on temperature-adjusted SYLGARD 184 Silicone Elastomer mounting plates using needles to expose their thoraxes. Sonicated Fluospheres (20 nm, Life Technologies) were diluted 1:10 with PBS and injected into the right atrium using a glass microcapillary for 10 s with mild pressure. Hearts were imaged under a Leica MZ 16FA microscope equipped with a GFP3 filter and videos recorded using the Leica LAS AF software.
RNA coimmunoprecipitation
RNA coimmunoprecipitation was carried out as previously described (Galagan et al., 2008). Magnetic Protein A and G beads (Life Technologies) were used for isolation of antibody-bound protein/RNA complexes. Coprecipitated RNA was reverse transcription using random hexamers, and cDNA content quantified by qPCR. Antibodies used were anti-EZH2 (Active Motif), anti-LSD1 (Abcam), and anti-SIRT6 (Abcam). For oligonucleotide binding potential calculations and RNA/dsDNA Interaction Assay, RNA was reverse transcribed using random hexamers, and cDNA were used for isolation of antibody-bound protein/RNA complexes. Coprecipitated RNA was reverse transcribed as described.

Binding Potential Calculations and RNA/dsDNA Interaction Assay
The average probability of single-stranded RNA was computed by solving with a length parameter of 200 and W = 1 (Ding et al., 2004). Base-pairing energy for an RNA/RNA duplex model for 40-bp regions along the Fendrr transcript and 2,000 bp around the TSS of Foxf1 and Pitx2 was calculated (Lorenz et al., 2011). The duplex energy is computed for each such region, staggered by 20 bp, and displayed in a heatmap. Probabilities are then averaged for a sliding window of 40 bp to give the average RNA accessibility of the region that is binding. The RNA/DNA interaction assay was essentially carried out as described (Besch et al., 2004). Briefly, 1 pmol of promoter fragment (–1 kb to +1 kb from the transcriptional start site) were incubated at 37°C for 30 min with 100 pmol of PsrolenC6-UCCCCUCUACUCUCCUCUCCUCUCCUCUCCUCUCUU-UbiotinTEG (Fendrr) or unspliced PsrolenC6-UCCCCUGUGGG UGGGGUGGGUGGGUCUU-UbiotinTEG RNA oligonucleotides (Biomers) (Schmitz et al., 2010). The reaction was UV (265 nm) treated as described. Preblocked M270 Streptavidin beads (Life Technologies) were used to precipitate bound DNA in the presence or absence of RNase H or V1. Fold enrichment was determined by the ratio of specific to unspecific DNA precipitate obtained from three replicates.

ACCESSION NUMBERS
The GenBank accession number for the Fendrr full-length cDNA sequence reported in this paper is JX073641. The GEO accession number for the RNA-seq data reported in this paper is GSE43078.

SUPPLEMENTAL INFORMATION
Supplemental Information includes three figures, one movie, and Supplemental Experimental Procedures and can be found with this article online at http://dx.doi.org/10.1016/j.devcel.2012.12.012.

ACKNOWLEDGMENTS
We thank Silke Sperling and Cornelia Dorn for discussion on the heart phenotype and qPCR primers for heart marker analysis; Marc Sultan, Alexander Kovacsics, and Matthias Linser for RNA sequencing; members of the animal facility for breeding of mice and strain maintenance; and Tracie Pennimpede for comments on the manuscript. We are grateful to Mikhail Sukchev for providing the modified RP23-455G4 BAC.

REFERENCES


