Myocardin is sufficient and necessary for cardiac gene expression in *Xenopus*

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Summary

Myocardin is a cardiac- and smooth muscle-specific co-factor for the ubiquitous transcription factor serum response factor (SRF). Using gain-of-function approaches in the *Xenopus* embryo, we show that myocardin is sufficient to activate transcription of a wide range of cardiac and smooth muscle differentiation markers in non-muscle cell types. We also demonstrate that, for the myosin light chain 2 gene (MLC2), myocardin cooperates with the zinc-finger transcription factor Gata4 to activate expression. Inhibition of myocardin activity in *Xenopus* embryos using morpholino knockdown methods results in inhibition of cardiac development and the absence of expression of cardiac differentiation markers and severe disruption of cardiac morphological processes. We conclude that myocardin is an essential component of the regulatory pathway for myocardial differentiation.

Key words: Tbx5, Gata4, Nkx2-5, Smooth muscle, Transgenesis

Introduction

Knowledge of the regulatory mechanisms underlying cardiac development is essential for understanding the molecular basis of congenital heart defects. During embryonic heart development, differentiation of cardiac muscle is regulated by interactions between a surprisingly large number of cardiac-restricted transcription factors. For example, the homeodomain transcription factor Nkx2-5 binds directly to the promoters of several cardiac differentiation genes (Chen and Schwartz, 1995; Durocher et al., 1997; Molkentin et al., 2000). However, Nkx2-5 is a relatively weak transcriptional activator and efficient transcription from its target promoters is dependent on the presence of additional regulatory factors. Proteins that interact with Nkx2-5 include the zinc finger transcription factor Gata4 (Durocher and Nemer, 1998; Sepulveda et al., 1998) the T box-containing proteins, Tbx5 and Tbx20 (Bruneau et al., 2001; Stennard et al., 2003) and the homeodomain protein Pitx2 (Ganga et al., 2003). Additional transcription factors, many of which are not cardiac specific, are also essential for embryonic heart development. These include the nuclear factor of activated T cell (NFAT) family of factors (Schubert et al., 2003; Bushdid et al., 2003) and the myocyte enhancer factor 2 (MEF2) family of transcription factors (Molkentin and Markham, 1993; Kuisk et al., 1996; Lin et al., 1997). Each of these proteins are believed to interact with other cardiac transcription factors to control cardiac gene expression (Wada et al., 2003; Black and Olson, 2003).

Numerous cardiac genes also contain binding sites for the ubiquitous transcription factor, serum response factor (SRF). The SRF binding site (the CArG box) has been demonstrated to be essential for myocardial expression of a number of genes including cardiac α-actin (Belaguli et al., 2000; Latinkic et al., 2002), atrial natriuretic factor (Argentin et al., 1994; Small and Krieg, 2003) and the sodium calcium exchanger (Cheng et al., 1999). The presence of CArG elements is not unique to cardiac promoters, however, as binding sites are also common in skeletal and smooth muscle gene promoters, as well as in the control regions of growth factor-inducible genes. Recent studies have shown that SRF activates transcription of smooth and cardiac muscle promoters in collaboration with myocardin, a cofactor that associates directly with SRF but does not bind DNA (Wang et al., 2001). Since myocardin is expressed in cardiac and smooth muscle, but not in skeletal muscle, interactions between myocardin and SRF may provide the mechanism by which cardiac and smooth muscle-specific promoters are distinguished from skeletal muscle promoters. Recent studies have emphasized the role of myocardin as a powerful activator of smooth muscle genes (Chen et al., 2002; Du et al., 2003; Wang et al., 2003) and the mouse knockout of myocardin results in embryonic death due to absence of vascular smooth muscle differentiation (Li et al., 2003). In
many respects therefore, myocardin has the properties of a master regulator of smooth muscle development.

The lack of a cardiac phenotype in myocardin knockout mice is seemingly at odds with our previous studies which showed that expression of a dominant negative of myocardin in *Xenopus* embryos was able to abolish cardiac gene expression, suggesting an important role for myocardin in heart development (Wang et al., 2001). However, a caveat in the interpretation of such dominant negative experiments is that such mutants can interfere with multiple transcriptional regulators. It has been proposed that redundant activities of the myocardin-related factors, MRTF-A and MRTF-B (Wang et al., 2002) may be sufficient to rescue heart development in myocardin mutant embryos but this possibility has not yet been addressed experimentally.

In this study, we show that myocardin is able to activate a large number of cardiac and smooth muscle differentiation genes in non-muscle cells. We also show that myocardin can function combinatorially with another cardiac-expressed transcription factor, Gata4, to achieve efficient transcription of cardiac differentiation markers. Conversely, depletion of myocardin in the developing embryo by antisense morpholino injection abolishes cardiac marker gene expression, indicating that myocardin is essential for regulation of cardiac differentiation.

Materials and methods

Embryological manipulations

*Xenopus laevis* embryos were staged according to Nieuwkoop and Faber (Nieuwkoop and Faber, 1994). *Xenopus* eggs were in vitro fertilized, dejellied using 2% L-cysteine (pH 8.0), and maintained in 0.2x MMR (Marc’s Modified Ringers). Targeted mRNA injections were performed in 0.4x MMR/4% Ficoll at the 8-cell stage. Different mRNAs (125 pg, 250 pg or 400 pg) were injected in a volume of 4.6 nl. Embryos were cultured in 0.2x MMR until a suitable stage and fixed in MEMFA for assay by in situ hybridization. In animal cap assays embryos were injected at the one-cell stage into the animal pole. Animal pole explants were dissected from mRNA-injected or un.injected control embryos at stage 8 in 1×NAM (Normal Amphibian Medium). Caps were cultured in 0.5× NAM containing gentamycin until the equivalent of stage 12.5 and RNA was extracted for RT-PCR analysis.

*Xenopus laevis* transgenesis

The NF1 promoter driven myocardin or GFP transgene was linearized with Pmel and transgenic *Xenopus* embryos were generated using previously described methods (Kroll and Amaya, 1996; Sparrow et al., 2000; Small and Krieg, 2003). Double transgenics were made using the NF1-GFP and NF1-myocardin constructs, and GFP expression in neural tissues was used as a control for transgenesis.

Whole-mount in situ hybridization

Whole-mount in situ hybridization was carried out using a modification of the method of Harland (Harland, 1991), using antisense digoxigenin-labeled probes transcribed using a MEGAscript kit (Ambion). For serial sections, embryos were post-fixed in 4% paraformaldehyde for 6 hours at room temperature and embedded in Paraplast. Transverse sections (10 µm) were cut on a microtome.

Cloning of *Xenopus laevis* myocardin

RT-PCR using degenerate primers designed against the conserved amino acid regions WETMEWL and IFNIDF within the human and mouse myocardin sequences was performed using random-primed adult Xenopus heart cDNA. After cloning and sequencing of the resulting 99 bp fragment, the remaining portions of the myocardin cDNA were amplified by 5’ and 3’ RACE using Xenopus heart cDNA prepared according to the manufacturer’s instructions (FirstChoice RLM-RACE Kit; Ambion). The final Xenopus myocardin sequence was determined by PCR amplification, cloning and sequencing of the entire myocardin coding region using the Expand High Fidelity PCR System (Roche).

RT-PCR of marker gene expression

Ten animal cap explants were harvested for each sample and RNA was isolated using buffer A/proteinase K. cDNA was prepared from one half of each RNA sample, and a minus RT negative control sample was prepared from the remaining RNA. One fiftieth of the cDNA sample was used as template in radioactive RT-PCR that included 0.3 µCi of α-3P in a 20 µl reaction. RT-PCR cycle number was determined to assure the reaction was in the linear range of amplification. PCR samples were separated on non-denaturing 5% acrylamide gels.

Primers

Primers used were as follows: calponin H1, 5’-GCACTGTACGGGAG-GATCAACG-3’ (forward) and 5’-CGATATCCCCTGGCACCTTT-3’ (reverse) (Tm=60°C); cardiac α actin (Niehrs et al., 1994) (Tm=63°C); cTnl (Vokes and Krieg, 2002) (Tm=63°C); Gata4, 5’-TCTGGCCCAACATGTGCT-3’ (forward) and 5’-CAGTTGACA-CATCTCGG-3’ (reverse) (Tm=56°C); Mez2A, 5’-CAGCTCAGCTTCATAT-3’ (forward) and 5’-TTCACTAGGAGCCTAAT-GCA3’ (reverse) (Tm=56°C); MHCα, 5’-ACAAAGTACGAGACT-GAGC-3’ (forward) and 5’-CTCTGACTCAGCTGGTATG-3’ (reverse) (Tm=60°C); MLC2, 5’-GAGGCACTTCAGCTATGCGA-3’ (forward) and 5’-GACCTCCAGAAGACATGTC-3’ (reverse) (Tm=60°C); MRF4, 5’-ATCAGGAGCAGAAGCCACAGA-3’ (forward) and 5’-TGATATGTCAGGGTGCTG-3’ (reverse) (Tm=58°C); MRTF-A, 5’-TGAGGTTAGCAAAATGAAATG-3’ (forward) and 5’-GGTAACTGAAGTGCCTAGA-3’ (reverse) (Tm=60°C); MRF-T B, 5’-TGTGAGTCTGATGCTGCT-3’ (forward) and 5’-CCAAGCATCATCTGTGTA-3’ (reverse) (Tm=60°C); Myf5, 5’-CATGTCGATGCTTGTCAGG-3’ (forward) and 5’-CAATCATGGGCAC-3’ (reverse) (Tm=58°C); MyoD, 5’-AACTGCTC-GTGTGCGTATGAGGTA-3’ (forward) and 5’-ATTGCTGGGGA-3’ (forward) and 5’-GGAAAGCTTGTTGAGA-3’ (reverse) (Tm=60°C); myocardin, 5’-GCCAAAAGCAAATTACAAGA-3’ (forward) and 5’-GGAAAGCGTCTG-3’ (reverse) (Tm=60°C); myogenin, 5’-CCGTGAGTATGACTGAC-3’ (forward) and 5’-GGCAGAAGCCCATTATAGA-3’ (reverse) (Tm=58°C); Nkx2-5, 5’-TCTGCAATCAGTGAAGGAA-3’ (forward) and 5’-AGGACTG-TGACTGATCT-3’ (reverse) (Tm=56°C); ODC (Bouwmeester et al., 1996) (Tm=64°C); SkMLC, 5’-TTGGTCAAGAGCGATCTGG-3’ (forward) and 5’-AGGTGTGTCTCTCTGAGA-3’ (reverse) (Tm=60°C); SM22, 5’-CTGAGTAGAAGCTTCTG-3’ (forward) and 5’-GGTACACTGTGATCTCACT-3’ (reverse) (Tm=60°C); SM actin, 5’-ACCAACTTACAACAGCATGATG-3’ (forward) and 5’-ACCAACTTACAACAGCATGATG-3’ (forward) and 5’-CAGACTACACAACTTGCAACA-3’ (reverse) (Tm=58°C); Xbra (Vokes and Krieg, 2002) (Tm=60°C).

Myocardin loss of function by morpholino oligonucleotide injection

Antisense morpholinos (MO1 5’-CAGCTTCTGCTGGTATT-3’ and MO2 5’-TGTGCCGAAACCAGAGTACCTG-3’) were directed against two independent sequences near the 5’ end of the myocardin transcript. The morpholinos were targeted to sequences that are identical in the A and B copies of the *Xenopus laevis* genes in order to inhibit translation of both mRNAs. A dose curve was determined with 2.5 ng, 5 ng, 10 ng and 20 ng of
Cardiac gene expression in Xenopus

morpholino, injected in one cell of a two-cell embryo so the uninjected side served as a negative control. A concentration-dependent phenotype was observed with an increasing percentage of asymmetric cardiac gene expression with increasing dose. MO-treated embryos were assayed using in situ hybridization and appropriate marker probes.

Results

Cloning and expression of Xenopus myocardin

The deduced amino acid sequence of the Xenopus laevis myocardin protein is presented in Fig. 1, aligned with the mouse and human myocardin protein sequences. Xenopus myocardin contains 918 amino acids with a predicted molecular mass of 101 kDa. We conclude that this protein represents the Xenopus orthologue of myocardin for the following reasons. First, Xenopus myocardin is 56% and 57% identical to the mouse and human proteins, respectively, and this level of sequence identity is similar to that of other regulatory proteins in the cardiogenic pathway, such as Gata4 and Nkx2.5. Second, the sequence identity between Xenopus myocardin and mouse myocardin-related factors, MRTF-A and B (MKL1 and MKL2 – Mouse Genome Informatics), is only 32% and 31% respectively. Third, a search of the draft Xenopus genomic sequence revealed no other genes with greater similarity to mammalian myocardin. Finally, the basic region of myocardin, which is involved in interactions with SRF (Wang et al., 2001) and the SAP domain, which is thought to function in chromatin remodeling (reviewed by Aravind and Koonin, 2000) are both highly conserved between frog and mouse (89% and 90%, respectively).

The expression pattern of myocardin during Xenopus development...

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**Fig. 1.** Alignment of frog, mouse and human myocardin proteins. The basic region (involved in SRF binding), the SAP domain (involved in chromatin remodeling), and the leucine zipper-like domain (dimerization domain), are labeled. The Xenopus myocardin protein is 56% and 57% identical to the mouse and human proteins, respectively. Accession number for Xenopus laevis myocardin is AY585230.
Development has been determined using whole-mount in situ hybridization (Fig. 2). Myocardin transcripts are not detectable in the early neurula embryo (stage 15; Fig. 2A) at a time when transcripts for the precardiac marker, Nkx2-5, are abundant (Fig. 2C). Myocardin expression is first detected in the later neurula embryo (stage 24) in the pre-cardiac patches of anterior lateral mesoderm (Fig. 2A’). This expression precedes, by approximately 3 hours, detection of transcripts for myosin heavy chain-α (MHCα) which is an early and robust marker of myocardial differentiation in the Xenopus embryo. In the mouse embryo, myocardin is co-expressed with Nkx2-5 in early cardiac primordia (Wang et al., 2001) but this does not appear to be the case in the frog embryo. At stage 27, myocardin transcript levels continue to increase (Fig. 2A’’). At this stage the domain of myocardin expression appears identical to that of MHCα, but is significantly more restricted than the Nkx2-5 expression domain (Fig. 2A’’’,B’’’,C’’’). Myocardin expression persists during subsequent cardiac development and is visible throughout the atrial and ventricular muscle layers of the tadpole heart (Fig. 2D). By the tadpole stage (stage 40), myocardin transcripts are also visible in visceral smooth muscle cells surrounding the looping gut (Fig. 2E,F) and in isolated smooth muscle precursor cells adjacent to the forming dorsal aorta (Fig. 2F). Overall, the expression of Xenopus myocardin in developing cardiac and smooth muscle tissues closely resembles the expression profile reported for the murine myocardin gene (Wang et al., 2001). Two additional Xenopus myocardin-related sequences, MRTF-A and MRTF-B have been reported (Wang et al., 2002) and in situ hybridization analysis of these sequences is shown in Fig. 2G and H, respectively. Neither gene shows detectable expression in the cardiogenic region of the embryo, even when the chromogenic detection reaction is continued until non-specific background staining becomes evident. RT-PCR analysis indicates that, surprisingly, myocardin, MRTF-A and MRTF-B transcripts are all present at significant levels in the fertilized egg, but transcripts decline to effectively undetectable levels by the gastrula stage. RT-PCR analysis of isolated heart patch tissue from the stage 28 embryo shows abundant expression of myocardin but no detectable expression of MRTF-A or B (Fig. 21). The absence of MRTF-A and B transcripts from the pre-cardiac region is important for interpretation of morpholino knockdown experiments described below.

Myocardin induces ectopic cardiac muscle gene expression in whole embryos

Previous studies using cells in culture showed that myocardin is able to activate reporter genes containing a range of myocardial (Wang et al., 2001; Wang et al., 2002) and smooth muscle promoters (Chen et al., 2002; Wang et al., 2003; Du et al., 2003). Myocardin is also able to activate expression of

![Fig. 2. Developmental expression of Xenopus myocardin and MRTF genes.](image-url)
endogenous smooth muscle genes (Chen et al., 2002; Du et al., 2003; Wang et al., 2003; Yoshida et al., 2003). We used the Xenopus embryo as an in vivo model system to investigate the potential of myocardin to regulate transcription of endogenous cardiac and smooth muscle genes. In these experiments, mRNA encoding myocardin was injected into single blastomeres of eight-cell embryos. The un.injected side of the embryo served as a negative control. At subsequent stages of development, expression of cardiac or smooth muscle markers was determined by in situ hybridization. Our results demonstrate that myocardin is sufficient to induce precocious and ectopic expression of cardiac markers. For example, expression of the cardiac-specific differentiation marker, MHCα, is normally initiated in the late neurula embryo (stage 25) and is undetectable at stage 14 (Fig. 3A). In embryos injected with myocardin mRNA however, high levels of ectopic MHCα transcripts were present in stage 14 embryos (Fig. 3B) approximately 24 hours before expression would normally be detected in the heart. Ectopic expression was observed in 65% of myocardin-injected embryos (13/20). Similarly, precocious and ectopic expression of cardiac α-actin was observed in myocardin-injected embryos (Fig. 3D,E) as was somewhat weaker expression of cardiac troponin I (cTnI), and the smooth muscle marker SM22 (data not shown). Ectopic expression of MHCα persisted through subsequent development, and appeared to be particularly strong in neural tissues (Fig. 3G). As shown in Fig. 3H, MHCα transcripts could be detected in isolated patches, apparently within tissues of the eye and neural tube. Examination of numerous sectioned embryos suggested that ectopic expression of cardiac markers was limited to ectodermal and mesodermal tissue layers because we never observed cardiac gene transcripts in endodermal derivatives, even when myocardin mRNA was specifically targeted to this germ layer. Finally, despite extended culturing of myocardin mRNA injected embryos, we never observed the presence of beating tissue or striated muscle at ectopic locations in the embryo.

While these embryo injection results show that myocardin is capable of activating ectopic cardiac marker expression in the embryo, it is important to note that not all cardiac differentiation markers were induced. For example, we never observed ectopic expression of myosin light chain-2 (MLC2) transcripts in these embryos, which is surprising since the MLC2 gene is regulated by SRF (Qasba et al., 1992; Latinkic et al., 2004) and because myocardin activates the MLC2 promoter in cultured cells (Wang et al., 2001). The failure of myocardin to activate MLC2 in Xenopus does not seem to be a dose effect, since injection of greater amounts of myocardin mRNA did not succeed in activating MLC2 expression.

**Transgenic expression of myocardin activates cardiac gene expression in neural tissues**

When mRNA is injected into a Xenopus embryo, translation of the mRNA commences almost immediately. In the experiments described above, the embryos were injected at the eight-cell stage, however, activation of the first tissue-specific transcription pathways did not commence until approximately the gastrulation stage of development (stage 10). It is possible
Myocardin activates cardiac and smooth muscle differentiation markers in animal cap explants

Since myocardin is able to activate cardiac tissue markers in whole Xenopus embryos, we wished to assess its ability to activate myocardial gene transcription in a more defined system. Animal cap explants from the Xenopus embryo, consisting entirely of na"ve ectodermal tissue, have been widely used to investigate gene expression (Cascio and Gurdon, 1987; Grainger and Gurdon, 1989; Howell and Hill, 1997; Tada et al., 1998) and are a convenient alternative to cultured cells. Animal caps typically differentiate to form epidermal tissue and never express cardiac genes (Fig. 4A, lane labeled uninjected). Myocardin-injected caps, however, express a wide range of cardiac and smooth muscle differentiation markers (lane labeled myocardin), including cardiac α-actin, MHCα, cardiac TnI, SM22, calponin H1 and smooth muscle actin. The myocardin cofactor SRF and the MADS box transcription factor Mef2a, are upregulated in myocardin expressing caps. The cardiogenic genes, Nkx2.5 and Gata4 are not expressed in myocardin-injected animal caps. The lane labeled 12.5 WE, represents the normal expression of the assayed genes in the whole embryo at the time that the animal cap explants were assayed. (B) Myocardin does not activate genes of the skeletal muscle or mesodermal pathways. Myocardin-injected animal caps were assayed by RT-PCR for the activation of mesodermal and skeletal muscle markers. The general mesoderm marker brachyury (Xbra) is not expressed in myocardin-injected caps. Furthermore, myocardin does not activate expression of the skeletal muscle transcription regulators, MyoD, Myf5, MRF4 and myogenin, or the skeletal muscle-specific differentiation marker skMLC.

As in the whole embryo experiments, myocardin did not activate expression of all myocardial genes. Of the markers tested, MLC2 was never expressed in animal caps (Fig. 4A), even when the dose of myocardin was increased approximately fourfold over the amount sufficient to activate MHCα (data not shown). SRF was not limiting in these experiments since coinjection of SRF mRNA, together with myocardin mRNA, did not alter the results (data not shown). It has been reported that expression of Gata4 in animal cap explants is sufficient to initiate the complete cardiac differentiation pathway, including formation of beating tissue (Latinkic et al., 2003). In that study, cardiac marker expression was first observed at about stage 28, corresponding to the normal time at which cardiac markers are observed in the intact embryo. To test whether more time might be required for expression of MLC2 we also examined animal cap explants cultured until stage 29-30. In all cases, the expression of markers at stage 29 was identical to that observed at stage 12.5, indicating that time of culture is not a significant factor in these experiments (data not shown).
These results suggest that, although myocardin is able to precociously activate transcription of a subset of myocardial markers, it is not sufficient to initiate the complete cardiac development program. Investigation of the expression of other cardiogenic genes supports this proposal. First, transcription of the 

-precociously activate transcription of a subset of myocardial markers, it is not sufficient to initiate the complete cardiac development program. Investigation of the expression of other cardiogenic genes supports this proposal. First, transcription of the Nkx2-5 or Gata4 transcription factors was not activated in response to myocardin (Fig. 4A). Both of these genes are essential for normal cardiogenesis (Lyons et al., 1995; Tanaka et al., 1999; Molkentin et al., 1997). We note, however, that expression of SRF and the MADS box transcription factor, Me2A, were both activated in animal caps (Fig. 4A), indicating that at least some cardiac regulatory factors lie downstream of myocardin and may play a role in ectopic activation of cardiac markers. Transcription of the myocardin gene itself, however, was not activated in animal caps (data not shown), indicating that myocardin does not directly regulate its own expression. We also addressed the possibility that the marker gene expression observed in response to myocardin might be due to activation of the skeletal muscle pathway. This is particularly relevant for the cardiac α-actin marker, which is expressed in both cardiac and skeletal muscle tissues in the embryo. RT-PCR analysis showed that no transcripts were present for the general mesoderm marker, brachyury (Xbra), the myogenic determination genes MyoD, Mf5, MRF4 or myogenin, nor for the skeletal muscle marker, skMLC (Fig. 4B), demonstrating that the skeletal muscle program was not activated in the animal cap explants.

**Myocardin cooperates with cardiogenic factors to regulate transcription**

The failure to observe MLC2 transcription in animal caps was unexpected since the MLC2 promoter is regulated by myocardin in transfection assays using COS cells (Wang et al., 2001). One possible explanation for these findings is that activation of MLC2 expression may require transcription factors, in addition to myocardin, that are not present in animal cap cells. Therefore, we tested the ability of Gata4, Nkx2-5 and Tbx5, all of which are important regulators of cardiac gene expression (Durocher et al., 1997; Chen and Schwartz, 1996; Lyons et al., 1995; Tanaka et al., 1999; Bruneau et al., 2001) to cooperate with myocardin in activation of MLC2 expression. Mixtures of mRNAs encoding all four factors were tested in the animal cap assay at stage 12.5 (Fig. 5A). First, we observed that co-expression of all four transcription factors succeeded in activating expression of MLC2 (lane labeled M+N+G+T). This activation was not observed using a mixture of the three transcription factors in the absence of myocardin (lane marked N+G+T). Second, the presence of all four transcription factors did not significantly increase MHCα or SM22 expression levels relative to myocardin alone, suggesting that the other factors are not required for efficient expression of these genes in the animal cap. Third, no beating tissue was observed in animal caps co-expressing all four transcription factors, even when the explants were cultured until the equivalent of stage 45, approximately 5 days after a beating heart would form in the intact embryo (data not shown). This result indicates that the presence of this particular combination of factors is not sufficient to activate the complete pathway leading to myocardial differentiation. Testing of myocardin with different combinations of transcription factors (Fig. 5B), revealed that the expression of myocardin and Gata4 alone was sufficient to activate MLC2 transcription in the animal cap. This result is consistent with recent transgenic studies of the Xenopus MLC2 promoter that show essential roles for SRE and GATA regulatory elements (Latinkic et al., 2004).

**Myocardin loss of function by morpholino knockdown results in a block to cardiac differentiation**

To determine whether myocardin is essential for expression of cardiac genes in the developing embryo, we utilized the antisense morpholino method for inhibition of translation of specific mRNAs. It was only possible to examine cardiac marker expression in these experiments because smooth muscle differentiation occurs rather late in Xenopus development (after about stage 35) and is therefore outside of the window for morpholino interference (Heasman et al., 2000). Two independent morpholinos, MO1 and MO2, complementary to non-overlapping sequences within the 5′ end of the Xenopus myocardin mRNA were prepared and control experiments demonstrated that these effectively inhibited translation of a myocardin fusion transcript in the embryo (Fig. 6A,B). Based on limited sequence conservation, neither of these morpholinos is expected to inhibit translation of MRTF-A or B. For loss-of-function experiments, MO1 was injected into one cell of a two-cell embryo, so that the uninjected side served as a stage-matched negative control. The injected
embryos were then raised until stage 28-29 when they were assayed for cardiac marker gene expression by in situ hybridization. Injection of 10 ng of MO1 resulted in a significant inhibition of $\text{MHC}\alpha$ expression on the side of injection (Fig. 6C and Table 1). Inhibition of $\text{MHC}\alpha$ expression was observed in 57% of experimental embryos (13/23). Using $\text{MLC2}$, an independent marker of cardiac differentiation, inhibition was observed in 86% of embryos (42/49). Asymmetry of cardiac marker expression was observed in only 4-5% of uninjected controls (Table 1). The independent morpholino sequence, MO2, also inhibited expression of $\text{MHC}\alpha$ and $\text{MLC2}$, although the efficiency was somewhat less than that observed for MO1 (Table 1). In situ hybridization detection of $\text{Nkx2-5}$ transcripts showed that expression of this precardiac marker sequence was unaffected by myocardin MO treatment (Fig. 6C). Similarly, Gata4 levels were not influenced by the presence of the myocardin MO (data not shown). These results indicate that precardiac tissues are still present in MO-treated embryos and that the $\text{Nkx2-5}$ and Gata4 expression pathways are independent of myocardin activity. Moreover, transverse sections of control and myocardin MO-treated embryos at the linear heart tube stage (stage 34) revealed that the normal morphogenic movements associated with heart tube formation (i.e. delamination) are disrupted on the MO-injected side while the uninjected side of the embryo appears normal (Fig. 6D). Overall, these loss-of-function studies show that myocardin activity is essential for expression of cardiac differentiation markers and for cardiac morphogenic movements during $\text{Xenopus}$ development.

### Discussion

**Myocardin activates endogenous expression of cardiac differentiation markers**

Several recent papers have emphasized the role of myocardin as a regulator of the smooth muscle differentiation pathway, but our results indicate that myocardin also plays a central role in the pathway leading to myocardial development. During $\text{Xenopus}$ development, expression of myocardin is initially
Development

promoter activated high levels of muscle markers, including myocardin initiated transcription of a number of smooth existing regulatory pathways. In the animal cap assays, specific transcription factors and without subverting pre-least some myocardial markers in the absence of other cardiac-indicates that myocardin is able to activate expression of at exception of endodermal tissue. Directed expression of observed at a variety of locations in the embryo, with the differentiation in the embryo.

Injection experiments show that expression of myocardin is able to activate high levels of expression of myocardial marker genes at ectopic locations in the Xenopus embryo (Fig. 3) or in animal cap tissue (Fig. 4). Ectopic expression of marker transcripts appeared to be most robust in neural tissues, but was observed at a variety of locations in the embryo, with the exception of endodermal tissue. Directed expression of myocardin in neural tissues using the neural β-tubulin promoter activated high levels of MHCα expression throughout neural tissues as late as the swimming tadpole stage. This indicates that myocardin is able to activate expression of at least some myocardial markers in the absence of other cardiac-specific transcription factors and without subverting pre-existing regulatory pathways. In the animal cap assays, myocardin initiated transcription of a number of smooth muscle markers, including SM22, SM actin and CalpH1. This is in agreement with previous studies that have demonstrated the ability of myocardin to activate endogenous smooth muscle genes in 10T1/2 fibroblasts and mouse embryonic stem cells (Du et al., 2003). Myocardin also activated a range of different myocardial marker genes in animal cap explants (Fig. 4). For all of these differentiation markers, significant levels of transcript had already accumulated by the gastrulation stage (stage 12.5) much earlier than the earliest differentiation in the intact embryo (stage 25). This observation suggests that myocardin can over-ride the normal temporal program of cardiac or smooth muscle development and cause the immediate activation of target genes. It is important to note however, that we never observed striated structures or beating tissue at ectopic locations in the myocardin-injected embryos, or in animal cap explants, indicating that myocardin alone is not sufficient to activate the complete pathway leading to myocardial differentiation in this context.

The observed ability of myocardin to cause ectopic transcription of myocardial markers is not a common property of cardiac transcription regulators. For example, numerous experiments have attempted to activate marker expression in the whole embryo or in animal cap explants, with Nkx2-5 and GATA factors, either alone or in combination (Cleaver et al., 1996; Chen and Fishman, 1996; Fu and Izumo, 1995; Jiang and Evans, 1996). In all cases, marker gene expression was either absent or extremely weak. Similarly, none of these transcription factors were capable of activating detectable expression of MHCα in our experiments. The recent observation that Nkx2-5 is an upstream regulator of myocardin (Ueyama et al., 2003) suggests that instances where Nkx2-5 overexpression successfully triggered cardiac marker expression (Chen and Fishman, 1996; Fu and Izumo, 1995) may have occurred via myocardin activation. An important exception to the preceding discussion is the recent observation that Gata4 is capable of generating beating cardiac tissue in animal cap explant cultures (Latinkic et al., 2003). In this case however, induction of the cardiogenic program requires nearly 10-fold higher levels of Gata4 mRNA than the amounts of myocardin mRNA used in our experiments (Figs 4, 5) and differentiation marker expression only occurs after extended culture. A plausible explanation for these results is that Gata4 initiates a cascade of events resulting in cardiac differentiation, while myocardin directly switches on transcription from target promoters.

Myocardin cooperates with other cardiac regulatory factors

Although several cardiac marker genes were transcriptionally activated in response to myocardin expression in embryos and animal caps, we were never able to detect expression of the MLC2 gene. This is surprising since myocardin is able to activate transcription from the MLC2 promoter in COS cells (Wang et al., 2001; Wang et al., 2002). Previous studies have shown that transcription of myocardial genes is often regulated by cooperative interactions between transcription factors. For example, interactions between SRF, Nkx2-5, Gata4 and Tbx5 are known to be important for maximal expression from the ANF and cardiac α-actin promoters (Chen and Schwartz, 1996; Durocher and Nemer, 1998; Lee et al., 1998; Bruneau et al., 2001). Our experiments show that interactions with other transcription factors may also be important for myocardin activity, since co-expression of Gata4 with myocardin results in the induction of MLC2 expression (Fig. 5). Although this observation is consistent with direct interactions of the myocardin and Gata4 proteins, we cannot exclude the possibility that Gata4 activates expression of other transcription factor(s), which then cooperate with myocardin to regulate MLC2. Previous studies have suggested that dimerization of myocardin is required for transcriptional activity, and that dimerization is facilitated by the presence of multiple SRF binding sites (CARG boxes), in the target promoter (Wang et al., 2003). We note that the Xenopus MLC2 gene contains two CARG boxes in the promoter region (Latinkic et al., 2004), but that, in this instance, myocardin requires cooperation with Gata4 to activate transcription from the MLC2 promoter.

Myocardin loss-of-function and the genetic pathway to heart development

Previous studies using dominant negative versions of myocardin in Xenopus embryos resulted in the elimination of heart differentiation (Wang et al., 2001) suggesting an essential role for myocardin in cardiac development. However, mouse embryos lacking myocardin activity develop a fairly normal heart and die of vascular defects, presumably resulting from loss of vascular smooth muscle differentiation (Li et al., 2003). The relatively mild cardiac phenotype in the myocardin knockout mouse could be due to redundancy with the myocardin related factors (MRTF-A and MRTF-B), which are expressed in the developing heart in mice and possess similar
transcriptional properties (Wang et al., 2002). Since the MRTF-A and MRTF-B orthologues are not expressed in the developing Xenopus heart (Fig. 2G-I) we were able to use antisense morpholino knockdown methods to determine the role of myocardin in heart development, in the absence of rescuing activities. In these experiments, expression of the myocardial markers, MHCα and MLC2 was dramatically reduced or eliminated using two different morpholinos (Fig. 6C and Table 1). This result is consistent with previous experiments in which expression of a dominant negative form of myocardin eliminated cardiac differentiation in the Xenopus embryo (Wang et al., 2001). Furthermore, myocardin MO-treated embryos show disruption of the normal morphological movements associated with heart tube formation (Fig. 6D).

Overall, these results indicate an essential role for myocardin in Xenopus heart development and suggest that cardiogenesis in myocardin-null mice is partially rescued by redundant activities of MRTF-A and/or MRTF-B.

One of the unresolved questions relating to myocardin activity is the mechanism by which tissue-specific expression of target genes is regulated. In relatively naïve cells like Xenopus animal cap cells (Fig. 4) or mouse ES cells (Du et al., 2003), myocardin activates transcription of both cardiac and smooth muscle genes. Depending on the particular cell line in which myocardin is expressed, a different profile of smooth muscle and cardiac differentiation markers may be activated (Chen et al., 2002; Du et al., 2003; Wang et al., 2003). During normal embryonic development however, activation of myocardin target genes appears to be almost completely tissue specific. For example, expression of the smooth muscle marker, SM22, is never observed in the heart of Xenopus embryos (data not shown), but SM22 expression is highly activated by myocardin in Xenopus animal cap cells, together with a number of myocardial markers. Other authors have previously proposed that myocardin interacts with additional, tissue-specific transcription factors to modulate, either positively or negatively, its transcriptional activity (Du et al., 2003; Ueyama et al., 2003; Wang et al., 2003). It is interesting to observe therefore, that co-expression of myocardin with three additional cardiogenic transcription factors, Gata4, Nkx2.5 and Tbx5, in animal cap explants activated expression of both cardiac and smooth muscle markers (Fig. 5A). This result implies that none of these transcription factors is sufficient for suppression of smooth muscle gene expression in the heart. Identification of the proteins that help to specify myocardin target selection will be a key step towards understanding the cardiac and smooth muscle regulatory pathways.

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References


