Developmental Regulation of Myosin Gene Expression in Mouse Cardiac Muscle

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Abstract. Expression of the two isoforms of cardiac myosin heavy chain (MHC), MHCα and MHCβ, in mammals is regulated postnatally by a variety of stimuli, including serum hormone levels. Less is known about the factors that regulate myosin gene expression in rapidly growing cardiac muscle in embryos. Using isoform-specific 35S-labeled cRNA probes corresponding to the two MHC genes and the two myosin alkali light chain (MLC) genes expressed in cardiac muscle, we have investigated the temporal and spatial pattern of expression of these different genes in the developing mouse heart by in situ hybridization. Between 7.5 and 8 d post coitum (p.c.), the newly formed cardiac tube begins to express MHCα, MHCβ, MLC1 atrial (MLC1A), and MLC1 ventricular (MLC1V) gene transcripts at high levels throughout the myocardium. As a distinct ventricular chamber forms between 8 and 9 d p.c., MHCβ mRNAs begin to be restricted to ventricular myocytes. This process is complete by 10.5 d p.c. During this time, MHCα mRNA levels decrease in ventricular muscle cells but continue to be expressed at high levels in atrial muscle cells. MHCα transcripts continue to decrease in ventricular myocytes until 16 d p.c., when they are detectable at low levels, but then increase, and finally replace MHCβ mRNAs in ventricular muscle by 7 d after birth. Like MHCβ, MLCIV transcripts become restricted to ventricular myocytes, but at a slower rate. MLCIV mRNAs continue to be detected at low levels in atrial cells until 15.5 d p.c. MLC1A mRNA levels gradually decrease but are still detectable in ventricular cells until a few days after birth. This dynamic pattern of changes in the myosin phenotype in the prenatal mouse heart suggests that there are different regulatory mechanisms for cell-specific expression of myosin isoforms during cardiac development.

Cardiac muscle is known to contain at least two different isoforms of myosin heavy chain (MHC) and two myosin alkali light chains (MLC), which are encoded by distinct genes (Mahdavi et al., 1982; Barton et al., 1985, 1988). The genes encoding the two MHC proteins, called MHCα and MHCβ (Hoh et al., 1978), are organized in tandem (Mahdavi et al., 1984) and are developmentally and hormonally regulated (Lompré et al., 1984). These genes are also regulated differentially in response to cardiac hypertrophy due to hemodynamic overload (Izumo et al., 1987; reviewed in Nadal-Ginard and Mahdavi, 1989). The MLC genes, MLC1A and MLCIV, are coexpressed and developmentally regulated in cardiac and skeletal muscle (Barton and Buckingham, 1985; Lyons et al., 1990b). These MLC genes are regulated differentially during cardiac hypertrophy in humans (Cummins, 1982; Kurabayashi et al., 1988) but not in rodents (Rovner et al., 1990), and do not appear to be hormonally regulated (Schwartz et al., 1982). In the adult rodent heart, MLCIV is present in the ventricles and MLC1A in the atria, while MHCα is the major isoform in both compartments.

Most of the reports on myosin expression in embryonic cardiac muscle have involved antibody studies of the chick heart. Zhang et al. (1986) and Sweeney et al. (1987) report that at Hamburger-Hamilton stage 10 (1.25 d in ovo), only the adult ventricular MHC is detectable. Approximately 1 d later, stage 12-15, atrial MHC starts to be expressed in embryonic chick hearts. There is one report of an antibody study of MHCs in the embryonic rat heart. De Groot et al. (1989) show that MHCα and MHCβ are coexpressed in tubular rat hearts (embryonic day 10-11). Biochemical studies of developing mammalian hearts have shown that MHCβ is the predominant MHC in late fetal ventricles (Lompré et al., 1981; Schwartz et al., 1982). However, there are variations in the developmental patterns of MHC protein.
expression in the ventricles of different mammalian species (Lompré et al., 1981). Variations in MHC proteins in atria and ventricles appear to be related to animal size (Syrovy, 1985). There are a few studies of the MLC protein content of fetal cardiac muscle; these have shown that MLC1A is expressed in fetal ventricles (Whalen and Sell, 1980; Cummins and Lambert, 1986).

We are interested in the regulation of myosin gene expression in the developing mammalian heart, particularly at early stages in the embryo. To characterize the normal pattern of expression of MHC and MLC genes, we have used isoform-specific cRNA probes to MHCα, MHCβ, MLC1A, and MLCIV mRNAs for in situ hybridization of the mouse embryonic and fetal heart. We show that, after an initial high level of coexpression in the myocardium of the cardiac tube at 8 d post coitum (p.c.), each of these transcripts has a different pattern of accumulation suggesting that each is regulated in a different cell-specific and stage-specific manner in developing atrial and ventricular myocytes.

Materials and Methods

Preparation and Prehybridization of Tissue Sections

The protocol that was used to fix and embed C3H and BALB/c mouse embryos, fetuses, and postnatal hearts is described in detail in Sassoon et al. (1988). Ages and numbers of embryos and fetuses examined are listed in Table I. Briefly, embryos were fixed in 4% paraformaldehyde in PBS, dehydrated, and infiltrated with paraffin. 5-7-μm-thick serial sections were mounted on subbed slides (Gall and Pardue, 1971). One to three sections were mounted per slide, deparaffinized in xylene, and rehydrated. The sections were digested with proteinase K, postfixed, treated with triethanolamine/acetic anhydride, washed, and dehydrated.

Probe Preparation

To distinguish between transcripts within the myosin multigene family, it is necessary to use probes derived from the 3' or 5' noncoding untranslated regions (UTR) of the mRNAs. Appropriate restriction fragments or oligonucleotides were subcloned into the vector, Bluescribe + (Stratagene Cloning Systems, La Jolla, CA) and grown in E. coli TGI. The following probes were used. 1) 3' UTR of mouse MLC1Atrial mRNA (Barton et al., 1988) 5'TTAATGAAAC TC CAAGC~TCTTTATTTC CA~GGTT-...
GTGGGTCAAGAGAAAGCATGTGATCCAGATCCGTAACAGTAACAGGGGCTGTGAATCCTGCTTCTCTCAAGCACCAGCAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAG   

Figure 2. MHCβ is restricted to ventricular cells at an early stage in cardiac muscle development. (a) Phase-contrast micrograph of a parasagittal section through a 9.5-d p.c. embryo with 21–24 somites. (b) Dark-field micrograph of the same section as in a hybridized to the MLCIV probe. (c) A parallel section hybridized with the MHCβ probe. (d) A parallel section hybridized to the MHCα probe. VA, ventriculoarterial portion; A, atrium; H, hyoid arch. Bar, 300 μm.

Figure 3. Myosin gene transcripts are detected in the developing sinuatrial transition (a–f, arrowheads). (a) Phase-contrast and (b) dark-field micrographs of a parasagittal section through a 10.5-d p.c. embryonic heart hybridized with the MLCIA probe. Serial slides were hybridized to the probes for (c) MHCα, (d) MHCβ, and (e) MLCIV. MHCβ transcripts continue to be expressed in the right side of the sinuatrial transition (d, right arrowhead). (f) A parallel section, 50 μm from that in e, was hybridized with the MLCIA probe, showing the sinuatrial transition (arrowhead) and the ventriculoarterial canal (VA; which is indicated by arrows in c and e). (There is a small fold in the section over the atrium in c.) T, trabeculae; A, atrium; V, ventricle. Bar, 300 μm.
Figure 4. Between 10.5 and 15.5 d.p.c., MLCIV transcripts gradually become restricted to ventricular cells. Parallel parasagittal sections through an 11.5-d.p.c. mouse heart hybridized with (a) the MLCIV probe and with the MHCα probe (b) phase micrograph and (c) corresponding dark-field micrograph. The boundary for restriction of atrial and ventricular transcripts is the atrioventricular transition (a and c, arrowheads). ECC, endocardial cushions; OR, outflow ridges; IVS, interventricular septum, VV, venous valves. Bar, 400 μm.

EMBL/GenBank/DDJB under accession numbers M12291 and X53490. The cRNA transcripts were synthesized according to manufacturer's conditions (Stratagene Cloning Systems) and labeled with 35S-UTP (>1,000 Ci/mmol; Amersham International, Amersham, UK). cRNA transcripts larger than 100 nucleotides were subjected to alkali hydrolysis to give a mean size of 70 bases for efficient hybridization.

Hybridization and Washing Procedures
Sections were hybridized overnight at 52°C in 50% deionized formamide, 0.3 M NaCl, 20 mM Tris-HCl, pH 7.4, 5 mM EDTA, 10 mM NaPO₄, 10% dextran sulfate, 1× Denhardt's, 50 μg/ml total yeast RNA, and 50–75,000 cpm/μl 35S-labeled cRNA probe. The tissue was subjected to stringent washing at 65°C in 50% formamide, 2×SSC, 10 mM DTT and washed in PBS before treatment with 20 μg/ml RNase A at 37°C for 30 min. Following washes in 2×SSC and 0.1×SSC for 15 min at 37°C, the slides were dehydrated and dipped in Kodak NTB-2 nuclear track emulsion and exposed for 1 wk in light tight boxes with dessicant at 4°C. Photographic development was carried out in Kodak D-19. Slides were analyzed using both light- and dark-field optics of a Zeiss Axiophot microscope.

Figure 5. Atrial-specific transcripts disappear from the ventricle in a gradient of expression. (a–d) Dark-field micrographs of parasagittal sections through a 15.5-d.p.c. mouse heart. (e–h) Dark-field micrographs of parasagittal sections through a 16.5-d.p.c. mouse heart. Serial slides at the two different stages were hybridized with the MHCα probe (d and h), the MLCIA probe (a and e), the MHCβ probe (c and g), and the MLCIV probe (b and f). R, ribs; pulmonary blood vessel (arrow). Bars: (a–d) 600 μm; (e–h) 750 μm.
Figure 6. At 15 d p.c., MHCα and MLC1A transcripts begin to be detectable around some blood vessels outside the heart. (a) Bright-field micrograph of a 15.5-d p.c. mouse thorax showing the inferior vena cava (IVC), which expresses MLC1A transcripts (b, arrows). At 17.5 d p.c. (c) MLC1A transcripts are detected in a sleeve of atrial muscle that surrounds some pulmonary vessels (arrowheads). Parallel sections of neonatal mouse hearts were hybridized with the probes for (d) MLC1A, (e) MHCα, and (f) MHCβ. Pulmonary vessels (d and e, arrowheads); LI, liver; A, atrium; L, lung; D, diaphragm. Bars: (a and b) 300 μm; (c) 800 μm; (d-f) 800 μm.

Results

By 8 d p.c. in the mouse embryo, a tubular heart has formed and the first myocardial contractions occur (Rugh, 1990; Sissman, 1970). At first, the tubular heart is S-shaped. Serial sections from the midsagittal section in Fig. 1 c in the order Fig. 1, c, b, d, and e show the lower half of the S-curve, or the atrioventricular junction (Pexeider et al., 1989), of the developing heart. At this stage, each of the four myosin transcripts that we studied is expressed at a high level in all of the myocardial cells (Fig. 1). This observation suggests that all of the myosin genes in the heart are upregulated initially in a coordinated fashion. These results are consistent with antibody studies of the myofibrillar proteins in the developing rodent heart, which have shown that, at embryonic day 10–11 in the rat, there is coexpression of MHCα and MHCβ throughout the heart (De Groot et al., 1989). Embryonic day 10 in the rat corresponds to 8 d p.c. in the mouse (Rugh, 1990). Three of the four cardiac myosin transcripts we studied, MHCβ, MLC1A, and MLCIV, are coexpressed in developing skeletal muscle. However, these transcripts are detected in cardiac muscle well before they are detected in developing somites (Fig. 1, b, d, and e; Lyons et al., 1990b).

The first major change detected in the pattern of myosin transcript distribution in the developing heart occurs around 9 d p.c. At this stage, a distinct atrium and ventricle have formed (Rugh, 1990; Theiler, 1989). In Fig. 2, parallel parasagittal sections of a 9.5-d p.c. embryo with 21–24 somites demonstrate that MLCIV mRNAs (Fig. 2 b) are detected in all myocardial cells, whereas MHCβ (Fig. 2 c) is largely restricted to cells in the ventricle and the outflow tract or ventriculoarterial portion (Pexeider et al., 1989). Only a few atrial cells continue to express MHCβ (Fig. 2 c). MHCα transcripts (Fig. 2 d) are present at high levels in both the atrium and ventricle, but are decreasing in the ventriculoarterial portion. MLCIA mRNAs are expressed in all myocardial cells at this stage (data not shown).

At 9 d p.c., trabeculations are first seen in the ventricles (Sissman, 1970), and they are clearly visible in ventricles of a 10-d p.c. mouse embryo with 28 somites (Fig. 3). In the
Figure 7. Between 17.5 d p.c. and 7 d after birth, atrial and ventricular cells switch to the adult pattern of myosin gene expression. Dark-field micrographs of parallel sections of a 7-d mouse heart hybridized with the probes for (a) MHCβ, (b) MHCα, (c) MLC1A, and (d) MLC1V. RC, red blood cells. Bar, 950 μm.

Table 1. Expression of Actin and Myosin Genes in Developing Mouse Cardiac Muscle

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developing heart, the growth rate of the trabeculated regions is thought to be greater than the non trabeculated portions of heart, because in the adult, the portion of the ventricular wall that is trabeculated accounts for >90% of the total ventricular mass (DeHaan and O’Rahilly, 1978). In the trabeculated ventricle, the levels of MHCα mRNAs decrease gradually beginning at 10 d p.c. (Fig. 3 c).

Between 10 and 12 d p.c., another difference in the spatial pattern of myosin gene expression in the embryonic heart is detected in the developing sinus atrial transition (Fig. 3). Transcripts for the atrial isoforms: MLCIA (Fig. 3, a, b, and f) and MHCα (Fig. 3 c), but not MLCIV (Fig. 3 e), even though it is coexpressed in atrial cells at this stage, are detected in the sinus atrial transition. MHCβ is detected at a low level in one portion of the sinus atrial transition (Fig. 3 d, right arrowhead). This result agrees in part with the observations of De Groot et al. (1989), who noted that MHCα and MHCβ proteins are coexpressed in the developing sinus node in rat embryos. In the sinus atrial transition, there is a distinct ring or column of cells (Anderson et al., 1978) that forms the primordium of the sinus node. Fig. 3 f is a parallel section, hybridized with the MLCIA probe, ~50 μm from the section in Fig. 3 e, showing the continuity of this ring of cells in the sinus atrial transition.

As development proceeds, the level of MHCα mRNAs decreases in the ventricle (Fig. 4, b and c) and MLCIV transcript levels decrease in the atrium (Fig. 4 a). Fig. 4 contains two parasagittal sections through the atrioventricular junction and ventriculoarterial septum of an 11.5-d p.c. mouse embryo. The endocardial cushions, outflow ridges, and a portion of the developing interventricular septum can be seen clearly in the phase-contrast micrograph (Fig. 4 b). The boundary for the expression of the atrial- and ventricular-specific transcripts is the atrioventricular transition (Fig. 4, arrowheads). The atrioventricular conduction system develops both in this transition and in a portion of the interventricular septum (Viragh and Challice, 1982).

The next major change in the spatial distribution of cardiac myosin transcripts in the developing fetal heart is shown in Fig. 5. At 15.5 d p.c., MLCIA transcripts (Fig. 5 a) and MHCα transcripts (Fig. 5 d) begin to disappear from the ventricle in a gradient of expression that runs from very low levels of expression in the ventricular wall to high levels of expression in the papillary muscles and interventricular septum. By 16.5 d p.c., MLCIA transcripts (Fig. 5 e) are only detected in the central portion of the ventricle, and MHCα (Fig. 5 h) transcripts have fallen to a very low level in the ventricle. Both MLCIA and MHCα mRNAs continue to be expressed at high levels in the atria (Fig. 5, a and e and d and h), and both MLCIV mRNAs (Fig. 5, b and f) and MHCβ mRNAs (Fig. 5, c and g) are expressed at high levels in the ventricles.

In addition to their expression within the heart itself, MLCIA and MHCα transcripts are expressed outside of the heart along the pulmonary and caval vessels. Fig. 6 a is a phase-contrast micrograph of a 15.5-d p.c. mouse showing the inferior vena cava which runs from the liver to the right atrium. Under dark-field illumination (Fig. 6 b), MLCIA transcripts can be seen over portions of the inferior vena cava (arrows) near the liver and close to the atrium. At 17.5 d p.c. (Fig. 6 c), and at birth (Fig. 6 d), MLCIA transcripts are detected around pulmonary vessels at some distance from the atrium. MHCα transcripts (Fig. 6 e) are also expressed around these vessels. These results are consistent with reports of myocardial extensions or sleeves over pulmonary and caval veins in rodents (Kramer and Marks, 1965; Nathan and Gloobe, 1970). The hybridization of the MHCα and MLCIA probes to the pulmonary and caval vessels is not due to crosshybridization with smooth muscle myosin transcripts since no hybridization was detected to the smooth muscle in other blood vessels, such as the aorta, or in the gut (data not shown).

After decreasing to their lowest level in the fetal ventricle (Fig. 5 h) at 16.5 d p.c., MHCα transcripts begin to increase rapidly. At birth, MHCα transcripts (Fig. 6 e) are present at higher levels than MHCβ transcripts (Fig. 6 f). This switch continues until MHCα transcripts (Fig. 7 b) have replaced MHCβ transcripts (Fig. 7 a) in the heart 7 d after birth. This result is consistent with the observation of Lompré et al. (1981), who detected only MHCα protein in 7-d postnatal mouse ventricles. Also at this stage, MLCIA transcripts (Fig. 7 c) are completely restricted to the atrium and only MLCIV transcripts (Fig. 7 d) are detectable in the ventricle.

Table I summarizes the results for in situ hybridization with each of the myosin probes used and lists the number of embryos, fetuses, or postnatal hearts examined at each stage. We did not detect any skeletal muscle-specific MHC or MLC at any stage in the developing heart (Lyons et al., 1990b). We also were unable to detect any MHC embryonic, which has been reported to be expressed in conductive tissue in rodent hearts (Gorza et al., 1988) around the time of birth (data not shown).

**Discussion**

We have described the temporal and spatial pattern of expression of four cardiac myosin genes in embryonic and fetal mouse cardiac muscle. Although three of the four myosin gene transcripts we studied are also expressed in skeletal muscle, these genes, encoding MHCβ, MLCIA, and MLCIV, are regulated differently in the two types of striated muscle (see Lyons et al., 1990b). With the exception of some head muscles, which coexpress developmental isoforms at all stages (Weiczoreck et al., 1985; Soussi-Yanicostas et al., 1990), myosin gene transcripts and proteins are expressed in a distinct sequence (Whalen et al., 1981; Lyons et al., 1983; Lyons et al., 1990a, b) during skeletal muscle development rather than being upregulated together initially and subsequently modulated during development.

Our results suggest that, in cardiac muscle, myosin genes are all expressed at high levels as soon as the cardiac tube forms, and that the expression of each gene is modulated in a different cell-specific manner during development. At 8 d p.c., in the tubular heart, before distinct atrial and ventricular chambers form, each of the myosin gene transcripts we studied are detected throughout the myocardium. This is consistent with the observation that the first myocardial contractions occur at 8 d p.c. in the mouse (Rugh, 1990; Sissman, 1970), suggesting that all of the myosin genes are expressed coordinately. In a similar fashion, cardiac and skeletal α-actin genes are probably coactivated early in cardiac development (Sassoon et al., 1988), although skeletal α-actin mRNAs are always detected at a low level in the
heart. The recent results of Rudnicky et al. (1990) concerning the differentiation of cardiac myocytes from DMSO-treated embryonal carcinoma cells in vitro support our findings. These authors found that MHCα, MHCβ, MLC2A, and MLCIV proteins were coexpressed in mononucleated myocytes, and they suggest that these cells are analogous to cells of the early embryonic myocardium.

Results of antibody studies of MHCs in the embryonic chick heart (Zhang et al., 1986; Sweeney et al., 1987) have shown that the ventricular MHC protein is expressed ~1 d before the atrial MHC protein is detected. We were not able to detect any differences in timing or localization of expression of the contractile protein genes we studied in the embryonic tubular heart of the mouse. In a mouse embryo without somites, at a stage slightly earlier than that shown in Fig. 1, we observed the same pattern of coexpression of the myosin isoforms (data not shown).

As the cardiac tube loops and rotates upon itself to form the distinct atrial and ventricular chambers, MHCβ transcript levels decrease rapidly in the atrium, but continue to be expressed at high levels in the ventricle. MHCβ has a lower myosin ATPase than MHCα (Hoh et al., 1978), and cardiac muscle cells expressing MHCβ have a lower velocity of shortening (Schwartz et al., 1981). These observations suggest that the higher levels of expression of MHCβ transcripts in the ventricle than in the atrium may correspond to the differences in hemodynamic load in the different chambers of the embryonic heart. This hypothesis is supported by the observation that, after birth, cardiac hypertrophy due to hemodynamic overload is accompanied by a reexpression of MHCβ transcripts in the rodent ventricle and a decrease in MHCα transcripts (e.g., Izumo et al., 1987). The changes in the pattern of expression of the MHC genes in the embryonic atria and ventricles may also be correlated with changes in the expression of other genes such as those encoding membrane proteins or cytoplasmic enzymes associated with contraction (Ingwall et al., 1985).

In the embryonic chick heart, MHC protein isoform expression is correlated with local differences in the contraction pattern of the heart (de Jong et al., 1987). There is coexpression of MHCα and MHCβ in parts of the heart with peristaltic contractions, but a single isoform of MHC protein is expressed in synchronously contracting parts of the heart (de Jong et al., 1987). The switch from peristaltic contraction to synchronous contraction in the chick ventricle coincides with the appearance of trabeculations in the ventricular myocardium and with a switch from coexpression of MHC proteins towards expression of MHCβ alone (de Jong et al., 1987).

The pattern of MLC gene expression in the developing mouse heart is not coordinated with that of the MHC genes. MHCβ mRNAs are restricted to ventricular cells, except for some cells of the sinusatrial transition, by 10.5 d p.c., but MLCIV mRNAs are detected in atrial cells at a high level until 11.5 d p.c., and at a low level until 15.5 d p.c. This result does not agree with that of Rovner et al. (1990), who noted that MLCIA is the exclusive MLCI mRNA expressed in the rat atrium throughout development. MLCIA transcripts continue to be expressed at a high level in ventricular cells as the level of MHCα transcripts drops off gradually in the embryonic mouse ventricle. When MHCα transcript levels increase in ventricular cells after 16.5 d p.c., MLCIA transcript levels do not increase, but continue to be restricted to the atrium. Since MLCIA transcripts are expressed in ventricles at stages where MHCβ is the predominant MHC isoform, and MLCIV is expressed in atria at stages where MHCα is the only MHC isoform, these MLCs must be able to freely associate with either MHC isoform. Whether this association of atrial and ventricular myosin isoforms plays a role in regulating contractility in the heart during development is not clear. There are conflicting reports on the effect of different MLC combinations with MHC on alterations in myosin ATPase and shortening velocity, which are known to be correlated (Barany, 1967). Wagner and Stone (1983) found that myosin alkali light chain exchange did not increase the ATPase activity of MHC SI fragments in vitro. However, Sweeney et al. (1988) reported differences in shortening velocities correlated with myosin alkali light chain ratios in isolated skeletal muscle fibers.

The spatial pattern of decrease in the levels of MLCIA transcripts in fetal ventricles is striking. Beginning at ~15 d p.c., MLCIA transcripts begin to disappear in a gradient running from the epicardium toward the endocardium. A similar gradient of expression has been observed for the disappearance of MHCβ protein in the postnatal developing rat heart (Deschene et al., 1987). These authors also found that MHCβ protein reappears later in the rat heart in a gradient of expression in the opposite direction to that in which it disappeared, i.e., the endocardium toward the epicardium. Reexpression of MHCβ protein does not occur in the mature mouse ventricle (Lompré et al., 1981). Hemodynamic factors are known to influence MHC and MLC expression in the adult heart (Swynghedauw, 1986), and have been implicated in the morphogenesis of the chick heart (Clark, 1984). It remains to be established whether developmental changes in the distribution of MHC and MLC isoforms are regulated by such factors as intracardial flow patterns, pressure gradients in various chambers, and transmural gradients of wall stress.

It has been clearly demonstrated that some myosin genes are regulated differently in response to cardiac hypertrophy due to hemodynamic overload. In adult rat hearts, which normally have very low levels of MHCβ transcripts, MHCβ mRNAs accumulate in the ventricles within 2 d of the onset of cardiac hypertrophy induced by pressure overload (Izumo et al., 1987; Schiaffino et al., 1989). As MHCβ expression increases with hypertrophy, MHCα expression decreases. The response to cardiac hypertrophy can vary between species. For example, MLCIV was shown to be induced in overloaded atria in human subjects (Cummins, 1982; Kurabayashi et al., 1988), but not in rats (McNally et al., 1989). Some myosin genes, such as MLCIA, appear to be less responsive to cardiac hypertrophy (Rovner et al., 1990). The mechanisms by which myosin genes are regulated in response to hypertrophy are not known.

The pattern of expression of the MHCα gene in the developing mouse heart is unique in that, after being gradually restricted to atrial cells in the embryo, MHCα transcripts are reexpressed in ventricular cells from 2 d before birth, and replace MHCβ transcripts by 7 d after birth. Lompré et al. (1984) have suggested that there may be two distinct, developmentally regulated MHCα gene transcripts that differ only at their 3' ends. Our results do not support, but do not rule out, this hypothesis since our MHCα probe is complementary to the 3' UTR of the MHCα gene transcript.

The reexpression of MHCα transcripts may be due to se-
rum thyroid hormone levels in the late fetal mouse, because thyroid hormone (T3) has been shown to upregulate MHCα expression and to downregulate MHCβ (Lompré et al., 1984). Even though thyroid hormone levels are low at birth (Gambke et al., 1983) in rodents, there may be sufficient T3 supplied by the maternal circulation to begin the switch from MHCβ to MHCα gene expression in the heart. Chizzonite and Zak (1984) showed that in rats made hypothyroid from 15 d p.c., the amount of MHCα protein in the ventricle at 19 d p.c. is reduced compared to euthyroid controls, and that by 7 d after birth, the hypothyroid ventricle contains only MHCβ. Thus, hypothyroidism apparently reverses the switch in the two isoforms, which normally occurs during development. Other factors than T3, such as dietary carbohydrate, glucocorticoids (Sheer and Morldn, 1984), and catecholamines, particularly norepinephrine (Bishopric et al., 1989), may also be involved in this transition.

With the exception of thyroid hormone/receptor complexes, which have been shown to interact directly with the MHCα gene promoter (Izumo and Mahdavi, 1988; Glass et al., 1989), differentiation and transcriptional factors implicated in the initiation of the myogenic program and in myosin gene regulation in the heart are still mostly unidentified. Of the factors that have been identified in skeletal muscle, MyoDI (Davis et al., 1987), myogenin (Wright et al., 1989), myf-5 (Braun et al., 1989), and myf-6 (Braun et al., 1990), none are expressed in cardiac muscle (Sassoon et al., 1989; Lyons et al., 1990a). Thus, the cardiac myosin genes that are coexpressed in skeletal muscle must be regulated by different mechanisms in cardiac and skeletal muscle.

Our results support the hypothesis that the mechanisms of myosin gene regulation in these two types of striated muscle must be quite different, since the developmental patterns of expression of myosin genes in skeletal muscle are unlike those detected in cardiac muscle. After an initial high level of coexpression in the myocardium of the embryonic cardiac tube, the expression of each myosin gene is modulated in a different cell-specific and stage-specific manner in developing atrial and ventricular myocytes.

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References


Mahdavi, V., M. Periasamy, and B. Nadal-Ginard. 1982. Molecular character-