Myofilament Calcium Sensitivity and Cardiac Disease
Insights From Troponin I Isoforms and Mutants

Margaret V. Westfall, Andrea R. Borton, Faris P. Albayya, Joseph M. Metzger

Abstract—The heightened Ca\(^{2+}\) sensitivity of force found with hypertrophic cardiomyopathy (HCM)—associated mutant cardiac troponin I (cTnIR145G; R146G in rodents) has been postulated to be an underlying cause of hypertrophic growth and premature sudden death in humans and in animal models of the disease. Expression of slow skeletal TnI (ssTnI), a TnI isoform naturally expressed in developing heart, also increases myofilament Ca\(^{2+}\) sensitivity, yet its expression in transgenic mouse hearts is not associated with overt cardiac disease. Gene transfer of TnI isoforms or mutants into adult cardiac myocytes is used here to ascertain if expression levels or functional differences between HCM TnI and ssTnI could help explain these divergent organ-level effects. Results showed significantly reduced myofilament incorporation of cTnIR146G compared with ssTnI or wild-type cTnI. Despite differences in myofilament incorporation, ssTnI and cTnIR146G expression each resulted in enhanced myofilament tension in response to submaximal Ca\(^{2+}\) under physiological ionic conditions. Myofilament expression of an analogous HCM mutation in ssTnI (ssTnIR115G) did not further increase myofilament Ca\(^{2+}\) sensitivity of tension compared with ssTnI. In contrast, there was a divergent response under acidic pH conditions, a condition associated with the myocardial ischemia that often accompanies hypertrophic cardiomyopathy. The acidic pH-induced decrease in myofilament Ca\(^{2+}\) sensitivity was significantly greater in myocytes expressing cTnIR146G and ssTnIR115G compared with ssTnI. These results suggest that differences in pH sensitivities between wild-type ssTnI and mutant TnI proteins may be one factor in helping explain the divergent organ and organismal outcomes in TnI HCM- and ssTnI-expressing mice. (Circ Res. 2002;91:525-531.)

Key Words: troponin I ☐ myofilament proteins ☐ hypertrophic cardiomyopathy ☐ heart

Familial hypertrophic cardiomyopathy (HCM) is an autosomal dominant disorder resulting from diverse mutations within thick and thin filament contractile proteins.\(^1,2\) Mutations within individual contractile proteins have been shown to cause primary alterations in myofilament Ca\(^{2+}\) sensitivity of force production in myocytes and in the hearts from animal models expressing these mutations.\(^3\) These changes in myofilament Ca\(^{2+}\) sensitivity are postulated to be important for development of the clinical and pathological manifestations of HCM.\(^4\) However, the mechanism whereby a primary change in myofilament Ca\(^{2+}\) sensitivity leads to the compensatory or dysfunctional structure/function responses observed in the human disease state is not well understood.

The thin filament regulatory protein troponin I (TnI) is known to directly influence the myofilament’s response to Ca\(^{2+}\) activation.\(^4\) The human cTnIR145G mutation,\(^5\) and the analogous cTnIR146G mutation in transgenic mouse hearts,\(^6\) increases myocardial Ca\(^{2+}\) sensitivity of tension. In transgenic mice, expression of cTnIR146G causes myocyte hypertrophy, myofibrillar disarray, fibrosis, and premature death, outcomes attributed to the cTnIR146G.\(^6\) For comparison, the slow skeletal troponin I (ssTnI) isoform, normally expressed only during early cardiac development,\(^7,8\) also increases myofilament Ca\(^{2+}\) sensitivity of tension,\(^4\) yet ssTnI transgenic mice have apparent normal cardiac morphology and life span.\(^9\) These findings suggest that other factors, together with heightened Ca\(^{2+}\) sensitivity, must be associated with the cTnIR146G mutation to cause these divergent organ-level outcomes between ssTnI and R146G transgenic mice. In the present study, Ca\(^{2+}\)–activated tension under physiological ionic conditions is measured in adult myocytes expressing ssTnI or cTnIR146G, for comparison to results previously reported in papillary muscles from transgenic mice.\(^6\) In addition, cTnIR146G expression levels in transgenic mice lacking detectable pathology do show evidence of myocardial hypoxia/ischemia.\(^5\) This appears significant, because myocardial ischemia has been documented in asymptomatic patients with HCM.\(^10\) Given that hypoxia/ischemia-mediated cellular acidosis is known to directly depress myocardial contractile function,\(^11-13\) we tested the hypothesis that under acidic pH conditions, ssTnI and cTnIR146G would have divergent effects on adult cardiac myocyte contractile function. To test this hypothesis, the influence of acidic conditions on myofilament tension is compared in adult...
ventricular myocytes expressing cTnI, ssTnI, mutant cTnI, or mutant ssTnI after gene transfer. Our results provide evidence that the apparent paradox of heightened Ca\(^{2+}\) sensitivity in myofilaments with mutant TnI or wild-type ssTnI is at least in part explained by the differential pH-dependent change in tension observed in myofilaments expressing mutant TnI proteins compared with wild-type ssTnI.

### Materials and Methods

#### Mutagenesis Strategy and Generation of Adenoviral Vectors

The rat cTnIR146G and rat ssTnIR115G mutants (Figure 1A) were constructed using a pGEMZ vector containing cTnI and ssTnI cDNAs (kind gifts of A. Murphy, MD, Johns Hopkins University, Baltimore, MD), respectively. The Strategene Quick Change site-directed mutagenesis kit\(^{16}\) was used to mutagenize pGEM-3ZcTnI and pGEM-3ZssTnI with oligonucleotide primers (cTnI primer 1: CGGCCCACTCTCCGCAGATGAGAATCTCAGCAG; cTnI primer 2: CTGTGAGATTCTCAGGGCCCTGGCCG; ssTnI primer 1: CGTCACCCCTCGGCGGGACCCTGGTCCGTGTCTC; primer 2: GAGACACCGACC-GGCCCAGGGTGGACG). A FLAG epitope (DYKDDDDK; Sigma) was engineered into the carboxyl-terminus of cTnI cDNA by PCR mutagenesis, as described by Michele et al.\(^{18}\) The 187-bp BamHI fragment of cTnIFLAG containing the FLAG epitope was ligated to a 594-bp COOH fragment of cTnIR146G to form cTnIR146GFLAG. Sequenced mutant TnI cDNA was subcloned into a shuttle vector\(^{16}\) to form pAdcTnIR146G, pAdssTnIR115G, pAdcTnIFLAG, and pAdcTnIR146GFLAG.

Recombinant replication-deficient adenovirus vectors were constructed by cotransfection of the shuttle vector containing the cDNA of interest with pJM17 in HEK 293 cells.\(^4\) Large preparations of each plaque-purified virus were separated on a CsCl\(_2\) gradient, stored in PBS, and titers obtained for each virus were on the order of 10\(^{10}\) plaque-forming units/mL.

#### Primary Cultures of Rat Ventricular Myocytes

Calcium-tolerant adult ventricular myocytes were isolated as described earlier.\(^{17}\) Details of the isolation procedure and viral incubations can be found in the expanded Materials and Methods section in the online data supplement available at http://www.circresaha.org.

#### Analysis of Protein Expression

Control and virus-treated cardiac myocytes cultured for 4 to 6 days were collected from each coverslip in sample buffer. Permeabilized myocytes were prepared by adding ice-cold relaxing solution (pH 7.0; see below) containing 0.1% Triton X-100 (TX-100) to myocytes for 1 minute, rinsing cells in relaxing solution lacking TX-100, and then collecting in sample buffer. Protein expression in intact and permeabilized myocytes was analyzed by Western blotting, as described by Westfall et al.\(^{18}\) using a 1:500 dilution of MAB 1691 (Chemicon), a monoclonal antibody recognizing all TnI isoforms, including cTnIFLAG and cTnIR146GFLAG. Sig-
ificant lower expression of cTnIR146GFLAG, relative to cTnIFLAG, was detected at 500 and 1000 MOI (multiplicity of infection) in adult cardiac myocytes 5 and 6 days after gene transfer. Samples in odd numbered lanes (ie, 1, 3, 5, 7, 9, 11, and 13) were collected on day 5, whereas samples in evenly numbered lanes (ie, 2, 4, 6, 8, 10, 12, and 14) were collected on day 6. Samples in lanes 1, 2, 5, 6, 11, and 12 received 500 MOI of virus, whereas myocyte samples shown in lanes 3, 4, 7, 8, 13, and 14 received 1000 MOI of indicated virus. Western blots were analyzed by incubating blots with MAB 1691 (1:500), a monoclonal Ab recognizing all TnI isoforms, including cTnIFLAG and cTnIR146GFLAG. Significant lower expression of cTnIR146GFLAG, relative to cTnIFLAG, was detected at 500 and 1000 MOI for both days 5 and 6 after gene transfer. Total TnI content remained unchanged in myocytes expressing cTnIR146G compared with endogenous TnI, although this mutant protein could not be distinguished from endogenous TnI on Western blots (see online data sup-plement). C. Representative Western blot analysis of cTnI, cTnIFLAG, and cTnIR146G expression in intact vs membrane-permeabilized myocytes 6 days after gene transfer. MAB 1691 mAb (1:500) was used to detect TnI expression. Proportion of cTnIFLAG or cTnIR146G expression relative to endogenous cTnI is not significantly affected by permeabilization of membranes. These results provide indirect evidence that neither mutant contractile protein detectably accumulates within the cytosol.

#### Indirect Immunodetection of Mutant TnI Expression and Myofilament Incorporation

Dual mAbs\(^{17,18}\) were used to determine the extent of thin filament remodeling resulting from mutant TnI expression within single cardiac myocytes in primary culture. To detect cTnIFLAG expres-
sion, the primary mAbs pairs used were the M2 anti-FLAG mAb (Sigma; 1:500) and MAB 1691 anti-TnI mAb (Chemicon; 1:500). Total replacement of cTnI with ssTnIR115G in myocytes was followed using the MAB 1691 and cTnI-specific TI-1 mAb,\(^{18}\) which does not recognize ssTnI. FLAG mAb and TI-1 mAb binding were each detected with a Texas Red–conjugated secondary goat anti-mouse Ab, whereas fluorescein isothiocyanate–conjugated goat anti-mouse Ab was used to detect MAB1691 binding. High-resolution images were obtained with a Noran OZ laser scanning
Measurement of Steady-State, Ca2+-Activated Tension in Single Cardiac Myocytes at pH 7.0 and 6.2

Single rod-shaped cardiac myocytes, attached to micropipettes coated with silicone adhesive, were permeabilized in 0.2% Triton X-100 for 1 minute. Sarcomere length was set at 2.20 μm and all tension measurements were performed at 15°C. Relaxing and activating solutions (pH 7.0 and pH 6.2) used for tension measurements contained 1 mmol/L free Mg2+, 4 mmol/L MgATP, 14.5 mmol/L creatine phosphate, 20 mmol/L imidazole, and sufficient KCl to yield an ionic strength of 180 mmol/L, as determined from the computer program by A. Fabiato. The pCa (−log[Ca2+]) of relaxing solution was 9.0, whereas the pCa of maximal activation solution was 4.0. Steady-state, Ca2+-activated isometric tension was measured at each pCa, as previously described in detail. Tension-pCa relationships were constructed by expressing tension (P) at various submaximal Ca2+ concentrations as a fraction of tension at maximal activation (Pm, pCa 4.0). Every third activation was performed at pCa 4.0 to bracket submaximal Ca2+ activations for normalization of tension. The Marquardt-Levenberg nonlinear least squares fitting algorithm was used to derive values for the Hill coefficient (nH) and Ca2+ required for half maximal activation (pCa50) from the tension/pCa relationship, using the Hill equation (\[P = (P_m - P) / (K^H + [Ca^{2+}]^H)\]), where P is the fraction of maximum tension (Pm), the pCa50 is used as an indicator of K, and nH is the Hill coefficient.

Statistics

Values are expressed as mean±SEM. Grouped comparisons were performed using an analysis of variance and post hoc Student-Newman-Keuls multiple comparison test, with a value of P<0.05 considered significantly different.

Results

Expression and Myofilament Incorporation of cTnIR144G

The extent of expression and myofilament incorporation of cTnIR144G in human myocardium5 and/or cTnIR144G in transgenic mice6 is not known. Expression of cTnIR144G in adult rat myocytes also could not be distinguished from endogenous cTnI by Western blot analysis (Figure 1B). Information about the degree of contractile protein expression and incorporation into the sarcomere is critical for subsequently establishing the specific effects of a particular isoform and/or mutation on the mechanical properties of myocytes. Thus, experiments initially focused on expression and myofilament incorporation of cTnIFLAG and cTnIR144GFLAG in adult rat cardiac myocytes, to distinguish the epitope-tagged TnI proteins from endogenous cTnI. cTnIR144G, cTnIFLAG, or cTnIR144GFLAG compared with control values (see online Table, available in the data supplement at http://www.circresaha.org). Maintenance of contractile protein stoichiometry and isoform expression, and the lack of cytosolic accumulation, together support the idea that each delivered mutant is specifically incorporated into the contractile apparatus by stoichiometric replacement of endogenous cTnI.

Immunolabeling experiments were carried out to directly analyze myofilament incorporation of mutant and wild-type TnI proteins in adult myocytes. A striated pattern of immunostaining was observed in controls (Figure 2A) and myocytes expressing cTnIFLAG or cTnIR144GFLAG (Figures 2C and 2E), using a mAb recognizing all isoforms of TnI. A striated immunolabeling profile was also observed with M2 anti-FLAG mAb in myocytes expressing cTnIFLAG and cTnIR144GFLAG (Figures 2D and 2F), but not control myocytes (Figure 2B). The consistent striated labeling pattern observed across the length and depth of myocytes expressing cTnIFLAG and cTnIR144GFLAG, and the absence of cytosolic accumulation of epitope-tagged protein further indicates there is specific incorporation of each mutant TnI protein into the myofilaments.

TnI Competition Assay

The differences in cTnIR144GFLAG replacement of cTnI compared with ssTnI7,14 and cTnIFLAG (Figure 1B) raised the possibility that cTnIR144G may not compete with equal effectiveness for sites within the myofilament. Cardiac myocytes exquisitely regulate total contractile protein.21 One potential therapeutic strategy for HCM mutations may be to competitively replace the human cTnIR144G mutation in the cardiac sarcomere via expression of wild-type cTnI. To test this idea in vitro, competition experiments were performed to determine whether vector-mediated cTnI expression could effectively out-compete cTnIR144G expression/incorporation at the level of the sarcomere (Figure 3). Adult myocytes were cotransduced with a range of AdcTnIFLAG doses, along with cTnI or cTnIR144G at a fixed titer. Western blot analysis indicated that cTnIFLAG expression is far lower in cTnI- compared with cTnIR144G-expressing myocytes. Thus, normal cTnI appears to have an advantage over mutant TnI for expression at the level of the sarcomere, over a broad range of transcriptional activation.

Myofilament Ca2+-Activated Tension in Myocytes Expressing cTnIR144G and ssTnI

The functional relationship between Ca2+ and steady state isometric tension was directly assessed in single, permeabil-
ized myocytes after TnI gene transfer. The position of the tension-pCa curve (pH 7.0), as measured by the pCa50, was comparable in control and AdcTnI-treated myocytes (Figure 4A). In contrast, the cTnIR146G mutation significantly increased pCa50 relative to control values, in agreement with earlier work in transgenic mouse myocardium. Replacement of endogenous cTnI with ssTnI also increased myofilament Ca2+/H11001 sensitivity, as demonstrated previously, and this increase was similar in magnitude to the increase observed with cTnIR146G (Figure 4A). Thus, under normal physiological activating conditions, cTnIR146G and ssTnI each cause heightened myofilament Ca2+/H11001 sensitivity.

Myocardial ischemia-mediated acidosis has been observed in patients with HCM. Evidence of ischemia has been detected in asymptomatic patients and transgenic mice. However, the effect of intracellular acidification on the contractile responses of myocytes expressing cTnIR146G is unknown. Thus, the tension-pCa relationship under acidic conditions (pH 6.2) was determined in myocytes expressing ssTnI, cTnI, and cTnIR146G (Figure 4B). Myocytes expressing cTnI and cTnIR146G responded to acidic pH with a large decrease in the pCa50, whereas the pH response was markedly blunted in myocytes expressing ssTnI (Figure 4B). We propose this difference in myofilament pH sensitivity between myocytes expressing cTnIR146G and ssTnI (Figure 4C) has important implications for the cardiac response to ischemia in patients carrying the HCM mutation (see Discussion).

Replacement of Endogenous cTnI With ssTnI Containing the Mutation Analogous to cTnIR146G

Acidosis decreases force generation in myocytes expressing normal and mutant cTnI. Thus, a mutant ssTnI, ssTnIR115G, was generated to determine whether the mutation itself alters myofilament pH sensitivity. Before functional studies, mutant ssTnI expression and incorporation were examined. In contrast to epitope-tagged cTnIR146G, comparable expression of ssTnI and ssTnIR115G was observed in intact and membrane-permeabilized myocytes (Figure 5A). Total ssTnI was unchanged in myocytes expressing ssTnI or ssTnIR115G, relative to a silver-stained portion of the gel, TnT, or Tm detection on Western blots (see online Table). Wild-type ssTnI and ssTnIR115G also were expressed to comparable levels in intact and membrane-permeabilized myocytes (Figure 5A). In immunolabeling experiments, cTnI-specific mAb labeling disappeared with ssTnI or ssTnIR115G expression (Figure 5B, right panel), whereas positive labeling continued to be present using a nonisoform-specific anti-TnI mAb (Figure 5B, left panel). These results indicate that, in contrast to cTnIR146G, ssTnIR115G and wild-type ssTnI each replace endogenous myofilament cTnI with similar efficiency.

Ca2+‐Activated Tension in Myocytes Expressing ssTnIR115G

Functional studies on permeabilized myocytes were performed to determine whether ssTnIR115G would influence...
pCa$_{50}$ results were compared at each pH using a 1-way ANOVA followed by a post hoc Newman-Keuls test, with $P<0.05$ considered significantly different from control (●) or cTnI (●). Maximum tension decreased markedly at pH 6.2 for each group of myocytes (results not shown), in agreement with earlier findings from cTnI- and ssTnI-expressing myocytes. Comparison of pCa$_{50}$ results in ssTnI vs cTnIR146G-expressing myocytes at pH 7.0 and pH 6.2. Results were compared by subtracting the average pCa$_{50}$ for myocytes expressing ssTnI from pCa$_{50}$ values obtained for myocytes expressing cTnIR146G. Statistical analysis was performed using a 1-way ANOVA and a post hoc Newman-Keuls test; *$P<0.05$ considered significantly different from the zero baseline. In B, $P<0.05$ considered significantly different from all other groups.

![Figure 4](image-url)  
**Figure 4.** Summary of pCa$_{50}$ comparisons at pH 7.0 and 6.2 in myocytes expressing TnI proteins. A, pCa$_{50}$ results at pH 7.0 for control, cTnI-, or cTnIR146G-expressing myocytes 5 to 6 days after gene transfer. B, pCa$_{50}$ results at pH 6.20 for control myocytes and myocytes expressing cTnI, cTnIR146G, or ssTnI 5 to 6 days after gene transfer (n=5 to 10). pCa$_{50}$ significantly decreased in each group of myocytes, but decreased to a significantly lesser extent in myocytes expressing ssTnI compared with cTnI or cTnIR146G.

**Discussion**

The heightened myofilament Ca$^{2+}$ sensitivity caused by HCM-associated mutant sarcomeric proteins has been proposed to be a key element in the development of organ-level disease. The present study shows that under physiological activating conditions, ssTnI and cTnIR146G similarly enhance myofilament Ca$^{2+}$ sensitivity of tension in adult cardiac myocytes. This presents a paradox whereby both ssTnI and cTnIR146G heighten Ca$^{2+}$ sensitivity, although only cTnIR146G leads to organ-level pathology and premature death in mice. We further show that myofilament pH sensitivity is an additional factor that, together with enhanced myofilament Ca$^{2+}$ sensitivity, may be important for the development of cardiac dysfunction caused by the HCM-associated cTnIR146G mutation. Specifically, under acidic pH conditions, enhancement of calcium sensitivity of contraction is lost in cTnIR146G compared with ssTnI (Figure 4C).

**Working Model: Progression From Enhanced Myofilament Ca$^{2+}$ Sensitivity to Cardiac Dysfunction**

The development of ventricular arrhythmia resulting from myocyte disarray is often assumed to be the primary entity involved in the premature deaths in HCM patients. However, multiple clinical studies have pointed to the possibility that localized or regional myocardial ischemia could also be a factor in the development of cardiac dysfunction, arrhythmia, and/or death. In support of this idea is the recent finding of myocytes with evidence of hypoxia in cTnIR146G mouse lines where hearts did not yet exhibit overt pathology. A model incorporating divergent myofilament pH sensitivity in conjunction with the enhanced myofilament Ca$^{2+}$ sensitivity in cTnIR146G versus ssTnI-expressing myocytes is proposed below. Our working hypothesis is that enhanced myofilament Ca$^{2+}$ sensitivity could work in parallel with greater pH sensitivity to cause progressive changes in myocardium-expressing cTnIR146G, but not ssTnI. The shared heightened myofilament Ca$^{2+}$ sensitivity of tension in myocytes expressing ssTnI or cTnIR146G will cause a slight slowing of myocardial relaxation, as demonstrated in transgenic mice expressing either TnI protein. This relaxation delay may only lead to subtle changes in working myocardium to compensate for delayed relaxation, including remodeling of the sarcomere or Ca$^{2+}$ handling protein content or function and/or alterations in the adrenergic signaling response. Short intervals of mild local ischemia resulting from myocardial bridging (eg, a band of overlying muscle that can result in systolic compression of a coronary artery), exercise, and/or stress within myocytes expressing cTnIR146G or ssTnI would initiate the divergent pathway leading to dysfunction in cTnIR146G-expressing myocardium. Specifically, the acidosis accompanying ischemia is predicted to decrease cardiac function to a greater extent in...
TnI is localized within the myocytes expressing ssTnIR115G, as indicated by the absence of cTnI immunolabeling in myocytes expressing ssTnIR115G. Lack of cTnI immunolabeling in myocytes expressing ssTnIR115G provides strong evidence that nascent TnI protein is replacing endogenous cTnI. Bar=25 μm, with inset images showing ~12 μm of each cell. C, Comparison of pCa values between myocytes expressing ssTnI vs ssTnIR115G at pH 7.0 and pH 6.2. pCa in myocytes from both groups responded similarly to pH 7.0, whereas the pCa decreased significantly more at pH 6.2 in myocytes expressing ssTnIR115G vs ssTnI (P<0.05).

**Implications of TnI Competition Assay**

Our results indicate there is diminished ability of cTnIR146G to replace endogenous cTnI within the sarcomere. In transgenic mice, cTnIR146G mRNA increased 2- to 10-fold, and thus, the reduced presence of cTnIR146G within the sarcomere is presumably due to a reduced ability of mutant cTnI to incorporate in myofilaments relative to wild-type cTnI. In the TnI competitive assay (Figure 3), titration of recombinant vectors containing wild-type and mutant TnIs supports this interpretation. This information may be useful in developing gene or protein-based therapeutic strategies for HCM. A possible explanation for the reduced myofilament incorporation of cTnIR146G relative to the other TnI proteins (Figures 1 and 5) is the presence of subtle conformational differences of the mutant TnI that influence the affinity of this protein for the myofilament binding sites. Previously, cTnI and cTnIR146G binding to immobilized TnC were reportedly not different, although the use of Tn concentrations associated with maximal TnC binding may have obscured differences in affinity. Regardless of the mechanism involved in reducing myofilament incorporation of this mutant TnI, our results indicate there is a potential treatment strategy available to minimize incorporation of mutant TnI in the sarcomere. Experimental approaches could involve gene or protein-based delivery/expression of normal TnI and/or partial suppression of the mutant allele. In addition, abolishing the pH sensitivity of cTnI through gene transfer may prevent maladaptive hypertrophy associated with mutations in different contractile proteins.

**Molecular Switch Functions of TnI**

The R145G mutation in human cTnI lies within the inhibitory peptide (IP; Figure 1A), a region postulated to act as an important molecular switch within TnI that toggles from actin to troponin C in the presence of Ca2+. The IP region is highly conserved among TnI isoforms, with a single substitution of Pro in ssTnI for Thr in cTnI at codon 144 in the rat sequence (Figure 1A). Previous studies on the IP region indicated this proline substitution does not change Ca2+-activated force properties. In contrast, functional results obtained in the present study indicate a single amino acid substitution (R→G), with a net decrease in positive charge, is sufficient to change myofilament Ca2+ sensitivity of tension (Figure 3). The heightened acidic pH response observed with cTnIR146G and ssTnIR115G, relative to ssTnI (Figures 3 and 4), indicates loss of positive charge at this residue also may influence myofilament pH sensitivity in an isoform-

---

**Figure 5. Expression, myofilament incorporation, and function in myocytes expressing ssTnI compared with ssTnIR115G.** A, Representative Western blot analysis of ssTnI and ssTnIR115G expression in intact and membrane permeabilized myocytes 6 days after gene transfer. MAB 1691 mAb (1:500) was used to detect TnI expression. Overall expression of ssTnI (92±3% of total TnI; n=12) and ssTnIR115G (84±6% of total TnI; n=12) and replacement of endogenous cTnI was not different in intact myocytes. Proportion of exogenous TnI (eg, cTnI, ssTnIR115G) relative to endogenous cTnI also is not significantly affected by permeabilization of membranes (% of Total TnI; ssTnIintact 91±5%, n=10; ssTnIperm 94±2%, n=10; P>0.05; ssTnIR115Gintact 84±5%, n=8; ssTnIR115Gperm 84±5%, n=8; P>0.05), an indication that exogenous contractile protein does not detectably accumulate within the cytosol. B, Representative confocal projection images of myocytes expressing cTnI (top) and ssTnIR115G (bottom). Left panels, Labeling with MAB 1691, a mAb recognizing all isoforms of TnI, and a secondary Ab conjugated to Texas Red. A striated pattern of labeling is present in myocytes expressing ssTnIR115G provides strong evidence that nascent TnI protein is replacing endogenous cTnI. Bar=25 μm, with inset images showing ~12 μm of each cell. C, Comparison of pCa50 values between myocytes expressing ssTnI vs ssTnIR115G at pH 7.0 and pH 6.2. pCa in myocytes from both groups responded similarly to pH 7.0, whereas the pCa decreased significantly more at pH 6.2 in myocytes expressing ssTnIR115G vs ssTnI (P<0.05).
independent manner. Other amino acid differences between cTnI and ssTnI may be involved in producing a similar change in myofilament Ca\(^{2+}\) and pH sensitivities of tension. The similar Ca\(^{2+}\) sensitivity and enhanced pH sensitivity observed in myocytes expressing ssTnIR115G or cTnIR146G relative to ssTnI-expressing myocytes support this view.

**Acknowledgments**

This work is supported by grants from the National Institutes of Health and American Heart Association (to J.M.M.). J.M. Metzger is an Established Investigator of the American Heart Association, and M.V. Westfall is the recipient of a Scientist Development grant from the American Heart Association. We appreciate helpful comments from Dan Michelet on earlier versions of this manuscript.

**References**


Myofilament Calcium Sensitivity and Cardiac Disease: Insights From Troponin I Isoforms and Mutants
Margaret V. Westfall, Andrea R. Borton, Faris P. Albayya and Joseph M. Metzger

_Circ Res._ 2002;91:525-531; originally published online August 22, 2002;
doi: 10.1161/01.RES.0000034710.46739.C0
_Circulation Research_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2002 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/91/6/525

Data Supplement (unedited) at:
http://circres.ahajournals.org/content/suppl/2002/09/14/91.6.525.DC1

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

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

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