

The myosin-interacting protein SMYD1 is essential for sarcomere organization

Steffen Just^{1,*}, Benjamin Meder^{2,*}, Ina M. Berger¹, Christelle Etard³, Nicole Trano², Eva Patzel¹, David Hassel², Sabine Marquart², Tillman Dahme¹, Britta Vogel², Mark C. Fishman⁴, Hugo A. Katus², Uwe Strähle³ and Wolfgang Rottbauer^{1,‡}

¹Department of Medicine II, University of Ulm, 89081 Ulm, Germany

²Department of Medicine III, University of Heidelberg, 69117 Heidelberg, Germany

³Institute of Toxicology and Genetics, Forschungszentrum Karlsruhe, Karlsruhe Institute of Technology (KIT), D-76021 Karlsruhe, Germany

⁴Novartis Institutes for BioMedical Research, Cambridge, MA 02139, USA

*These authors contributed equally to this work

‡Author for correspondence (wolfgang.rottbauer@uniklinik-ulm.de)

Accepted 12 May 2011

Journal of Cell Science 124, 3127–3136

© 2011. Published by The Company of Biologists Ltd

doi: 10.1242/jcs.084772

Summary

Assembly, maintenance and renewal of sarcomeres require highly organized and balanced folding, transport, modification and degradation of sarcomeric proteins. However, the molecules that mediate these processes are largely unknown. Here, we isolated the zebrafish mutant *flatline* (*fla*), which shows disturbed sarcomere assembly exclusively in heart and fast-twitch skeletal muscle. By positional cloning we identified a nonsense mutation within the SET- and MYND-domain-containing protein 1 gene (*smyd1*) to be responsible for the *fla* phenotype. We found SMYD1 expression to be restricted to the heart and fast-twitch skeletal muscle cells. Within these cell types, SMYD1 localizes to both the sarcomeric M-line, where it physically associates with myosin, and the nucleus, where it supposedly represses transcription through its SET and MYND domains. However, although we found transcript levels of thick filament chaperones, such as Hsp90a1 and UNC-45b, to be severely upregulated in *fla*, its histone methyltransferase activity – mainly responsible for the nuclear function of SMYD1 – is dispensable for sarcomerogenesis. Accordingly, sarcomere assembly in *fla* mutant embryos can be reconstituted by ectopically expressing histone methyltransferase-deficient SMYD1. By contrast, ectopic expression of myosin-binding-deficient SMYD1 does not rescue *fla* mutants, implicating an essential role for the SMYD1–myosin interaction in cardiac and fast-twitch skeletal muscle thick filament assembly.

Key words: SMYD1, Myosin, Thick filament assembly, Zebrafish

Introduction

Coordinated synthesis, assembly and renewal of numerous contractile, structural and regulatory proteins into sarcomeric units are crucial to maintain proper heart and skeletal muscle function throughout life. However, little is known about the molecules that mediate these fundamental processes. The zebrafish is an established model organism to identify genes that are required to build and maintain the contractile muscle apparatus, thereby offering insights into the underlying molecular mechanisms and serving as a model for human muscle diseases (Rottbauer et al., 2006; Sehnert et al., 2002). Additionally, a growing body of evidence implies that correct sarcomere assembly involves several auxiliary proteins (Barral et al., 1998; Barral et al., 2002; Epstein and Thomson, 1974; Hobert et al., 1999; Miller et al., 2008; Venolia and Waterston, 1990).

Proteins containing SET [SU(VAR)3-9, Enhancer of zeste and Trithorax] and MYND (Myleoid, Nervy and DEAF-1) domains (SMYDs) are known to regulate gene transcription, mostly by mediating chromatin modifications (Rice and Allis, 2001). SET-domain-containing proteins can modulate transcription by methylating unacetylated lysine residues on histone tails [histone methyltransferase (HMT) activity] (Rea et al., 2000),

whereas MYND-domain-containing proteins usually repress transcription by recruiting histone deacetylases (HDACs) (Gottlieb et al., 2002). Interestingly, SMYD proteins are also known to regulate non-histone protein functions by site-specific methylation of their target proteins, such as p53 or VEGFR1 (Huang and Berger, 2008; Huang et al., 2006; Kunizaki et al., 2007). In mammals, five SMYD proteins have been identified so far (SMYD1–SMYD5) but little is known about their *in vivo* functions.

SMYD1 (known as mBop in mouse), is strongly expressed in cardiac and skeletal muscle cells. Its transcription in the anterior heart field is regulated by myocyte enhancer factor-2c (MEF2c), and in skeletal muscle cells by myogenic differentiation antigen 1 (MYOD) (Phan et al., 2005). In contrast to SMYD2-nullizygous mice, SMYD1-deficient mice lack proper development of the right ventricular chamber and die at embryonic day 10.5 (Gottlieb et al., 2002; Phan et al., 2005). In zebrafish, knockdown of the zebrafish SMYD1 isoforms, SMYD1a and SMYD1b by morpholino-modified antisense oligonucleotides leads to impaired heart and skeletal muscle function due to disturbed myofibril organization (Tan et al., 2006). SMYD2, although highly expressed in cardiomyocytes, was recently found to be dispensable for cardiac development because cardiac-

specific deletion of SMYD2 in mice does not interfere with normal heart morphogenesis and function (Diehl et al., 2010).

Here, in search for key regulators of cardiac and skeletal muscle function, we isolated the recessive lethal zebrafish mutant *flatline* (*fla*), which displays severe cardiac and skeletal muscle dysfunction due to impaired myofibrillogenesis. By positional cloning, we demonstrate that a nonsense mutation in SMYD1, a heart and fast-twitch muscle fiber HMT, is responsible for the *fla* phenotype. We find that SMYD1 localizes to the sarcomeric M-line where it interacts with myosin. Remarkably, heart and skeletal muscle function of *fla* embryos can be restored by ectopic expression of HMT-deficient SMYD1 but not by myosin-binding-deficient SMYD1. Taken together, our findings imply that SMYD1 plays an essential role in myosin thick filament assembly exclusively in cardiomyocytes and fast-twitch skeletal muscle cells.

Results

Heart and skeletal muscle function is impaired in the zebrafish mutant *flatline*

In search for key-regulators of cardiac and skeletal muscle function, we isolated in a large-scale ENU-mutagenesis screen, the recessive embryonic lethal zebrafish mutant *flatline* (*fla^{mvo47a}*) (Warren and Fishman, 1998). *fla* mutants displayed severe cardiac and skeletal muscle dysfunction with complete penetrance in various genetic backgrounds (TL, WIK and TüAB) (Fig. 1A,B; supplementary material Fig. S1A).

Usually, by 22 hours post fertilization (hpf) in wild-type embryos the heart tube is formed and a peristaltic contraction wave passes through the heart. By contrast, although the *fla* heart tube jogs correctly and myo- and endocardial cell layers were clearly defined in these embryos, *fla* mutant hearts did not display any contraction (supplementary material Fig. S1B–G;

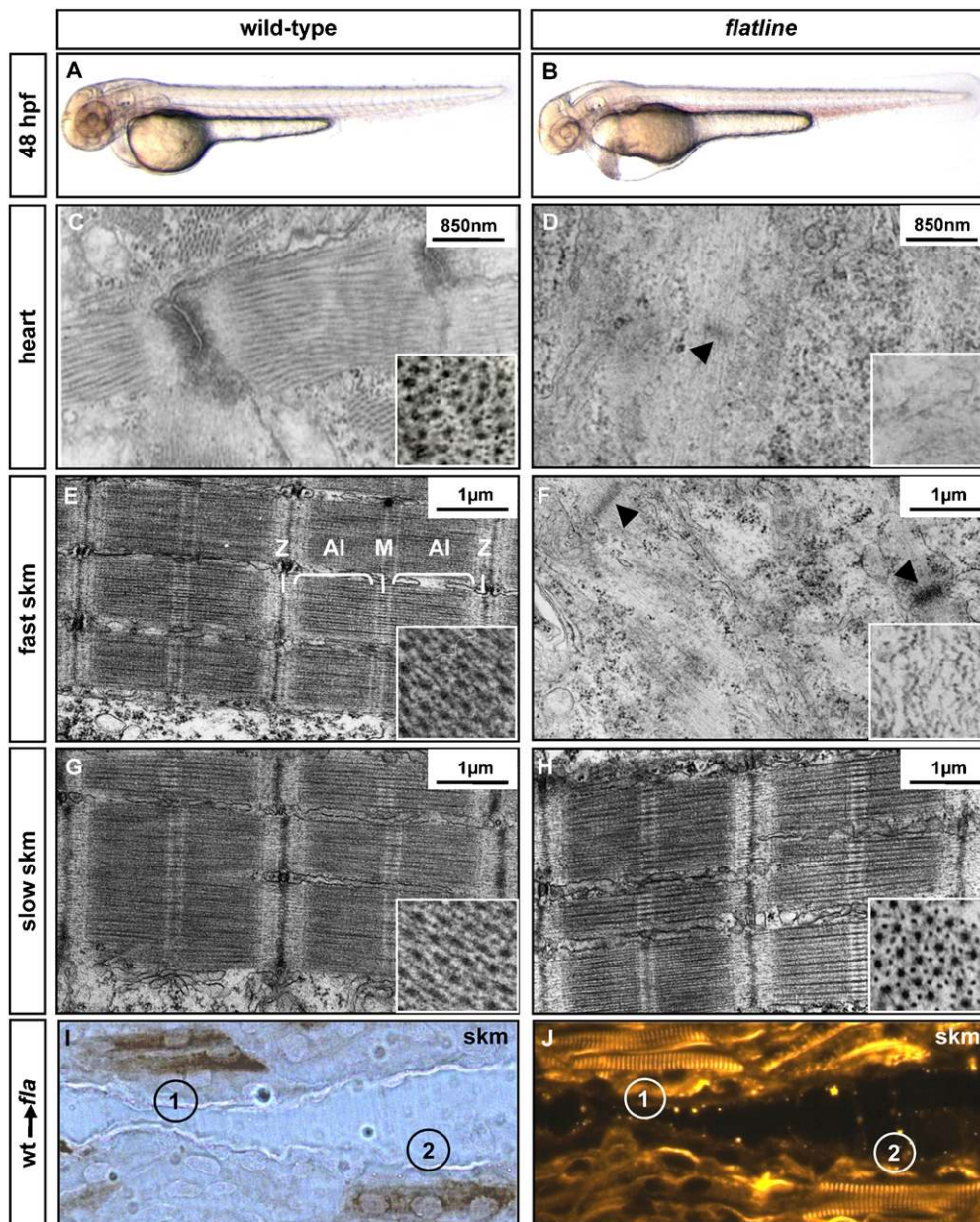


Fig. 1. Disrupted myofibrillogenesis in *fla* cardiomyocytes and fast-twitch skeletal muscle cells. (A,B) Lateral view of wild-type (A) and *fla* mutants (B) at 48 hpf. *fla* mutants develop pericardial edema owing to the absence of cardiac contractility. (C–H) Electron microscopic analysis of parasagittal and transversal (insets C–H) sections through cardiac and somitic muscle cells of wild-type and *fla* at 48 hpf. In contrast to the wild-type (C), cardiomyocytes of *fla* (D) completely lack sarcomeric structures. Only premature sarcomeric structures, such as stress fibers or Z-bodies can be detected in *fla* cardiomyocytes (D, arrowhead). Compared with wild-type (E), *fla* fast-twitch skeletal muscle fibers (F) fail to develop sarcomeric structures (arrowheads show Z-bodies). By contrast, myofibrillogenesis of slow-twitch skeletal muscle fibers (G,H) is not affected in *fla*. (I,J) *fla* acts cell-autonomously in cardiomyocytes and fast-twitch skeletal muscle cells. α -Actin immunostain (J) of Biotin-labeled transplanted wild-type cells (1 and 2) (I), showing normal formation of sarcomeric units in these cells. skm, skeletal muscle.

supplementary material Movie 1). To examine whether, similar to the situation in the zebrafish mutants *island beat* and *reggae* (Hassel et al., 2008; Rottbauer et al., 2001), disturbed cardiac excitation is responsible for cardiac acontractility in *fla*, we next monitored calcium transients in *fla* hearts by high-resolution fluorescent microscopy. However, similar to the situation in wild-type hearts, in *fla* hearts a calcium wave commenced in the sinus venosus region, then migrated through the atrium and then the ventricle of the non-beating *fla* heart (supplementary material Fig. S1H,I; supplementary material Movie 2), indicating that the *fla* mutation does not impact on cardiac electrical impulse generation and propagation, but rather leads to electromechanical uncoupling of cardiomyocytes. In addition to their cardiac phenotype, *fla* mutants displayed severe impairment of skeletal muscle function. When touch-stimulated, *fla* mutants displayed, in contrast to wild-type embryos, only a shiver response, which does not generate enough force for the *fla* embryo to execute a 'flight response' (supplementary material Movie 3).

Next, to evaluate whether defective myofibrillar organization is the cause for the dysfunction of cardiac and skeletal muscles in *fla*, we assayed their ultrastructure. Usually, by 24 hpf in wild-type zebrafish, thick and thin filaments are arrayed in well-aligned overlapping filament bundles, interconnected by sarcomeric Z-discs. By contrast, in *fla* cardiomyocytes sarcomeric units were completely absent (Fig. 1C,D). Remarkably, similar to other zebrafish myofibrillogenesis mutants such as *tell tale heart*, *steif* or *pickwick* (Etard et al., 2007; Rottbauer et al., 2006; Xu et al., 2002), premature sarcomeric structures such as I-Z-I bundles could be detected in *fla* cardiomyocytes (Fig. 1D, arrowhead). By contrast, we never observed myosin bundles in *fla* mutant muscles, implying that *fla* might interfere either with early myosin assembly or stability. Similarly, in *fla* skeletal muscles we found that sarcomerogenesis was abolished in fast-twitch fibers (Fig. 1E,F), whereas sarcomeric units were properly organized in *fla* slow-twitch fibers (Fig. 1G,H).

To determine whether *fla* acts cell-autonomously or non-cell-autonomously, we generated genetic mosaics of hearts and skeletal muscle by transplanting *fla* mutant cells into wild-type embryos and vice versa. We found that, when wild-type cells contributed to mutant hearts, they contracted spontaneously and vigorously in *fla* ventricles and atria ($n=9$), whereas *fla* cardiomyocytes adjacent to the transplanted cells did not contract (supplementary material Movie 4). By contrast, *fla* cardiomyocytes that are transplanted into wild-type hearts did not contract ($n=4$) (supplementary material Movie 5). As shown by electron microscopy and immunohistological analysis, transplanted wild-type cells had proper myofibrillar architecture, including regular arrays of thick and thin myofilaments, and Z-discs as well as intercalated discs (Fig. 1I,J; supplementary material Fig. S2A,B), whereas surrounding fast-twitch myocytes were devoid of intact sarcomeric units. Hence, *fla* acts cell-autonomously in heart and fast-twitch skeletal muscle sarcomerogenesis.

flatline (*fla*^{mvo47a}) encodes zebrafish SET- and MYND-domain-containing protein 1

To reveal the ENU-induced genetic defect of *fla*, we performed a genome-wide study of microsatellite marker segregation by bulked segregant analysis and linked *fla* as inbetween the microsatellite markers Z20180 and Z65535 on chromosome 8. Genetic fine-mapping by recombination analysis of 1595 *fla*

mutant embryos restricted the *fla* locus to the bacterial artificial chromosome (BAC) RPC171-6G18. Further recombination analysis placed *Fatty-Acid-Binding protein 1b* (*FABP1b*, XP_001332792) and the *SET- and MYND-domain-containing protein 1* (*smyd1*, ABC54713) within the *fla* genetic interval. By sequencing wild-type and *fla* cDNA, we found the *fla* mutation to be a thymine-to-adenine nucleotide transversion (UGU→UGA) in codon 73 of zebrafish *smyd1*, whereas in FABP1b no mutation was detected. The identified mutation was predicted to change the amino acid cysteine to a stop codon and hence to cause premature termination of translation of both zebrafish *smyd1* isoforms, *smyd1a* and *smyd1b*, at amino acid position 73 (C73stop) (Fig. 2A). To test whether the predicted truncated SMYD1 proteins were stable and thereby might have acted as dominant negatives, we generated expression plasmids of N-terminal V5-tagged wild-type or *fla* mutant SMYD1. Whereas in vitro translated wild-type SMYD1 accumulated in reticulocyte lysates, no truncated SMYD1 proteins accumulated to detectable levels (supplementary material Fig. S2C). Because mutant SMYD1 proteins were not stable, lack of SMYD1 rather than a dominant-negative effect of truncated SMYD1 appears to cause the *fla* mutant phenotype.

To evaluate whether ectopic expression of wild-type RNA encoding *smyd1* can restore *fla* heart and skeletal muscle function, we injected either 50 pg of wild-type (*smyd1b*^{wt}) or *fla* mutant (*smyd1b*^{fla}) mRNA into one-cell stage *fla* mutants (*fla*^{mvo47a-/-}) derived from intercrossing *fla* heterozygous zebrafish ($n=373$). As shown in Fig. 2D, in $70 \pm 10.8\%$ of homozygote mutant *fla* embryos heart and skeletal muscle function could be completely restored by injection of wild-type *smyd1* mRNA. Hearts of injected *fla* mutants contracted vigorously, blood circulation was established and mutant embryos displayed coordinated skeletal muscle movements (supplementary material Movie 6). Additionally, *fla* sarcomeres were restored (Fig. 2B-E). Similar effects and efficacy were observed when injecting 50 pg of *smyd1a* mRNA into one-cell stage *fla* mutant embryos ($n=47$). To validate that finding that cardiac and skeletal muscle dysfunction in *fla* mutants is indeed caused by loss of SMYD1 function, we injected morpholino-modified antisense oligonucleotides, either directed against the translational start site (MO1-*zsmyd1*) or the splice donor site of exon 3 (MO2-*zsmyd1*) of *smyd1* into one-cell stage wild-type zebrafish embryos. When injected with 2.5 ng of MO1-*zsmyd1* or MO2-*zsmyd1*, $97 \pm 2\%$ of the embryos ($n=460$ and 403, respectively) displayed the *fla* mutant phenotype accompanied by the absence of cardiac contractility and severe skeletal muscle dysfunction (Fig. 2F-I). As in *fla* mutants, ultrastructural analysis of MO1-*zsmyd1*-injected embryos revealed disrupted sarcomerogenesis in cardiomyocytes and fast-twitch skeletal muscle cells (Fig. 2I). By contrast, injection of 5-bp mismatch control morpholinos (5mmMO) did not impact on heart and skeletal muscle function (Fig. 2H).

***smyd1* expression is restricted to nuclei and M-lines of cardiomyocytes and fast-twitch skeletal muscle cells and associates with sarcomeric myosin**

From mouse and zebrafish in situ hybridization studies, *smyd1* is known to be restricted to heart and skeletal muscle tissue (Gottlieb et al., 2002; Tan et al., 2006) (Fig. 3A,B). As outlined above, *fla* mutants have sarcomerogenesis defects only in cardiac and fast-twitch skeletal muscle fibers, whereas slow-twitch fibers

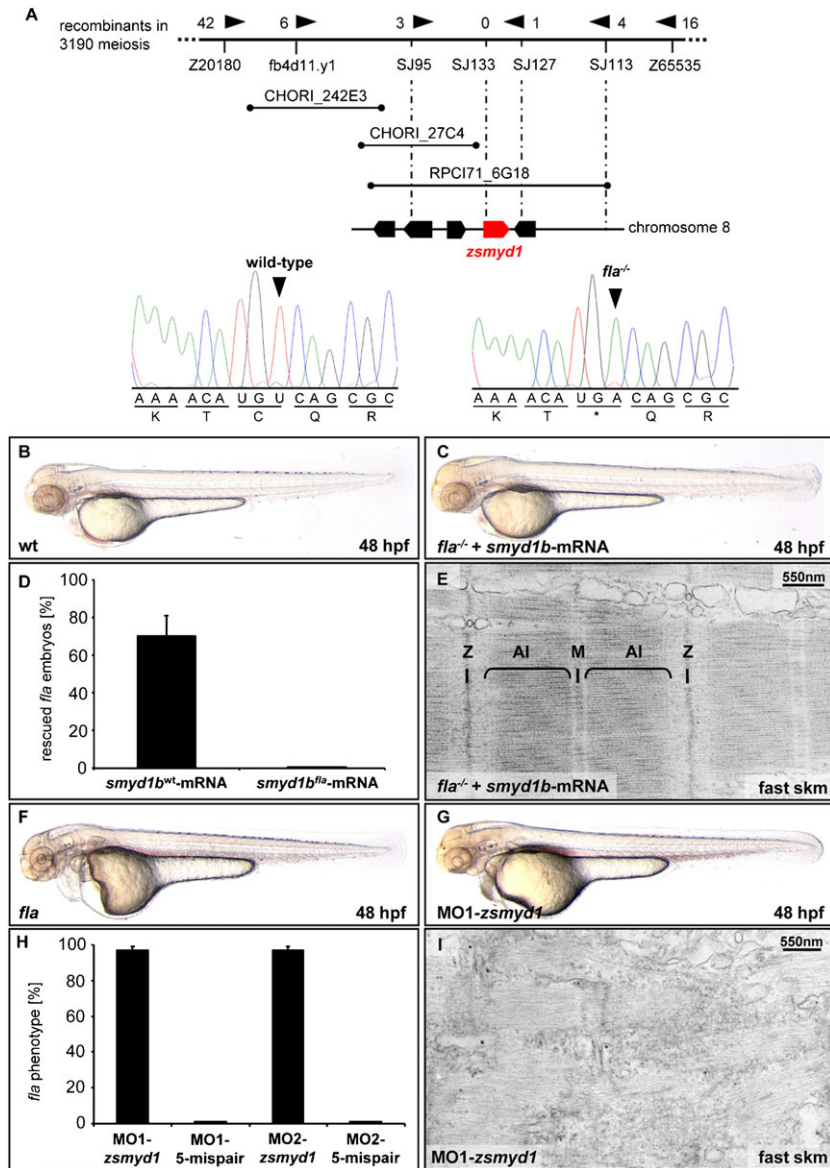


Fig. 2. *fla* encodes zebrafish SMYD1. (A) Genetic and physical map of the zebrafish *fla* region. A point mutation was identified in exon 2 of the *smyd1* gene. In the chromatograms, the *fla* nonsense mutation in codon 73 of *smyd1* is indicated with an arrowhead. Morpholino knockdown of *smyd1* phenocopies, whereas ectopic expression of wild-type (wt) SMYD1 suppresses, the *fla* mutant phenotypes. (B–E) Ectopic expression of wt *smyd1b* mRNA (*smyd1b*^{wt}) can rescue the heart and skeletal muscle phenotype of 70% of *fla* mutants, whereas injection of *fla* mutant mRNA (*smyd1b*^{*fla*}) has no effect. (E) Ultrastructural architecture of fast-twitch skeletal muscle cells is restored by the ectopic expression of wt *smyd1b* RNA. (F–I) Inhibition of *smyd1* function by morpholino injection phenocopies the *fla* heart and skeletal muscle phenotype. (F–H) 97% of wt embryos injected with MO1-*zsmyd1* or MO2-*zsmyd1* (G) are indistinguishable from *fla* mutants (F) and display lack of cardiac contractility and impairment of skeletal muscle function, whereas injection of corresponding 5-bp mispair morpholinos do not evoke a heart and skeletal muscle phenotype (H). (I) Electron microscopy analysis of *smyd1* injected with MO1-*zsmyd1* reveals disruption of myofibrillar organization in fast-twitch skeletal muscle cells. All error bars represent s.d. skm, skeletal muscle.

are devoid of any structural or functional defects. Hence, to evaluate whether *smyd1* was differentially expressed in slow- and fast-twitch skeletal muscle cells, we assayed *smyd1* RNA distribution in these two muscle compartments. As shown in Fig. 3C–E, *smyd1* RNA was exclusively present in the fast-twitch fiber compartment of zebrafish trunk muscles, whereas slow-twitch fibers were devoid of *smyd1* RNA.

To evaluate, where SMYD1 protein localizes within heart and skeletal muscle cells, we performed immunohistological stainings using a SMYD1-specific antibody. As expected for proteins with HMT activity, SMYD1 localized in the nuclei of cardiomyocytes (Fig. 3F–H). Furthermore, we found SMYD1 to be distributed in a striped pattern within the cytoplasm, implicating association with sarcomeric proteins. As shown by co-immunostaining of SMYD1 and myomesin in murine heart, SMYD1 localized at the M-line – the anchorage point of myosin – of muscle cells (Fig. 3I, J). To assess whether SMYD1 directly interacted with myosin at the M-line, we performed in vitro pull-down assays using GST-tagged SMYD1b and sarcomeric

myosin. As shown in Fig. 3K, SMYD1b was indeed capable of specifically binding myosin. To narrow down the location of the SMYD1–myosin interaction site, we generated distinct domain-specific deletion variants of SMYD1b and again tested their ability to interact with myosin (Fig. 3K). Interestingly, only full-length SMYD1b and the C-terminal deletion variant SMYD1b^{391del}, but not SMYD1b^{278del} and SMYD1b^{89del}, were capable of binding myosin, implicating an essential role of amino acids 278–391 of SMYD1b for the physical interaction with myosin.

To investigate whether, similar to other myosin-interacting proteins, such as UNC-45b or Hsp90a, intracellular localization of SMYD1 is dynamic, we tracked the localization of transiently overexpressed SMYD1a in a model of decelerated myofibrillogenesis in zebrafish muscle cells (Etard et al., 2008). Therefore, we constructed a SMYD1a–GFP chimeric gene, co-injected the construct with low levels of UNC-45b-specific morpholinos, to slow down myofibril formation in fertilized zebrafish eggs, and followed the localization of the

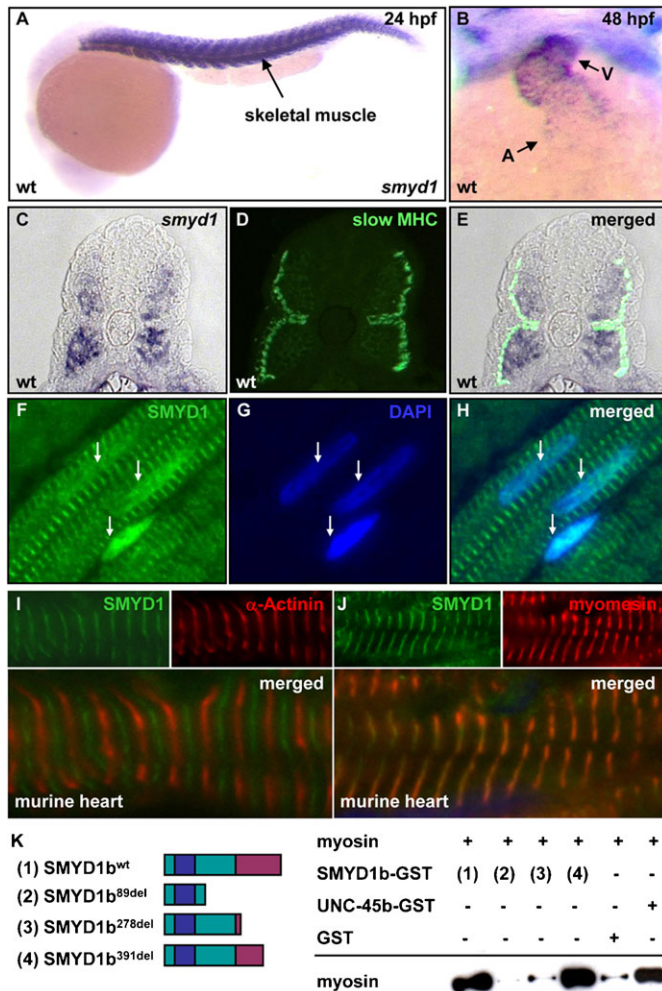


Fig. 3. SMYD1 is expressed in the heart and fast-twitch skeletal muscle cells, and interacts with myosin at the sarcomeric M-line. (A,B) *smyd1* RNA is strongly expressed in somitic muscle cells (A) and both heart chambers (B). (C–E) *smyd1*-specific in situ hybridization, in combination with an immunostain of slow-twitch skeletal muscle fibers (F59, green) of transversal sections through the somitic muscles of a wild-type (wt) embryo. *smyd1* is expressed in fast-twitch and is absent in slow-twitch skeletal muscle cells. (F–H) Immunohistochemistry of murine heart sections reveals that SMYD1 protein (green) localizes to the sarcomere and the nucleus of cardiomyocytes. Cell nuclei are counterstained with DAPI (blue). (I,J) Co-immunostains of SMYD1 and α -Actinin (I), as well as SMYD1 and myomesin (J), in murine heart sections reveal localization of SMYD1 to sarcomeric M-lines. (K) The scheme outlines different SMYD1b deletion variants that are used for the myosin in vitro pull-down assay (turquoise, pre-SET and post-SET domain; blue, MYND domain; purple, C-terminus). SMYD1b^{wt}-GST (lane 1) and SMYD1b^{391del}-GST (lane 4) proteins interact with myosin from rabbit muscle in an in vitro pull-down assay, whereas SMYD1b^{89del}-GST (lane 2) and SMYD1b^{278del}-GST (lane 3) do not bind myosin. GST (lane 5) and UNC-45b (lane 6) are used as negative and positive myosin-binding controls, respectively.

fusion protein by confocal microscopy. Remarkably, we found that SMYD1a-GFP protein accumulates in a double-banded pattern characteristic of the myosin in the A-band at 48 hpf (Fig. 4A). Furthermore, we show by co-immunostaining with antibodies directed against α -actinin that SMYD1a-GFP had shifted back to the sarcomeric M-line at 72 hpf (Fig. 4B–E),

demonstrating that SMYD1a colocalizes with myosin at the sarcomeric A-band during myofibrillogenesis and associates with the M-line when myofibril assembly is completed. These findings suggest that SMYD1 plays a crucial role during early myosin assembly.

SMYD1, Hsp90a1 and UNC-45b are co-regulated during sarcomere assembly in zebrafish

SMYD1 is known to regulate gene transcription by methylating histones. Hence, we wondered whether altered transcription of sarcomeric constituents was responsible for defective sarcomerogenesis in *fla* mutants. Interestingly, we find that mRNA levels of various myofibrillar components, such as the thin filament components α -tropomyosin (*tpm4*), troponin T (*tnnt*), the thick filament components cardiac myosin light chain 2 (*cmc2*), cardiac myosin light chain 1 (*cmc1*), ventricular-specific myosin heavy chain (*vmhc*) and atrial myosin heavy chain (*amhc*) and the elastic filament *titin* are not differentially regulated in *fla* embryos (Fig. 5A; supplementary material Fig. S3A), indicating that altered transcription of sarcomeric components does not account for disturbed sarcomerogenesis in *fla* heart and skeletal muscle. Next, to identify transcriptional targets of SMYD1 that might account for defective sarcomerogenesis in *fla*, we assayed transcriptional profiles of 36-hour-old *fla* mutants and wild-type littermates using cDNA expression arrays. Interestingly, we found that transcripts encoding muscle chaperones and co-chaperones such as heat shock protein 90- α 1 (*hsp90a1*) and *unc-45b*, which are known to be crucial for regular sarcomere assembly, were strongly upregulated in *fla* (up to 8-fold) (supplementary material Fig. S3B). These findings were confirmed both by qRT-PCR (relative expression of *hsp90a1* = 3.8 ± 1.2 and *unc-45b* = 3.5 ± 1.1 ; $n=5$, $P<0.01$) and in situ hybridization (Fig. 5B–G). As revealed by western blot analyses, Hsp90a protein levels were also severely increased in *fla* mutants compared with those in wild-type littermates (supplementary material Fig. S3C). To assess whether upregulation of molecular chaperones in *fla* cardiomyocytes and fast-twitch skeletal muscle cells was induced by cellular stress evoked by defective sarcomerogenesis, we evaluated the expression of Hsp90a1 in the zebrafish cardiac myofibrillogenesis mutants *silent heart* (*sih*) (Troponin T deficiency) and *tell tale heart* (*tel*) (MLC2 deficiency) (Rottbauer et al., 2006; Sehnert et al., 2002). Interestingly, although, similar to *fla* mutants, no sarcomeric units were built in cardiomyocytes of *sih* and *tel* mutants, *hsp90a1* was not up-regulated in these mutants (Fig. 5H–K), indicating that the induction is not a common mechanism in response to defective sarcomere assembly.

Molecular chaperones, such as Hsp90a1 and UNC-45b, are essential for proper folding of thick filament myosin during myofibrillogenesis. Very recently, it has been shown that overexpression of UNC-45b in zebrafish muscle cells leads to impaired sarcomere organization (Bernick et al., 2010). Thus, to investigate whether downregulation of UNC-45b in *fla* mutant embryos might rescue myofibrillogenesis, we injected ‘sub-effective’ doses (i.e. doses unable to induce a muscle phenotype in wild-type embryos) of UNC-45b-specific morpholinos into homozygous *fla* mutant embryos and evaluated heart and skeletal muscle function through high-resolution video microscopy.

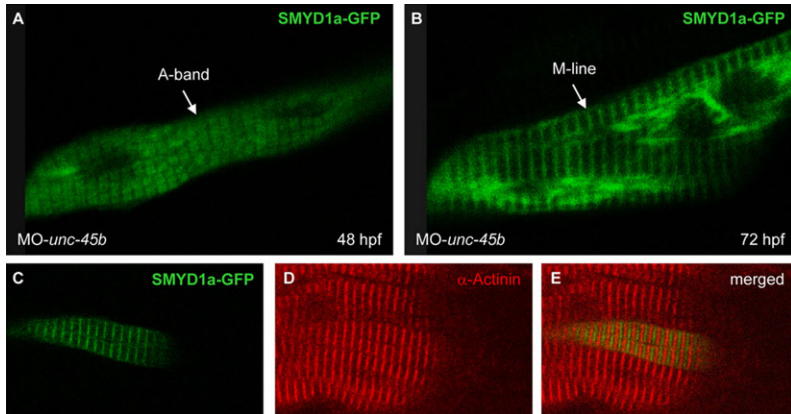


Fig. 4. SMYD1a-GFP associates with nascent myosin.

(A–E) Co-injection of low levels of UNC-45b morpholinos, as a model of decelerated myofibrillogenesis, and *smyd1a-gfp* plasmids. (A) At 48 hpf, SMYD1a-GFP first colocalizes with myosin in the sarcomeric A-band. (B) At 72 hpf, when myofibril assembly is completed, SMYD1a-GFP shuttles to the M-line. (C–E) Immunostains with α -Actinin-specific antibodies reveal striation, confirming relocalization of SMYD1a-GFP to sarcomeric M-lines.

Interestingly, we found that knocking down UNC-45b in *fla* mutant embryos did not reconstitute heart and skeletal muscle function ($n=67$), implying that overexpression of UNC-45b is not the molecular cause of the observed muscle phenotype in *fla*. In the zebrafish mutants *akineto* and *steif*, which are deficient in the myosin chaperones Hsp90a1 and UNC-45b, respectively, *hsp90a1* and *unc-45b* mRNA levels are strongly elevated (Etard et al., 2007; Hawkins et al., 2008). Hence, to evaluate whether SMYD1 was also upregulated in Hsp90a1- and UNC-45b-deficient zebrafish embryos, we assayed SMYD1 transcript levels by antisense RNA in situ hybridization. We found strong upregulation of *smyd1* in Hsp90a1- and UNC-45b-deficient embryos (Fig. 6A–D). Surprisingly, we also found that the *smyd1* transcript levels were substantially upregulated in *fla* heart and skeletal muscle cells (Fig. 6E,F), suggesting that SMYD1, Hsp90a1 and UNC-45b are co-regulated during zebrafish sarcomerogenesis.

Loss of Hsp90a1 or UNC-45b function results in the destabilization and degradation of their client protein myosin (Barral et al., 1998; Hawkins et al., 2008; Landsverk et al., 2007). Strikingly, and in contrast to their unchanged transcript levels, protein levels of sarcomeric myosins were severely downregulated in *fla*, implying that loss of SMYD1 function, similar to the situation in Hsp90a1- and UNC-45b-deficient embryos, leads to the destabilization and subsequent degradation of myosin proteins in *fla* mutants (Fig. 6G; supplementary material Fig. S3D).

SMYD1 HMT activity is dispensable for thick filament assembly in vivo

In addition to its localization at the M-line of heart and fast-twitch skeletal muscle cells, SMYD1 is present in the cell nucleus where it is known to regulate gene transcription through

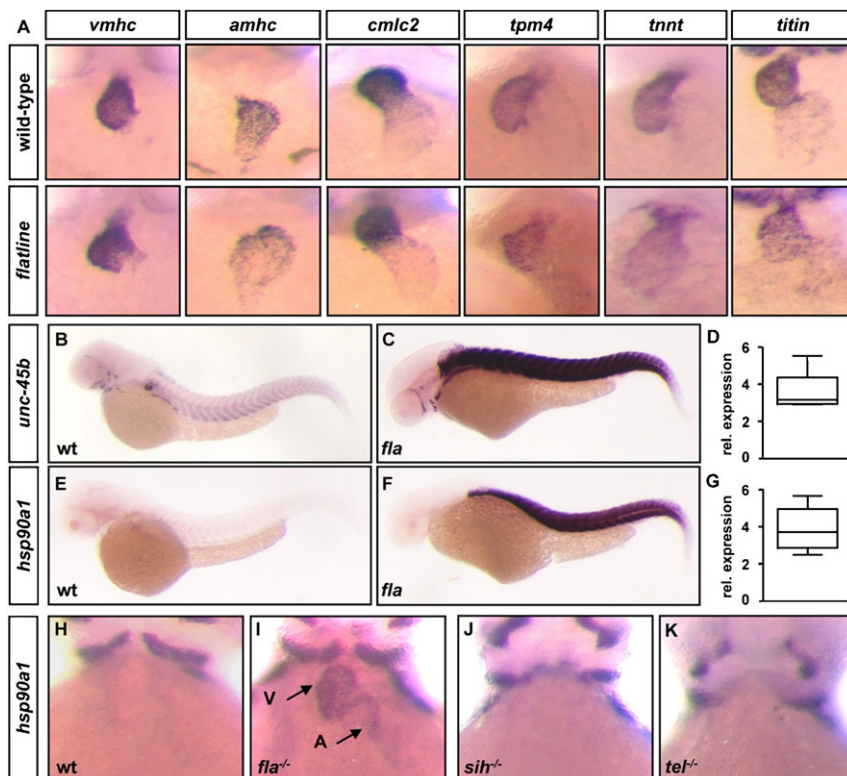


Fig. 5. Increased RNA levels of thick filament chaperones *unc-45b* and *hsp90a1* in *fla* heart and fast-twitch skeletal muscle cells. (A) mRNA levels of sarcomeric constituents are not affected by the *fla* mutation. In situ hybridizations of thick- (*cmlc2*, *vmhc*, *amhc*), thin- (*tpm4*, *tnnt2*) and elastic-filament (*titin*) transcripts in *fla* mutants at 48 hpf indicate that their transcription is not affected by the loss of SMYD1 function. By contrast, *unc-45b* (B–D) and *hsp90a1* (E–G) are strongly upregulated in cardiomyocytes and fast-twitch skeletal muscle cells of *fla* compared with that in wild-type (wt) embryos at 48 hpf, as revealed by in situ hybridization and qRT-PCR. (H–K) Muscle chaperone *hsp90a1* is only upregulated in *fla* (I; V, ventricle, A, atrium) but not in other zebrafish mutants with disturbed sarcomeric units, such as *silent heart* (*sih*) (J) and *tell tale heart* (*tel*) (K). All error bars represent s.d.

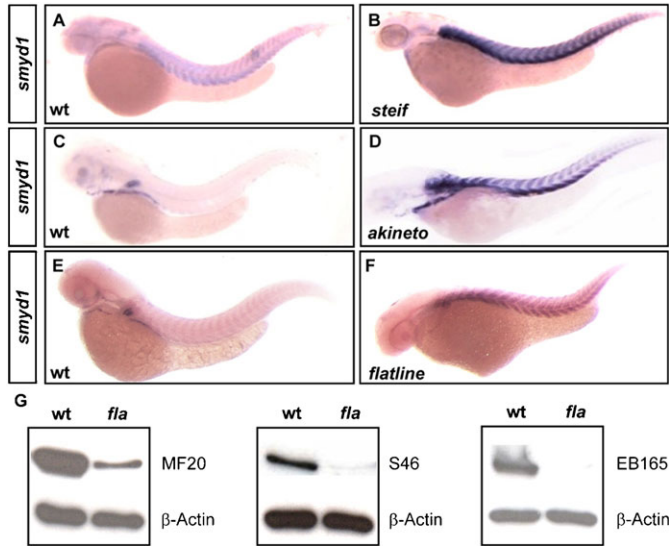


Fig. 6. Hsp90a1, UNC-45b and SMYD1 are co-regulated during sarcomerogenesis. (A–D) Expression of *smydl* is elevated in the thick filament mutants *steif* (B) and *akineto* (D) at 48 hpf. (E,F) *smydl* mRNA levels are also increased in *fla* embryos. (G) As shown by western blotting, protein levels of distinct sarcomeric myosins, such as atrial and ventricular meromyosin (MF20), atrial-specific myosin heavy chain (S46) and fast-twitch skeletal muscle myosin (EB165) are substantially reduced in *fla* at 48 hpf. β -actin is used as control.

methylating histones. To assess whether the HMT activity was indispensable for thick filament assembly in *fla* heart and fast-twitch skeletal muscles or whether the interaction of SMYD1 and myosin was pivotal for regular sarcomerogenesis, we first generated a construct that expressed HMT-deficient SMYD1b (SMYD1b^{Y247F}) (Brown et al., 2006), injected the mRNA into *fla* mutants and evaluated its capability to reconstitute heart and skeletal muscle function and structure. Strikingly, we found that 50 pg of *smydlb*^{Y247F} mRNA efficiently rescued the *fla* phenotype ($61.2 \pm 7.0\%$; $n=47$, three experiments) (Fig. 7A,E). Hearts of *fla* mutants injected with *smydlb*^{Y247F} mRNA contracted vigorously and mutant embryos displayed coordinated skeletal muscle movements (supplementary material Movie 7). Accordingly, we found reconstitution of sarcomerogenesis in fast-twitch skeletal muscle cells (Fig. 7C), demonstrating that SMYD1 HMT activity is dispensable for thick filament assembly. By contrast, overexpression of SMYD1b^{278del} (50 pg per embryo), a SMYD1 deletion variant where the SET and MYND domain is preserved but the myosin interaction site is absent, in *fla* mutants did not reconstitute heart and skeletal muscle function and structure ($n=31$, three experiments) (Fig. 7B,F; supplementary material Movie 8). Additionally, no sarcomeres were built in *fla* embryos injected with *smydlb*^{278del} mRNA (Fig. 7D), indicating that the SMYD1–myosin interaction is pivotal for sarcomere assembly in zebrafish heart and fast-twitch skeletal muscle cells.

Discussion

Although timely and spatially coordinated assembly of a large number of striated muscle proteins is crucial for regular heart and skeletal muscle function, so far surprisingly little is known about the molecular control mechanisms that guarantee proper

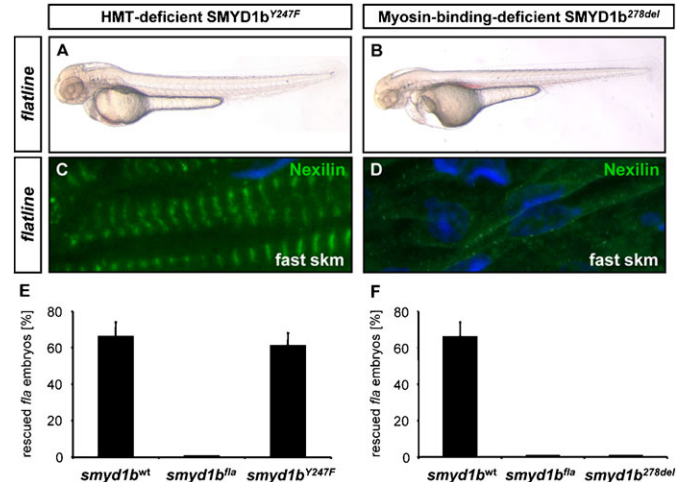


Fig. 7. HMT activity of SMYD1 is dispensable, whereas Myosin-binding is crucial for thick filament assembly. (A,E) Ectopic expression of wild-type and HMT-deficient *smydlb* (*smydlb*^{Y247F}) rescues the heart and fast-twitch skeletal muscle phenotype of *fla* embryos (*smydlb*^{wt}, $66.1 \pm 8.1\%$; *smydlb*^{Y247F}, $61.2 \pm 7.0\%$; $n=3$), whereas injection of *fla* mutant mRNA (*smydlb*^{fla}) has no effect. (C) As shown by immunohistochemistry with an antibody against the Z-disc protein Nexilin, sarcomerogenesis is reconstituted in fast-twitch skeletal muscle cells of *fla* embryos injected with *smydlb*^{Y247F} mRNA. (B,F) By contrast, injection of myosin-binding-deficient *smydlb* (*smydlb*^{278del}) into *fla* embryos does not reconstitute heart and fast-twitch skeletal muscle function. (D) As shown by Nexilin immunohistochemistry, no sarcomeres are built in fast-twitch skeletal muscle cells of *fla* embryos injected with *smydlb*^{278del} mRNA. All error bars represent s.d.

shuttling, processing and assembly of sarcomeric components. Here, we demonstrate that SMYD1 is crucial in orchestrating thick filament assembly in cardiomyocytes and fast-twitch skeletal muscle cells in zebrafish.

SMYD1 is exclusively expressed in cardiomyocytes and skeletal muscle cells in mice and zebrafish (Gottlieb et al., 2002; Phan et al., 2005; Tan et al., 2006). Targeted deletion of *smydl* in mice results in embryonic lethality at \sim E10.5, most probably owing to reduced levels of Hand2 in the precardiac mesoderm, leading to impaired development of the right ventricular chamber and left ventricular contractile failure (Gottlieb et al., 2002). Both murine and zebrafish SMYD1 can act as HMTs (Gottlieb et al., 2002; Tan et al., 2006). Accordingly, localization of SMYD1 in the nucleus is indispensable for its function as HMT. Interestingly, as well as its expression in the nucleus we find significant amounts of SMYD1 localizes to the sarcomeric M-line of cardiac myocytes. Furthermore, in a model of decelerated myofibrillogenesis (Etard et al., 2008), we find that the subcellular localization of SMYD1 is highly dynamic. We show that SMYD1 first associates with the A-band, where unfolded Myosin resides. Later on, SMYD1 shuttles to the sarcomeric M-line when myofibrillogenesis is completed. These results are supported by our finding that SMYD1 physically interacts with sarcomeric myosin, implying that there is an active role of SMYD1 for the assembly of myosin filaments. However, several muscle proteins such as Muscle Lim Proteins (MLPs), the Nuclear Factor Of Activated T Cells 3 (NF-AT3), Core-binding factor β (CBF β) and Muscle-Specific Ring Finger Proteins (MURFs) show a similar intracellular distribution, with binding to specific sarcomeric sites, such as the M-line, I-band or Z-disc, and also having a functional role within the nucleus. Interestingly,

upon defined stimuli, such as biomechanical stress or denervation, all these proteins then translocate to the cell nucleus to impact on gene transcription (Ecarnot-Laubriet et al., 2000; McElhinny et al., 2002; Meder et al., 2010; Nicol et al., 2000). Similarly, SMYD1 binding to the M-line might also serve as a buffer to maintain balanced levels of nuclear SMYD1 activity and to guarantee immediate crosstalk between sarcomeres and the nucleus. Interestingly, SMYD2, another member of the SMYD protein family, was found to methylate not only histones but also non-histone proteins, such as p53 (Huang et al., 2006). Furthermore, SMYD3 was found to dimethylate Vascular Endothelial Growth Factor Receptor 1 (VEGFR1), which leads to an enhanced kinase activity of VEGFR1 (Kunizaki et al., 2007). Similarly, SMYD1 might also function as a methyltransferase with M-line proteins as a substrate. In this context, it is interesting that modification of myosin through methylation has been known about for more than 30 years but the functional role of this modification and the proteins that transfer methyl groups to myosin are still unknown (Huszar and Elzinga, 1972).

We find that SMYD1 is expressed only in cardiomyocytes and fast-twitch skeletal muscle cells but not slow-twitch skeletal muscle cells. These findings are in contrast to recent observations using a *smyd1*-GFP transgenic zebrafish line suggesting that SMYD1 is expressed in the heart and both skeletal muscle fiber types, with a stronger signal intensity in the slow-twitch fiber population (Du et al., 2006). These contradictory findings might be explained by the complex orchestration of regulatory signals within a distinct promoter region. In the context of the *smyd1* promoter, it is probable that important regulatory elements or sites of selective DNA methylation, restricting the expression of SMYD1 to cardiomyocytes and fast-twitch skeletal muscle cells, are not included in the *smyd1*-GFP transgenic promoter construct used during the generation of the transgene. Our findings are also supported by the fact that defective sarcomerogenesis is only present in the heart and fast-twitch skeletal muscles, but not slow-twitch muscle fibers. Nevertheless, it will be interesting to dissect the regulatory elements excluding SMYD1 from the slow-twitch fiber cell population.

To our knowledge, SMYD1 is the first protein that controls myofibrillar assembly exclusively in fast-twitch skeletal muscle cells and cardiomyocytes. Recently, two proteins have been found to control slow-twitch skeletal muscle cell differentiation and myofiber arrangement without an effect on cardiomyocytes and fast-twitch fibers. By characterizing the zebrafish mutant *u-boot* (*ubo*), the SET-domain-containing protein Blimp-1 was found to be essential for slow-twitch fiber specification downstream of Hedgehog (Hh) signaling (Baxendale et al., 2004). Consequently, the homeobox gene *prox1* was shown to act downstream of Blimp-1 to regulate exclusively slow-twitch myofibrillar assembly (Roy et al., 2001).

Whereas mRNA levels of the main sarcomeric components, such as myosins, are unaffected by loss of SMYD1 function, protein levels of these myofibrillar constituents are severely downregulated in cardiomyocytes and fast-twitch skeletal muscle cells. As shown recently, a loss-of-function mutation in the muscle chaperone Hsp90a1 in the zebrafish mutant *akineto* leads to severe defects in skeletal muscle sarcomerogenesis due to impaired thick filament assembly (Hawkins et al., 2008). Remarkably, and similar to the situation in *fla*, myosin protein levels are severely reduced in this mutant. Another muscle chaperone, UNC-45b, interacts with Hsp90a1 to guide the

assembly of myosins into sarcomeric units (Srikakulam and Winkelmann, 1999). UNC-45b-deficient zebrafish embryos and worms have strongly disorganized sarcomeres, although initial Z-body formation and the basal organization of thick filaments seems not to be altered, implicating a rather restricted role of UNC-45b in the integration of thick filaments into sarcomeres (Barral et al., 2002; Etard et al., 2007). Strikingly, not only the loss but also elevated levels of UNC-45b result in inhibition of sarcomere assembly in worms and zebrafish, indicating that muscle chaperone levels have to be precisely balanced for unconstrained sarcomerogenesis and myosin stability (Bernick et al., 2010; Hoppe et al., 2004; Janiesch et al., 2007; Landsverk et al., 2007). We find UNC-45b expression levels to be severely upregulated in *fla*. Interestingly, a mild knockdown of UNC-45b in *fla* mutant embryos does not reconstitute heart and skeletal muscle function, implying that overexpression of UNC-45b is not the molecular cause of the observed muscle phenotype in *fla*.

SMYD1 is known to regulate target gene transcription by methylating histones in the nucleus. We find here that SMYD1 also exhibits nucleus-independent functions, such as interaction with sarcomeric myosin proteins. Remarkably, we find that SMYD1 HMT activity is dispensable for sarcomerogenesis in *fla* because thick filament assembly is restored by ectopic expression of HMT-deficient SMYD1. By contrast, myosin-binding-deficient SMYD1 does not reconstitute heart and fast-twitch skeletal muscle function, demonstrating that the SMYD1-myosin interaction is pivotal for proper thick filament assembly. These findings suggest that SMYD1, similar to Hsp90a1 or UNC-45b, also plays a role in myosin processing or chaperoning during myofibrillogenesis (Etard et al., 2007; Hawkins et al., 2008; Landsverk et al., 2007).

Chaperones and associated proteins are increasingly recognized as important regulators that balance the dynamics of sarcomeric unit synthesis and degradation in the heart and skeletal muscles. However, the mechanisms by which these fundamental processes are controlled are only poorly understood. In *fla*, we now show for the first time that SMYD1 is a binding partner of myosin and that this interaction is crucial for thick filament assembly in heart and fast-twitch skeletal muscle cells. Strategies that target these mechanisms might ultimately lead to novel treatment concepts for skeletal myopathies and heart muscle diseases.

Materials and Methods

Cell transplantation, injection procedures and virtual M-mode measurement

Care and breeding of zebrafish *Danio rerio* was as described previously (Rottbauer et al., 2005). The present study was performed after securing appropriate institutional approvals. It conforms to the Guide for the Care and Use of Laboratory Animals published by the 'US National Institutes of Health' (NIH Publication No. 85-23, revised 1996). Pictures and movies were recorded at 72 hpf. To inhibit pigmentation, 0.003% 1-phenyl-2-thiourea was added to the embryo medium (Bendig et al., 2006a). Cell transplantation was performed and analyzed essentially as described previously (Rottbauer et al., 2002). Embryos used for transplantation were produced by intercrossing *fla*^{+/−} fish, thus yielding a wild-type to mutant embryo ratio of 3:1. 3% tetramethylrhodamin dextran and 3% biotin dextran (Molecular Probes, Invitrogen) were mixed in 0.2 M KCl and microinjected into donor embryos at the one-cell stage. Labeled donor cells were transplanted at the early sphere stage and embryos were assessed by fluorescence microscopy at 24 and 48 hpf. To confirm the integration of labeled donor cells into acceptor embryo heart and skeletal muscles, whole embryos were stained with anti-biotin antibodies (DAB), fixed with 4% paraformaldehyde, embedded in JB-4 and sectioned. Labeled donor embryos were genotyped using polymorphic markers flanking the *fla* gene. Morpholinos were directed against a splice donor site (MO2-*zsmyd1*, 5'-GGACGTTGACGTACCACGCCGAGGA-3') and the translational start site of *smyd1* (MO1-*zsmyd1*, 5'-AAAACTCCACAACTCCATTCTG-

3'). Two *smyd1*-specific 5-bp mismatch control morpholinos (MO1-*zsmyd1mm*, 5'-AAAAAGTTTCGAGAAAGTCGATTCTG-3' and MO2-*zsmyd1mm*, 5'-GGACCTTGACCTAGCACCCAGCA-3') (GENETOOLS, LLC) were injected at the same concentration as a negative control. UNC-45b-specific morpholinos were directed against the translational start site of zebrafish *unc-45b* (Etard et al., 2007). Sense-capped RNA was synthesized using the mMACHINE system (Ambion) from pCS2*zsmyd1* (Rottbauer et al., 2005). All error bars represent standard deviations (s.d.). To analyze contractile force of wild-type and mutant hearts, we undertook M-mode measurements with the help of the zebraFS software application (<http://www.benegfx.de>) (Medler et al., 2009).

Transmission electron microscopy, in situ hybridization, immunostaining and immunoblotting

Electron micrographs were obtained essentially as described previously (Rottbauer et al., 2001). Whole-mount RNA in situ hybridization was carried out essentially as described previously (Rottbauer et al., 2005) using a full-length *smyd1* antisense probe, as well as antisense probes for zebrafish *mlc2*, *vmhc*, *amhc*, *titin*, *tpm4*, *tnnt*, *hsp90a1* and *unc-45b*. Immunostaining of zebrafish embryos fixed in Dent's fix were carried out with antibodies against slow muscle myosin heavy chains (F59) (DSHB) and Nexilin (BD Biosciences). Embryos were embedded in JB-4, 5- μ m sections were cut and dried, and the cell nuclei were counterstained with DAPI (VectaShield) (Bendig et al., 2006b). Immunostaining of mouse heart paraffin sections were carried out with antibodies against SMYD1 (Abcam), α -actinin (Sigma) and myomesin (DSHB), and cell nuclei were counterstained with DAPI. For immunoblotting, proteins were separated by SDS-PAGE and transferred onto polyvinylidene fluoride (PVDF) membrane. Blots were probed with antibodies against muscle myosin heavy chains (MF20, S46, EB165) (DSHB), Hsp90a (Abcam) and β -actin (Sigma) and signals detected by chemiluminescence (polyclonal anti-rabbit-IgG antibody conjugated to horseradish peroxidase).

Genetic mapping, positional cloning and mutation detection

DNA from 24 *fla^{mv047a}* mutant and 24 wild-type embryos was pooled and bulked segregation analysis was performed as described (Rottbauer et al., 2005). RNA from *fla* mutant and wild-type embryos was isolated using TRIzol (Life Technologies) and reverse transcribed. Eight independent *smyd1* cDNA clones from mutant and wild-type embryos were sequenced. Genomic DNA from *fla* mutant and wild-type embryos was sequenced around the point-mutation.

Microarray and quantitative real-time PCR

For microarray analysis 25 *fla* mutant and 25 wild-type embryos were collected at 36 hpf, and RNA was isolated with TRIzol reagent. A clean-up of the RNA was performed by using the RNeasy Kit (Qiagen). Microarray analysis was performed by Atlas Biolabs (Berlin) using a zebrafish-specific Affymetrix chip. Quantitative real-time PCR was carried out according to standard protocols with the SYBR-Green method using an ABI 7000. All error bars represent standard deviations (s.d.).

Expression and purification of recombinant SMYD1 and UNC-45b

smyd1 variants and *unc-45b* were subcloned into the pDEST24 and/or pCNA3.1/nV5-DEST vector (Invitrogen). GST-tagged SMYD1 and UNC-45b fusion proteins were expressed in *Escherichia coli* BL21-AI by inducing bacteria with 0.1% arabinose overnight at 30°C. Bacteria were harvested by centrifugation and resuspended in lysis buffer [150 mM NaCl, 50 mM Tris-HCl pH 7.4, 5 mM EDTA at pH 7.4, 1% Triton X-100 and protease inhibitors (Complete, Roche)]. Bacterial cells were disrupted by sonification, and cell debris was removed by centrifugation (14,000 g for 30 minutes at 4°C). GST fusion proteins were purified with glutathione-Sepharose matrix (Amersham). For pull-down analyzes, myosin isolated from rabbit muscle (Fluka, 70045) was incubated at room temperature for 1 hour with the glutathione-Sepharose matrix and GST-SMYD1 complex. After washing and boiling for 10 minutes at 95°C, the proteins were separated by SDS page, transferred onto a PVDF membrane and probed with antibodies against muscle myosin heavy chain (MF20) (DSHB). In vitro translation of wild-type and mutant SMYD1 was performed using the TNT coupled reticulocyte lysate system (Promega).

This work was supported by Deutsche Forschungsgemeinschaft (DFG) Ro2173/2-1, Ro2173/2-2, Ro2173/3-1 and Ro2173/4-1, Bundesministerium für Bildung und Forschung 01GS0108, 01GS0420, 01GS0836, 01GS1104 (NGFNplus), and Insight-DCM, the European Union (EU-Inheritance), Association Francaise contre les Myopathies (AFM) and ZF-Health.

Supplementary material available online at

<http://jcs.biologists.org/lookup/suppl/doi:10.1242/jcs.084772/-/DC1>

References

- Barral, J. M., Bauer, C. C., Ortiz, I. and Epstein, H. F. (1998). Unc-45 mutations in *Caenorhabditis elegans* implicate a CRO1/She4p-like domain in myosin assembly. *J. Cell Biol.* **143**, 1215-1225.
- Barral, J. M., Hutagalung, A. H., Brinker, A., Hartl, F. U. and Epstein, H. F. (2002). Role of the myosin assembly protein UNC-45 as a molecular chaperone for myosin. *Science* **295**, 669-671.
- Baxendale, S., Davison, C., Muxworthy, C., Wolff, C., Ingham, P. W. and Roy, S. (2004). The B-cell maturation factor Blimp-1 specifies vertebrate slow-twitch muscle fiber identity in response to Hedgehog signaling. *Nat. Genet.* **36**, 88-93.
- Bendig, G., Grimmer, M., Huttner, I. G., Wessels, G., Dahme, T., Just, S., Trano, N., Katus, H. A., Fishman, M. C. and Rottbauer, W. (2006a). Integrin-linked kinase, a novel component of the cardiac mechanical stretch sensor, controls contractility in the zebrafish heart. *Genes Dev.* **20**, 2361-2372.
- Bendig, G., Huttner, I. G., Grimmer, M., Dahme, T., Wessels, G., Just, S., Katus, H. A., Trano, N., Fishman, M. C. and Rottbauer, W. (2006b). Integrin-linked kinase, a novel component of the cardiac mechanical stretch sensor, controls contractility in the zebrafish heart. *Genes Dev.* **20**, 2361-2372.
- Bernick, E., Zhang, P. and Du, S. (2010). Knockdown and overexpression of Unc-45b result in defective myofibril organization in skeletal muscles of zebrafish embryos. *BMC Cell Biol.* **11**, 70.
- Brown, M. A., Sims, R. J., 3rd, Gottlieb, P. D. and Tucker, P. W. (2006). Identification and characterization of Smyd2: a split SET/MYND domain-containing histone H3 lysine 36-specific methyltransferase that interacts with the Sin3 histone deacetylase complex. *Mol. Cancer* **5**, 26.
- Diehl, F., Brown, M. A., van Amerongen, M. J., Novoyatleva, T., Wietelmann, A., Harriss, J., Ferrazzi, F., Bottger, T., Harvey, R. P., Tucker, P. W. et al. (2010). Cardiac deletion of Smyd2 is dispensable for mouse heart development. *PLoS ONE* **5**, e9748.
- Du, S. J., Rotllant, J. and Tan, X. (2006). Muscle-specific expression of the *smyd1* gene is controlled by its 5.3-kb promoter and 59-flanking sequence in zebrafish embryos. *Dev. Dyn.* **235**, 3306-3315.
- Ecarnot-Laubriet, A., De Luca, K., Vandroux, D., Moisan, M., Bernard, C., Assem, M., Rochette, L. and Teyssier, J. R. (2000). Downregulation and nuclear relocation of MLP during the progression of right ventricular hypertrophy induced by chronic pressure overload. *J. Mol. Cell. Cardiol.* **32**, 2385-2395.
- Epstein, H. F. and Thomson, J. N. (1974). Temperature-sensitive mutation affecting myofilament assembly in *Caenorhabditis elegans*. *Nature* **250**, 579-580.
- Etard, C., Behra, M., Fischer, N., Hutcheson, D., Geisler, R. and Strahle, U. (2007). The UCS factor Steif/Unc-45b interacts with the heat shock protein Hsp90a during myofibrillogenesis. *Dev. Biol.* **308**, 133-143.
- Etard, C., Roostalu, U. and Strahle, U. (2008). Shuttling of the chaperones Unc45b and Hsp90a between the A band and the Z line of the myofibril. *J. Cell Biol.* **180**, 1163-1175.
- Gottlieb, P. D., Pierce, S. A., Sims, R. J., Yamagishi, H., Weihe, E. K., Harriss, J. V., Maika, S. D., Kuziel, W. A., King, H. L., Olson, E. N. et al. (2002). Bop encodes a muscle-restricted protein containing MYND and SET domains and is essential for cardiac differentiation and morphogenesis. *Nat. Genet.* **31**, 25-32.
- Hassel, D., Scholz, E. P., Trano, N., Friedrich, O., Just, S., Medler, B., Weiss, D. L., Zitron, E., Marquart, S., Vogel, B. et al. (2008). Deficient zebrafish ether-a-go-go-related gene channel gating causes short-QT syndrome in zebrafish reggae mutants. *Circulation* **117**, 866-875.
- Hawkins, T. A., Haramis, A. P., Etard, C., Prodromou, C., Vaughan, C. K., Ashworth, R., Ray, S., Behra, M., Holder, N., Talbot, W. S. et al. (2008). The ATPase-dependent chaperoning activity of Hsp90a regulates thick filament formation and integration during skeletal muscle myofibrillogenesis. *Development* **135**, 1147-1156.
- Hoert, O., Moerman, D. G., Clark, K. A., Beckerle, M. C. and Ruvkun, G. (1999). A conserved LIM protein that affects muscular adherens junction integrity and mechanosensory function in *Caenorhabditis elegans*. *J. Cell Biol.* **144**, 45-57.
- Hoppe, T., Cassata, G., Barral, J. M., Springer, W., Hutagalung, A. H., Epstein, H. F. and Baumeister, R. (2004). Regulation of the myosin-directed chaperone UNC-45 by a novel E3/E4-multiubiquitylation complex in *C. elegans*. *Cell* **118**, 337-349.
- Huang, J. and Berger, S. L. (2008). The emerging field of dynamic lysine methylation of non-histone proteins. *Curr. Opin. Genet. Dev.* **18**, 152-158.
- Huang, J., Perez-Burgos, L., Placek, B. J., Sengupta, R., Richter, M., Dorsey, J. A., Kubicek, S., Opravil, S., Jenuwein, T. and Berger, S. L. (2006). Repression of p53 activity by Smyd2-mediated methylation. *Nature* **444**, 629-632.
- Huszar, G. and Elzinga, M. (1972). Homologous methylated and nonmethylated histidine peptides in skeletal and cardiac myosins. *J. Biol. Chem.* **247**, 745-753.
- Janiesch, P. C., Kim, J., Mouysset, J., Barikbin, R., Lochmuller, H., Cassata, G., Krause, S. and Hoppe, T. (2007). The ubiquitin-selective chaperone CDC-48/p97 links myosin assembly to human myopathy. *Nat. Cell Biol.* **9**, 379-390.
- Kunizaki, M., Hamamoto, R., Silva, F. P., Yamaguchi, K., Nagayasu, T., Shibuya, M., Nakamura, Y. and Furukawa, Y. (2007). The lysine 831 of vascular endothelial growth factor receptor 1 is a novel target of methylation by SMYD3. *Cancer Res.* **67**, 10759-10765.
- Landsverk, M. L., Li, S., Hutagalung, A. H., Najafav, A., Hoppe, T., Barral, J. M. and Epstein, H. F. (2007). The UNC-45 chaperone mediates sarcomere assembly through myosin degradation in *Caenorhabditis elegans*. *J. Cell Biol.* **177**, 205-210.
- McElhinny, A. S., Kakinuma, K., Sorimachi, H., Labeit, S. and Gregorio, C. C. (2002). Muscle-specific RING finger-1 interacts with titin to regulate sarcomeric

- M-line and thick filament structure and may have nuclear functions via its interaction with glucocorticoid modulatory element binding protein-1. *J. Cell Biol.* **157**, 125-136.
- Meder, B., Laufer, C., Hassel, D., Just, S., Marquart, S., Vogel, B., Hess, A., Fishman, M. C., Katus, H. A. and Rottbauer, W.** (2009). A single serine in the carboxyl terminus of cardiac essential myosin light chain-1 controls cardiomyocyte contractility in vivo. *Circ. Res.* **104**, 650-659.
- Meder, B., Just, S., Vogel, B., Rudloff, J., Gartner, L., Dahme, T., Huttner, I., Zankl, A., Katus, H. A. and Rottbauer, W.** (2010). JunB-CBF β signaling is essential to maintain sarcomeric Z-disc structure and when defective leads to heart failure. *J. Cell Sci.* **123**, 2613-2620.
- Miller, R. K., Qadota, H., Mercer, K. B., Gernert, K. M. and Benian, G. M.** (2008). UNC-98 and UNC-96 interact with paramyosin to promote its incorporation into thick filaments of *Caenorhabditis elegans*. *Mol. Biol. Cell* **19**, 1529-1539.
- Nicol, R. L., Frey, N. and Olson, E. N.** (2000). From the sarcomere to the nucleus: role of genetics and signaling in structural heart disease. *Annu. Rev. Genomics Hum. Genet.* **1**, 179-223.
- Phan, D., Rasmussen, T. L., Nakagawa, O., McAnally, J., Gottlieb, P. D., Tucker, P. W., Richardson, J. A., Bassel-Duby, R. and Olson, E. N.** (2005). BOP, a regulator of right ventricular heart development, is a direct transcriptional target of MEF2C in the developing heart. *Development* **132**, 2669-2678.
- Rea, S., Eisenhaber, F., O'Carroll, D., Strahl, B. D., Sun, Z. W., Schmid, M., Opravil, S., Mechtler, K., Ponting, C. P., Allis, C. D. et al.** (2000). Regulation of chromatin structure by site-specific histone H3 methyltransferases. *Nature* **406**, 593-599.
- Rice, J. C. and Allis, C. D.** (2001). Histone methylation versus histone acetylation: new insights into epigenetic regulation. *Curr. Opin. Cell Biol.* **13**, 263-273.
- Rottbauer, W., Baker, K., Wo, Z. G., Mohideen, M. A., Cantiello, H. F. and Fishman, M. C.** (2001). Growth and function of the embryonic heart depend upon the cardiac-specific L-type calcium channel α_1 subunit. *Dev. Cell* **1**, 265-275.
- Rottbauer, W., Saurin, A. J., Lickert, H., Shen, X., Burns, C. G., Wo, Z. G., Kemler, R., Kingston, R., Wu, C. and Fishman, M.** (2002). Reptin and pontin antagonistically regulate heart growth in zebrafish embryos. *Cell* **111**, 661-672.
- Rottbauer, W., Just, S., Wessels, G., Trano, N., Most, P., Katus, H. A. and Fishman, M. C.** (2005). VEGF-PLC γ pathway controls cardiac contractility in the embryonic heart. *Genes Dev.* **19**, 1624-1634.
- Rottbauer, W., Wessels, G., Dahme, T., Just, S., Trano, N., Hassel, D., Burns, C. G., Katus, H. A. and Fishman, M. C.** (2006). Cardiac myosin light chain-2: a novel essential component of thick-myofilament assembly and contractility of the heart. *Circ. Res.* **99**, 323-331.
- Roy, S., Wolff, C. and Ingham, P. W.** (2001). The u-boot mutation identifies a Hedgehog-regulated myogenic switch for fiber-type diversification in the zebrafish embryo. *Genes Dev.* **15**, 1563-1576.
- Sehnert, A. J., Huq, A., Weinstein, B. M., Walker, C., Fishman, M. and Stainier, D. Y.** (2002). Cardiac troponin T is essential in sarcomere assembly and cardiac contractility. *Nat. Genet.* **31**, 106-110.
- Srikulam, R. and Winkelmann, D. A.** (1999). Myosin II folding is mediated by a molecular chaperonin. *J. Biol. Chem.* **274**, 27265-27273.
- Tan, X., Rotflant, J., Li, H., De Deyne, P. and Du, S. J.** (2006). SmyD1, a histone methyltransferase, is required for myofibril organization and muscle contraction in zebrafish embryos. *Proc. Natl. Acad. Sci. USA* **103**, 2713-2718.
- Venolia, L. and Waterston, R. H.** (1990). The unc-45 gene of *Caenorhabditis elegans* is an essential muscle-affecting gene with maternal expression. *Genetics* **126**, 345-353.
- Warren, K. S. and Fishman, M. C.** (1998). "Physiological genomics": mutant screens in zebrafish. *Am. J. Physiol.* **275**, H1-H7.
- Xu, X., Meiler, S. E., Zhong, T. P., Mohideen, M., Crossley, D. A., Burggren, W. W. and Fishman, M. C.** (2002). Cardiomyopathy in zebrafish due to mutation in an alternatively spliced exon of titin. *Nat. Genet.* **30**, 205-209.