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Activation of MAPK pathways links LMNA mutations to cardiomyopathy in Emery-Dreifuss muscular dystrophy

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Mutations in LMNA, which encodes nuclear Lamins A and C cause diseases affecting various organs, including the heart. We have determined the effects of an Lmna H222P mutation on signaling pathways involved in the development of cardiomyopathy in a knockin mouse model of autosomal dominant Emery-Dreifuss muscular dystrophy. Analysis of genome-wide expression profiles in hearts using Affymetrix GeneChips showed statistically significant differences in expression of genes in the MAPK pathways at the incipience of the development of clinical disease. Using real-time PCR, we showed that activation of MAPK pathways preceded clinical signs or detectable molecular markers of cardiomyopathy. In heart tissue and isolated cardiomyocytes, there was activation of MAPK cascades and downstream targets, implicated previously in the pathogenesis of cardiomyopathy. Expression of H222P Lamin A in cultured cells activated MAPKs and downstream target genes. Activation of MAPK signaling by mutant A-type lamins could be a cornerstone in the development of heart disease in autosomal dominant Emery-Dreifuss muscular dystrophy.

Introduction
Dilated cardiomyopathy is the most serious aspect of Emery-Dreifuss muscular dystrophy (EDMD), which is also characterized by contractures of the elbows, Achilles’ tendons, and spine and progressive muscle wasting in a humero-peroneal distribution (1). Initially described as an X-linked inherited disorder, autosomal dominant and recessive forms are also recognized, with the dominant form being most prevalent. X-linked EDMD arises as a consequence of mutations in emerin (EMD) (2), encoding the ubiquitously expressed inner nuclear membrane protein emerin (3, 4). Autosomal dominant and recessive EDMD arise from mutations in LMNA (5, 6). Several other diseases affecting striated muscles or other tissues are also caused by different LMNA mutations (7).

LMNA encodes A-type nuclear lamins, of which Lamin A and Lamin C are the predominant somatic cell isoforms (8). Nuclear lamins are intermediate filament proteins that polymerize to form 10-nm diameter filaments on the inside of the inner nuclear membrane (9–12). The lamina interacts with integral proteins in the inner nuclear membrane, provides anchorage sites for chromatin, and structurally supports the nuclear envelope (7). Many disease-causing A-type lamin mutants induce abnormal nuclear envelope architecture (7).

Although A-type lamins are expressed in most human tissues, EDMD selectively affects striated muscle and tendons. The reason for this tissue-selective phenotype is not clear, but 2 hypotheses have emerged to explain it (7). The mechanical stress hypothesis proposes that mutations in A-type lamins lead to increased nuclear fragility and eventual nuclear disruption in tissues subjected to mechanical strain and is based primarily on observations in cultured cells. The gene expression hypothesis proposes that mutations in A-type lamins lead to abnormal tissue-specific gene regulation and is based on findings that A-type lamins and associated proteins bind to chromatin and transcriptional regulators. These 2 models are not mutually exclusive, as defective nuclear mechanics have been linked to altered expression of stress-activated genes in fibroblasts lacking A-type lamins (13). However, despite data obtained mostly from cultured cells and in vitro binding assays that have lead to the mechanical stress and gene expression hypotheses, there are scant experimental results linking mutations in A-type lamins to pathogenic pathways in affected tissues. Here we report results of an analysis, using hearts from a mouse model of EDMD, exploring effects of an A-type lamin mutation on gene expression and signaling pathways involved in development of cardiomyopathy.

Results
Gene expression profiling in hearts from mice with Lmna H222P mutation. To identify abnormal expression of genes involved in development of cardiomyopathy caused by Lmna mutation, we carried out a genome-wide RNA expression analysis in hearts from LmnaH222P/H222P and LmnaH222P/+/+ mice. A detailed description of these mice has been previously published (14). Male LmnaH222P/H222P mice develop cardiac chamber dilation, decreased left ventricle fractional shortening and hypokinesis detectable by echocardiography at 8 weeks of age. At 12 weeks of age, conduction system abnormalities become pronounced, characterized primarily by an increased PR interval on electrocardiograms. Histological analysis shows left ventricular fibrosis, fiber degeneration, and atrial dilation by 16 weeks of age.
Male mice die between 4 and 9 months of age. To focus on primary events and avoid interference caused by fibrotic cells and nonspecific tissue damage in hearts from older mice, we analyzed samples from mice at 10 weeks of age. There are no histological detectable abnormalities in hearts of mice at this age (see below). We also used hearts from heterozygous Lmna+/H222P mice, which develop signs of cardiomyopathy at 24 months of age (Bonne et al., unpublished observations) and have normal life spans.

Hearts were isolated and transcription profiles determined using amplified RNA for microarray analyses. We used Affymetrix Mouse Genome 430 2.0 Arrays, which contain 45,101 probes sets for representing genes with significant differences in expression between hearts from control mice (Figure 1B). The 104 probes sets identified in hearts from LmnaH222P/+ mice corresponded to 92 upregulated genes, 69 known genes, and 23 cDNAs with unknown functions (Supplemental Table 1; supplemental material available online with this article; doi:10.1172/JCI29042DS1). The 12 downregulated genes included 6 known genes and 6 uncharacterized cDNAs. The number of upregulated genes corresponding to the probe sets identified in hearts from LmnaH222P/+ mice was 94, which included 73 known genes and 21 cDNAs of unknown function (Supplemental Table 2). The number of downregulated genes was 20, including 8 known genes and 12 cDNAs with unknown functions. There were 57 similar probe sets between hearts from LmnaH222P/+ and LmnaH222P/H222P mice (Figure 1C). The 104 probes sets identified in hearts from LmnaH222P/+ mice was 20, including 8 known genes and 12 cDNAs with unknown functions. There were 57 similar probe sets between hearts from LmnaH222P/+ and LmnaH222P/H222P mice (Figure 1C).

To validate expression of selected transcripts identified by microarray analysis, we performed real-time PCR using RNA extracted from mouse hearts (Figure 1C). Genes encoding heavy and light chains of myosins (Myh7, Myh4, Myh7), actin-α2 (Acta2), sarcolipin (Sln), and pituitary tumor-transforming 1 (Pttg1) were selected as representative. There was a correlation between real-time PCR results and altered expression detected by microarrays for these genes with greater than 2-fold differences in expression in hearts from both LmnaH222P/+ and LmnaH222P/H222P mice (Figure 1C).

Many genes, including some muscle-specific genes, were identical in hearts from LmnaH222P/+ and LmnaH222P/H222P mice, with significantly
altered expression compared with those of controls (Supplemental Table 3). Myl4, Myl7, Myh7, and Sln were upregulated in hearts from both LmnaH222P/H222P and LmnaH222P/+ mice. There was also increased expression of genes encoding LIM domain family members, including Pdlim3 and Fhl1. However, it appeared that increased expression of muscle-specific genes was greater in hearts of LmnaH222P/H222P mice than in LmnaH222P/+ mice (Supplemental Tables 2 and 1, respectively).

Statistically significant increases in RNA transcripts encoding atrial natriuretic factor and actin-α2 were observed only in hearts from LmnaH222P/H222P mice (Supplemental Table 2).

We used ermineJ software, which analyzes gene ontology terms applied to genes, to identify functional classes of genes differentially expressed in hearts of LmnaH222P/+ and LmnaH222P/H222P mice compared with those expressed in controls. Analysis using functional class scoring improves sensitivity by statistically evaluating genes in biologically meaningful groups. In hearts from LmnaH222P/H222P mice, the highest scoring gene ontology classes were genes encoding proteins involved in inflammation and fibrosis (Table 1). However, these classes were not significantly altered in hearts from LmnaH222P/+ mice. Differential expression of genes encoding muscle components, including myosins and sarcomeric proteins, achieved statistical significance in hearts from both LmnaH222P/H222P and LmnaH222P/+ mice (Table 1). Genes encoding various proteins involved in transcription and translation also demonstrated significant differences in expression, some only in hearts of LmnaH222P/H222P and heterozygotes (Table 1).

### Table 1

Top-scoring gene ontology terms in hearts of LmnaH222P/H222P and LmnaH222P/+ mice

<table>
<thead>
<tr>
<th>GO term</th>
<th>GO identification number</th>
<th>H222P/H222P</th>
<th>H222P/+</th>
</tr>
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<tr>
<td><strong>Inflammation</strong></td>
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<td>Antigen presentation</td>
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<tr>
<td><strong>Fibrosis</strong></td>
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<tr>
<td>Muscle myosin</td>
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<td>0.4948603</td>
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<tr>
<td>Structural constituent of muscle</td>
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<td>poly(A) binding</td>
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GO, gene ontology. ERmineJ uses q values to determine which gene sets are statistically significant between hearts from LmnaH222P and LmnaH222P/H222P and hearts from LmnaH222P and LmnaH222P/H222P.
Analysis of markers of cardiomyopathy in hearts from mice with Lmna H222P mutation. Several genes discovered through microarray analysis to be differentially expressed in hearts of Lmna H222P knockin mice appeared to be involved in pathological changes of cardiomyopathy. Activation of genes encoding proteins involved in inflammation and fibrosis has been reported in previous studies of cardiomyopathies in humans and mice (15, 16) and is consistent with pathological changes that develop in hearts of LmnaH222P/H222P mice (14). However, histological examination did not reveal inflammation or fibrosis in hearts from LmnaH222P/H222P mice at 10 weeks (Figure 2A). This suggests that detection of molecular signatures using microarrays is more sensitive than conventional histology in detecting inflammation and fibrosis.

Deregulation of genes encoding muscle components and involved in muscle organization has been described in other studies of dilated cardiomyopathies (17, 18). We therefore used immunoblotting to analyze expression of β-myosin heavy chain (β-MHC) and myosin light chain 2 (MLC-2) polypeptides, as their genes showed significantly increased expression in hearts from mutant mice. Hearts from LmnaH222P/+ and LmnaH222P/H222P mice had 5.3-fold and 6.1-fold increases in β-MHC and 7.1-fold and 6.8-fold increases in MLC-2 expression, respectively, compared with controls (Figure 2B). We also measured expression of atrial natriuretic factor (ANF), which is upregulated in heart failure, and its expression was increased in hearts from LmnaH222P/H222P mice by approximately 6-fold compared with controls (Figure 2B). However, the increase of ANF was not statistically significant in hearts from LmnaH222P/+ mice. This is consistent with results of microarray analysis and cardiac chamber dilation in hearts of LmnaH222P/H222P mice at 8 weeks of age (14).

MAPK pathways involved in development of cardiomyopathy are activated in hearts of Lmna H222P mice. Our functional class scoring analysis revealed significant differences in expression of genes encoding proteins in MAPK pathways in Lmna H222P mouse hearts (Table 1). Individual genes in MAPK pathways with significantly different expressions (q < 0.05) in hearts from LmnaH222P+/− and LmnaH222P/H222P mice, as identified using the Database for Annotation, Visualization and Integrated Discovery (DAVID) Bioinformatics Database (http://david.abcc.ncifcrf.gov/), are listed in Supplemental Tables 4 and 5. Because enhanced JNK cascade activity, a branch of MAPK pathways, has been shown to cause cardiomyopathy and conduct defects (19, 20), we focused our attention on the MAPK pathways. We first evaluated phosphorylation of 2 MAPKs, JNK and ERK1/2 (pJNK and pERK1/2, respectively), in hearts from LmnaH222P−/−, LmnaH222P+/−, and LmnaH222P/H222P mice. These kinases are activated by phosphorylation. Immunoblotting with anti-pJNK Ab demonstrated 5-fold and 9-fold increases in pJNK in hearts from LmnaH222P+/− and LmnaH222P/H222P mice, respectively (Figure 3A). PERK1/2 was also significantly increased in hearts from LmnaH222P+/− and LmnaH222P/H222P mice (2.3-fold and 2.1-fold, respectively) (Figure 3A). Infiltration of cells other than cardiomyocytes could be a potential confounding variable accounting for detection of activated MAPKs in heart tissue. To remove the influence of such cells, we tested whether JNK and ERK1/2 were activated in isolated ventricular cardiomyocytes from LmnaH222P−/−. Expressions of pERK1/2 and pJNK were increased 4-fold and 12-fold, respectively, in cardiomyocytes from LmnaH222P/H222P mice compared to those from LmnaH222P+/− mice (Figure 3A).

pJNK and pERK1/2 activate a series of downstream target genes, including those encoding bcl-2, Elk1 and c-Jun (21–23). Immunoblotting with Abs against bcl-2 and Elk1 demonstrated increased expression of these proteins in hearts from both LmnaH222P+/− and LmnaH222P+/− mice compared with LmnaH222P+/− mice (Figure 3B). pc-Jun was also increased in hearts from LmnaH222P+/−/− but not LmnaH222P+/− mice (Figure 3B). Increases in Elk1, bcl-2, and pc-Jun were also detected in isolated ventricular cardiomyocytes from LmnaH222P+/−/−. These data indicate aberrant activation of MAPK signaling in hearts from both LmnaH222P+/−/− and LmnaH222P+/− mice. However, the degree of enhanced signaling appeared to be greater in hearts from homozygous mutant mice.

To analyze in vivo activation of MAPK, we used an Ab that recognized pERK1/2 in sections of heart tissue. Immunofluorescence staining of heart sections from LmnaH222P+/− mice with these antibodies revealed a faint, rather diffuse pattern, whereas fluorescence in hearts from LmnaH222P+/−/− mice was more intense and predominantly nuclear (Figure 4A). Quantitative analysis of individual cardiomyocyte nuclei in the sections confirmed that anti-pERK Ab labeled both cytoplasm and nucleus in hearts from LmnaH222P+/− mice but essentially only the nucleus in hearts from LmnaH222P+/−/− mice (Figure 4B).
Fluorescence intensity of nuclear labeling was significantly higher in heart cells of Lmna<sup>H222P/H222P</sup> mice compared with Lmna<sup>+/+</sup> mice (Figure 4C). These results demonstrate greater activation and nuclear translocation of a MAPK in hearts from Lmna<sup>H222P/H222P</sup> mice compared with controls.

To determine whether MAPK activation is observed only in the heart, we measured expression of downstream target genes Elk1, junD, c-Jun, and Elk4 in different tissues. Real-time PCR showed significantly increased expression mostly in hearts from Lmna<sup>H222P/H222P</sup> mice (Figure 5). There was also increased expression of Elk4 in skeletal muscle of Lmna<sup>H222P/H222P</sup> mice.

Our initial analyses used hearts from mice 10 weeks of age, when Lmna<sup>H222P/H222P</sup> mice already have slight ventricular dilatation (14). Activation of fibrosis genes was also detected at this time. These alterations could affect cardiac cells and secondarily stimulate MAPK cascades. We therefore use real-time PCR to analyze expression of c-Jun, Elk1, JunD, and Elk4 in hearts from Lmna<sup>+/+</sup> and Lmna<sup>H222P/H222P</sup> mice at 4, 7, and 10 weeks of age. In hearts from 10-week-old Lmna<sup>H222P/H222P</sup> mice, there was activation of Vegf, a marker of fibrosis, as well as Myl7 and Shn. Expression of c-Jun, Elk1, JunD, and Elk4 was also significantly increased (Figure 6). In 7-week-old Lmna<sup>H222P/H222P</sup> mice, there was increased cardiac expression of Myl7 but not Vegf or Shn, and expression of c-Jun, Elk1, JunD, and Elk4 was still increased (Figure 6). At 4 weeks of age, there was only increased cardiac JunD expression in Lmna<sup>H222P/H222P</sup> mice (Figure 6). These results show that MAPK activation precedes increased expression of a fibrosis marker and 2 muscle-specific genes in hearts of Lmna<sup>H222P/H222P</sup> mice.

Expression of Lamin A with the H222P aa substitution activates JNK and ERK and alters their subcellular localization. To determine whether expression of Lamin A with the H222P aa substitution is responsible for activation of MAPK signaling, we measured pERK1/2 and pJNK in transiently transfected Cos-7 and C2C12 cells expressing GFP fusions of wild-type and H222P Lamin A. Immunoblotting with Abs against total ERK1/2 and pERK1/2 demonstrated that expression of H222P Lamin A increased the amount of phosphorylated protein (Figure 7, A and B). The increase was significant compared with that of nontransfected cells and cells expressing the GFP fusion of wild-type Lamin A.

Translocation of pERK1/2 and pJNK from cytoplasm to nucleus is required for activation of downstream targets (24, 25). In nontransfected Cos-7 and C2C12 cells, pERK1/2 was mainly distributed in the cytoplasm (Figure 7, C and D). When transfected with a plasmid expressing the GFP fusion of wild-type Lamin A, pERK1/2 was also mainly distributed in cytoplasm (Figure 7, C and D). In contrast, expression of a GFP fusion of H222P Lamin A induced translocation of pERK1/2 into the nucleus (Figure 7, C and D). Approximately 80% of Cos-7 and C2C12 cells expressing H222P Lamin A showed a nuclear localization of pERK1/2. Nuclear localization of pERK1/2 was observed in only 15% of Cos-7 cells and 30% of C2C12 cells expressing wild-type Lamin A and was not observed in untransfected cells (Figure 7, E and F). Similar results were obtained for pJNK (Supplemental Figure 1). Hence, expression of H222P Lamin A stimulates phosphorylation and nuclear translocation of JNK and ERK1/2. While MAPKs were activated in C2C12 myoblasts transfected with H222P Lamin A, activated MAPK was not detected in skeletal muscle from Lmna<sup>H222P/H222P</sup> mice. However, myoblasts are only a small component of heterogeneous skeletal muscle sections. Furthermore, in humans with EDMD and in Lmna<sup>H222P/H222P</sup> mice, skeletal muscle is variably affected.

Expression of Lamin A with aa substitutions identified in EDMD associated with cardiomyopathy activates JNK and ERK. To further evaluate the effects of Lamin A mutants on activation of MAPK pathways, we examined expression of c-Jun and Elk1 reporter genes. We transiently transfected Cos-7 cells with plasmids encoding GFP fusions of H222P Lamin A as well as wild-type Lamin A and 5 other Lamin A mutants. Cells were simultaneously transfected with plasmids encoding a reporter system to detect c-Jun or Elk1 promoter activities. Expression of H222P Lamin A and Lamin A with the N195K, R298C, and N456I aa substitutions found in EDMD significantly increased activity of the c-Jun and Elk1 promoters (Figure 8). Overexpression of wild-type Lamin A and
Lamin A with a R482W mutation found in subjects with Dunnigan-type partial lipodystrophy did not significantly increase their activity. However, expression of Lamin A with an aa substitution that causes EDMD (T528K) did not significantly increase c-Jun and Elk1 promoters activities in this assay. A possible explanation of this observation may be that a GFP fusion of this mutant folds abnormally or is not as stable as the others when overexpressed in transfected cells. These results show that expression of A-type lamins with aa substitutions encoded by LMNA mutations causing cardiomyopathy leads to stimulation of downstream target genes in MAPK cascades in cultured cells.

Discussion
Although the causative genetic mutations have been identified and the descriptive pathology well documented, cellular mechanisms linking mutations in LMNA to cardiomyopathy are unknown. While several investigators have hypothesized that LMNA mutations lead to alterations in gene expression that could have tissue-selective pathogenic consequences (7), altered expression of functional groups of genes or activation of signal transduction pathways that might mediate the development of disease have not been demonstrated in affected tissues. We addressed this issue by using genome-wide profiling in hearts from a mouse model of autosomal dominant EDMD. Our analysis led us to focus on MAPK signaling because in a genome-wide expression analysis, several genes related to this pathway had significantly altered expression in hearts of mice with the Lmna H222P mutation prior to development of significant cardiomyopathy.

In hearts of Lmna H222P/H222P mice, we found significantly increased expression of transcripts encoding several downstream components of MAPK cascades, such as c-Jun and Elk1, only by using real-time PCR. Increased expression of these transcripts, which was approximately 2-fold, was not detected in our microarray analysis. Similar discrepancies between microarrays and real-time PCR have been reported (26, 27), especially when the absolute expression levels are low or when the differences between experimental and control are relatively small, which was the case for the transcripts we measured. In addition to increased expression of transcripts encoding several components, activation of MAPK cascades in hearts of Lmna H222P mice was also strongly supported by increased levels of selected encoded proteins, increases in nuclear pERK1/2, and activation of ERK1/2 and JNK in cells transfected with constructs encoding Lamin A with aa substitutions that cause EDMD.

MAPKs are successively acting phosphorylases that function as regulators of cell growth, differentiation, and transformation and have been implicated in many physiological and pathological processes (22, 28, 29). Several downstream target genes are activated by MAPKs, and we found this to be true for Elk1, Bcl-2, JunD, Elk4, and c-Jun in hearts from Lmna H222P mice. Activation of these targets can in turn regulate expression of additional genes.

Figure 4
Immunofluorescence microscopic analysis of pERK1/2 in heart sections from Lmna H222P/H222P mice. (A) Sections of frozen heart from Lmna+/+ (top panel) and Lmna H222P/H222P (bottom panel) mice were analyzed by immunofluorescence microscopy using Ab recognizing pERK1/2. Sections were counterstained with DAPI. Scale bars: 50 μm. (B) Quantification of pERK1/2 labeling in cardiomyocytes from Lmna+/+ mice and Lmna H222P/H222P mice. Cardiomyocytes are delimited by dotted line and intensity of emitted fluorescence is measured along the yellow line (a to b). Position of the nucleus and intensity of fluorescence using anti pERK1/2 Ab is shown in the diagram of a single cardiomyocyte. (C) Bars indicate intensity of pERK1/2 fluorescence in the nucleus of Lmna+/+ and Lmna H222P/H222P cardiomyocytes. Values are mean ± SD from 90 cardiomyocytes from 2 different hearts per group (*) P < 0.05.
including those encoding proteins involved in sarcomere structure, cardiomyofiber organization, and other aspects of heart function (30, 31). Abnormal expression of these proteins can lead to cardiomyopathy (Figure 9).

MAPK activation occurred prior to significant cardiomyopathy in Lmna<sup>H222P/H222P</sup> mice and also in Lmna<sup>H222P/+</sup> mice, which do not develop clinical heart disease until 2 years of age. This is consistent with the hypothesis that activation of MAPK signaling underlies development of disease instead of occurring as a consequence of disease. The temporal differences in the development of cardiomyopathy in heterozygous and homozygous mice may be due to dosage, as there appeared to be more significant activation of JNK and increased expression of its downstream targets bcl-2 and phosphorylated c-Jun in hearts from Lmna<sup>H222P/H222P</sup> mice compared with hearts from Lmna<sup>H222P/+</sup> mice. Several genes were also activated or repressed in heterozygous mice compared with homozygous mice; however, how this is related to development of disease remains to be investigated.

Results from previous studies have implicated activation of MAPKs in development of cardiomyopathy. Petrich et al. (19, 20) generated transgenic mice expressing an activated mutant of MKK7, a kinase-activating JNK, specifically in heart. These mice developed dilated cardiomyopathy. Similar results have been observed in transgenic mice overexpressing mutants of MKK3 and MKK6, kinases that also activate MAPKs (32). Nicol et al. (33) generated transgenic mice overexpressing MEK5, which activates ERK, in hearts, and these mice developed dilated cardiomyopathy. JNK is also activated in dilated human hearts (34, 35). Recently, Rodriguez-Viciana et al. demonstrated that mutations in MEK1 and MEK2, which encode kinases that activate ERK1 and ERK2, cause cardio-facial-cutaneous syndrome (36). The MEK mutants were more active than wild type in phosphorylating ERK. Transgenic mice expressing activated MEK1 similarly have enhanced ERK1/2 signaling and develop cardiomyopathy (37). Activation of the ERK cascade has also been reported in caveolin-3 (38), caveolin-1 (39), and p85 subunit of class IA PI3K (40) knockout mice, all of which develop cardiomyopathy at 2 months of age.

While it remains unclear how A-type lamins with aa substitutions activate MAPKs, our results show that they do so when expressed in transfected cells. Activation of the ERK subfamily of MAPKs is mediated by receptor protein tyrosine kinases or G-protein–coupled receptors (41). JNK subfamily of MAPK is activated by osmotic stress (42) and physical stress (43). It is possible that abnormalities in the nuclear lamina lead to activation of G-protein–coupled or other receptors via an unknown mechanism (Figure 9). Several investigators have hypothesized that alterations in response to stress may underlie the development of striated muscle diseases caused by LMNA mutations (7). Abnormal responses to stress in cells with abnormalities in A-type lamins could therefore potentially have an impact on activation of JNK (Figure 9). Fibroblasts from mice lacking A-type lamins have increased nuclear deformation and impaired viability under mechanical strain as well as attenuated NF-κB–regulated transcription in response to stress (14). In addition, we observed that expression of H222P Lamin A in transfected cells lead to enhanced nuclear translocation of activated ERK and JNK. Smith et al. (44) have demonstrated that suppression of cell proliferation after retinoic acid–induced endoderm differentiation of embryonic stem and carcinoma cells is achieved by restricting nuclear entry of activated MAPK, and an intact cytoskeleton is required for the restraint. Hence, interactions between the nuclear lamina and cytoskeletal components could potentially influence nuclear translocation of activated MAPKs, with abnormalities in the lamina enhancing their nuclear localization. Recently, Ivorra et al. (45) highlighted a direct interaction between A-type lamins and the transcription factor c-Fos. This raises the possibility that A-type lamins may bind to components of MAPK cascades and that the H222P aa substitution may alter such an interaction. This hypothesis remains to be tested.

A fetal-like gene expression program encoding cytoskeletal proteins is characteristic of many types of cardiomyopathy (17, 18, 46–49) and is similarly initiated during cardiac remodel-
ing due to mechanical strain, such as in hypertensive cardiomyopathy (50, 51). Increases in ventricular expression of ANF have been documented in experimental models of heart failure and cardiomyopathy (29, 38, 52–55) as well as in human heart failure (56). Our analysis identified 104 and 114 genes that were differentially expressed in hearts from Lmna<sup>H222P/+</sup> and Lmna<sup>H222P/H222P</sup> mice, respectively. These included several in the cardiac fetal gene expression program, such as those encoding β-MHC (Myh7), MLC-2 (Myl4, Myl7), and ANF (Anf). However, changes in the levels of these genes were different in hearts of Lmna<sup>H222P/+</sup> and Lmna<sup>H222P/H222P</sup> mice. For example, the log<sub>2</sub>-fold changes in expression of Myh7 were 2.38 in hearts of Lmna<sup>H222P/+</sup> mice and 3.49 in hearts of Lmna<sup>H222P/H222P</sup>. Log<sub>2</sub>-fold changes in expression of Myl4 were 3.84 in hearts of Lmna<sup>H222P/+</sup> and 4.66 in hearts of Lmna<sup>H222P/H222P</sup> mice. Anf was not differentially expressed in hearts of Lmna<sup>H222P/+</sup> mice compared with wild-type mice but was upregulated significantly in hearts of Lmna<sup>H222P/H222P</sup> mice. These different degrees of gene expression changes may reflect the early onset of heart failure in Lmna<sup>H222P/H222P</sup> mice, which develop symptoms at approximately 2 months of age. In contrast, Lmna<sup>H222P/+</sup> mice exhibit a decrease in left ventricular fractional shortening only at 2 years of age (Bonne et al., unpublished observations).

Expression of genes encoding skeletal muscle α-actin (57) and c-myc (58), which are reexpressed during cardiac remodeling, was not increased in hearts of Lmna<sup>H222P/</sup> or Lmna<sup>H222P/H222P</sup> mice. These genes are activated in an early response against passive tension, for example in cardiac hypertrophy secondary to pressure overload. Failure of activation of these genes is consistent with our observation of dilated cardiomyopathy without cellular hypertrophy or disarray in hearts of Lmna<sup>H222P/H222P</sup> mice (14). The observed upregulation of genes encoding extracellular matrix proteins, such as those encoding collagen I<sub>α1</sub> (Col1a2), decorin (Den), and matrix metalloproteinase 14 (Mmp14), may underlie the development of fibrosis in hearts of Lmna<sup>H222P/H222P</sup> mice.

Our results provide a foundation upon which pharmacological interventions for treatment or prevention of cardiomyopathy in EDMD can be based. If mutant A-type lamins activate JNK and ERK, which in turn lead to gene expression alterations responsible for the development of cardiomyopathy, MAPK inhibitors could potentially be used to treat or prevent disease. MAPK inhibitors have been studied as potential therapeutic agents for a wide range of diseases. JNK inhibitors have been shown to be beneficial in reducing myocardial ischemic injury (59), stroke (60), hearing impairment (61), and various neurodegenerative disorders (62). The availability of MAPK inhibitors with in vivo activities makes possible clinical trials to prevent or treat cardiomyopathy in Lmna<sup>H222P/H222P</sup> mice. In addition, knockout mouse models of ERK1/2 and JNK have been generated (63). Crossing those mice with Lmna<sup>H222P/H222P</sup> mice may also establish whether abolishing the function of MAPKs can rescue cardiomyopathy.

Analysis of genome-wide expression changes in hearts from Lmna<sup>H222P</sup> mice revealed significant alterations in expression of genes involved in inflammation and fibrosis prior to detectable abnormalities in hearts examined using conventional histological methods. Ultimately, fibrosis with minimal inflammation occurs in hearts of Lmna<sup>H222P/H222P</sup> mice (14) as well as in hearts of Lmna<sup>N195K/N195K</sup>, another model of EDMD (64). This suggests that in addition to treatment with MAPK inhibitors, early treatment with antiinflammatory or antifibrotic agents may benefit human subjects with EDMD.

Methods

Mice. Lmna<sup>H222P</sup> knockin mice were generated and genotyped as described (14). Hearts were isolated from male Lmna<sup>H222P/H222P</sup>, Lmna<sup>H222P/</sup> and Lmna<sup>-/-</sup> mice at 4, 7, and 10 weeks of age. For all immunoblotting and real-time PCR experiments, Lmna<sup>H222P/H222P</sup> and Lmna<sup>H222P/</sup> mice were compared directly with Lmna<sup>-/-</sup> littermates. For microarray analysis, mice were taken from 5 different litters of crosses between Lmna<sup>H222P/</sup> mice. Control Lmna<sup>-/-</sup> mice were taken from each of the litters from which Lmna<sup>H222P/H222P</sup> and Lmna<sup>H222P/</sup> were used.

Figure 6

Time-course expression of genes activated by MAPK in hearts from Lmna<sup>H222P/H222P</sup> mice at 4, 7, and 10 weeks of age. Expression of Myl7, Vegf, Sln, c-Jun, Elk1, JunD, and Elk4 in hearts of Lmna<sup>-/-</sup> and Lmna<sup>H222P/H222P</sup> mice is shown. Bars indicate the fold overexpression of the indicated mRNA normalized to Gapdh as calculated by the ΔΔC<sub>T</sub>-method. Values are mean ± SD for 6 samples per group (*<i>P</i> < 0.05, **<i>P</i> < 0.005).
RNA isolation. Total RNA was extracted using the RNeasy isolation kit (QIAGEN) according to the manufacturer’s instructions. Adequacy and integrity of extracted RNA were determined by gel electrophoresis, and concentrations were measured by ultraviolet absorption spectroscopy.

Microarray processing. We used GeneChip Mouse Genome 430 2.0 Arrays (Affymetrix), which contain 45,101 probe sets corresponding to known genes and expressed sequence tags. Complementary DNA synthesis, cRNA synthesis, and labeling were performed as described in the Affymetrix GeneChip Expression Analysis Technical Manual. Hybridization, washing, staining, and scanning of arrays were performed at the GeneChip Core Facility of the Columbia University Genome Center.

Microarray data analysis. Image files were obtained through Affymetrix GeneChip software and analyzed by robust multichip analysis using Affymetrix microarray “.cel” image files and GeneTraffic 3.0 software (Stratagene). Robust multichip analysis is composed of 3 steps: background correction, quantile normalization, and robust probe set summary. Genes were identified as being differentially expressed if they met a false discovery rate threshold of q < 0.05 in a 2-tailed Student’s t test and showed at least a 2-fold difference in expression independent of absolute signal intensity. We have made the gene expression data available in the National Center for Biotechnology Information’s Gene Expression Omnibus (GEO; http://www.ncbi.nlm.nih.gov/geo/), accessible through GEO Series accession numbers GSE6397 and GSE6398.

Analysis of functional groups of genes. Gene expression changes related to functional groups were analyzed using the class score method in ermineJ (version 2.1.12; http://www.bioinformatics.ubc.ca/ermineJ/) to provide a statistical confidence to functional groupings (65). The algorithm takes as input the log-transformed 2-tailed Student’s t test P values of genes that are members of a single gene ontology class and estimates the probability that the set of q values would occur by chance. Significant gene ontology terms were identified using a false discovery rate of...
0.05. For automated functional annotation and classification of genes of interest based on gene ontology terms, we used the DAVID database (http://david.abcc.ncifcrf.gov/) (66).

**Real-time PCR analysis.** We synthesized cDNA using Omniscript Reverse Transcriptase (QIAGEN) on total cellular RNA. For each replicate in each experiment, RNA from tissue samples of different animals was used. Primers were designed to correspond to mouse RNA sequences using Primer3 (http://frodo.wi.mit.edu/cgi-bin/primer3/primer3_www.cgi). The real-time PCR reaction contained iQ SYBR Green Supermix (Bio-Rad), 200 nM of each primer, and 0.2 μl of template in a 25-μl reaction volume. Amplification was carried out using the MyiQ Single-Color Real-Time PCR Detection System (Bio-Rad) with an initial denaturation at 95°C for 2 minutes followed by 50 cycles at 95°C for 30 seconds and 62°C for 30 seconds. Relative levels of mRNA expression were calculated according to the ΔΔCT method (67). Individual expression values were normalized by comparison with Gapdh mRNA.

**Extraction of proteins from hearts and immunoblotting.** Hearts were excised from mice and snap-frozen in liquid nitrogen–cooled isopentane. To obtain protein extracts, both ventricles were homogenized in extraction buffer (25 mM Tris [pH 7.4], 150 mM NaCl, 5 mM EDTA, 10 mM sodium pyrophosphate, 1 mM Na3VO4, 1% SDS, 1 mM dithiothreitol) containing protease inhibitors (25 mg/ml aprotinin and 10 mg/ml leupeptin). Protein samples were subjected to SDS-PAGE, transferred to nitrocellulose membranes, and blotted with primary Abs against Elk1 (Santa Cruz Biotechnology Inc.), ERK1/2 (Santa Cruz Biotechnology Inc.), pERK1/2 (Cell Signaling Technology), JNK1 (Santa Cruz Biotechnology Inc.), pJNK (Cell Signaling Technology), bcl-2 (Santa Cruz Biotechnology Inc.), pc-Jun (Santa Cruz Biotechnology Inc.), pERK1/2 (Cell Signaling Technology), β-MHC (Santa Cruz Biotechnology Inc.), MLC-2 (Santa Cruz Biotechnology Inc.), ANF (Santa Cruz Biotechnology Inc.), β-actin (Santa Cruz Biotechnology Inc.).

**Figure 8**
Activation of c-Jun and Elk1 by expression of Lamin A mutants. Cos-7 cells were transiently transfected with plasmids encoding wild-type Lamin A, Lamin A with the indicated amino acid substitution and the associated phenotype to each mutation (e.g., EDMD or familial partial lipodystrophy [FPLD]), or empty vector control. After 24 hours, luciferase activities induced by expression of c-Jun and Elk1 were measured in cell lysates and normalized to β-gal activities obtained from a protein encoded by a cotransfected plasmid. Results are mean ± SD of 5 experiments (*P < 0.05, **P < 0.005).

**Figure 9**
Model of how abnormalities of A-type lamins in the nuclear lamina may lead to cardiomyopathy. Abnormalities of A-type lamins in the nuclear lamina activate MAPK cascades, possibly via heterotrimeric G-protein receptors or by inducing stress responses by unknown mechanisms (?). This leads to activation of G-proteins (RAS and RAC), protein kinase (RAF), and subsequent enhanced phosphorylation of ERK and JNK1/2, resulting in nuclear translocation. In the nucleus, pERK1/2 and pJNK activate transcription factors such as Elk1, bcl-2, JunD, c-Jun, and Elk4, leading to increased synthesis of these proteins. Increased amounts and activities of transcription factors activated by pJNK and pERK1/2 alter expression of other genes, some encoding components of muscle fibers and sarcomeres. aberrant expression of these proteins leads to development of cardiomyopathy.
Immunofluorescence staining for pERK1/2 was performed on frozen sections (8 μm) of transversal cardiac muscles by fixing them in 3.7% formaldehyde in PBS for 15 minutes, then blocking in 5% fetal goat serum in PBS/triton for 1 hour. Cells were incubated in blocking solution with anti-pERK1/2 monoclonal antibody (Cell Signaling Technology) overnight at 4°C followed by PBS washing and incubation with Texas red–conjugated goat anti-mouse IgG secondary antibody (Invitrogen) and counterstained with 0.1 μg/ml DAPI (Sigma-Aldrich). Intensity of pERK1/2 in cardiocytes was measured using Scion Imaging software (version alpha 4.0.3.2, Scion Corp.) and normalized to the appropriate total extract to control for protein loading. Data are reported as mean ± SD and are compared with respective controls using a 2-tailed Student’s t test.

**Immunohistochemistry.** Immunofluorescence microscopy was performed on a Microphot SA (Invitrogen). Sections were counterstained with 0.1 μg/ml DAPI (Sigma-Aldrich) and secondary Texas red–conjugated goat anti-rabbit secondary Abs (Invitrogen). For immunohistochemistry, frozen sections (8 μm) of transversal cardiac muscles were fixed in 3.7% formaldehyde in PBS for 15 minutes and then blocked in 5% fetal calf serum in PBS/triton for 1 hour. Cells were incubated in blocking solution with anti-pERK1/2 monoclonal antibody (Cell Signaling Technology) overnight at 4°C followed by PBS washing and incubation with Texas red–conjugated goat anti-mouse IgG secondary antibody (Invitrogen) and counterstained with 0.1 μg/ml DAPI (Sigma-Aldrich). Intensity of pERK1/2 in cardiocytes was measured using Scion Imaging software (version alpha 4.0.3.2, Scion Corp.). Data are reported as mean ± SD and are compared with respective controls using a 2-tailed t test.

**Primary culture and isolation of ventricular myocytes. Lmna+/+ and Lmna−/−/−/− knockin mice (10 weeks of age) were anesthetized with pentobarbital. Ventricular cardiomyocytes were isolated as described in the Alliance for Cellular Signaling procedure protocol PP00000125 (http://www.signaling-gateway.org/data/ProtocalLinks.html).** For immunoblotting, cells were washed in 4°C PBS and lysed in extraction buffer. Lysates were centrifuged at 16,000 g at 16,000 g at 4°C for 10 minutes in methanol at -20°C or lyzed in extraction buffer for subsequent immunoblotting.

**Plasmid construction.** To generate constructs to express laminas in transfected cells, cDNAs encoding wild-type Lamin A and Lamin with H222P, N195K, R298C, R482W, N456I, and T528K aa substitutions were cloned in pEGFP-C1 plasmid (Clontech) between XbaI and BamHI restriction endonuclease sites.

**Cell culture and transfection to examine MAPK activation and localization.** Cos-7 and C2C12 cells were maintained in Dulbecco’s modified Eagle’s medium supplemented with 10% fetal calf serum and 0.5% gentamycin at 37°C in a humidified atmosphere of 95% air and 5% CO2. Cells were transfected with plasmids encoding GFP–wild-type Lamin A and GFP–H222P Lamin A using Lipofectamine 2000 (Invitrogen) according to the manufacturer’s instructions. Cells were analyzed 48 hours after transfection. Cells were either fixed for 10 minutes in methanol at -20°C or lyzed in extraction buffer for subsequent immunoblotting.

**Immunofluorescence microscopy.** For immunofluorescence staining, fixed cells were incubated with rabbit Abs that recognize pERK1/2 or pJNK (Cell Signaling Technology). Cells were then washed and incubated with Texas red–conjugated goat anti-rabbit secondary Abs (Invitrogen). For immunohistochemistry, frozen sections (8 μm) of transversal cardiac muscles were fixed in 3.7% formaldehyde in PBS for 15 minutes and then blocked in 5% fetal goat serum in PBS/Triton X-100 for 1 hour. Abs used for immunohistochemistry were primary rabbit anti-pERK1/2 (Cell Signaling Technology) and secondary Texas red–conjugated goat anti-rabbit (Invitrogen). Sections were counterstained with 0.1 μg/ml DAPI (Sigma-Aldrich). Immunofluorescence microscopy was performed on a Microphot SA (Nikon) microscope attached to a Spot RT slide camera (Diagnostic Instruments). Images were processed using Adobe Photoshop 6.0 (Adobe Systems). Fluorescence intensity in cardiocytes was measured using Scion Imaging software (Scion Corp.). Data are reported as mean ± SD and are compared with respective controls using a 2-tailed t test.

**Luciferase reporter gene assays.** Luciferase reporter assays for c-Jun and Elk1 activation were carried out using PathDetect Trans-Reporting System (Stratagene). Cos-7 cells were plated in 12-well plates. The following day, cells were transfected with pEGFP-N1 constructs encoding wild-type and mutant Lamin A proteins, pFA2-cJun or pFA2-Elk1, and pFR-Luc (Stratagene) using Lipofectamine 2000 (Invitrogen). To correct for transfection efficiency, a plasmid encoding β-gal (Promega) was cotransfected. After 24 hours, cells were trypsinized and protein lysates obtained and extracted according to the manufacturer’s instructions (Promega). Luciferase activity was measured with a luminometer.

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