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Rapamycin reverses hypertrophic cardiomyopathy in a mouse model of LEOPARD syndrome–associated PTPN11 mutation

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LEOPARD syndrome (LS) is an autosomal dominant “RASopathy” that manifests with congenital heart disease. Nearly all cases of LS are caused by catalytically inactivating mutations in the protein tyrosine phosphatase (PTP), non-receptor type 11 (PTPN11) gene that encodes the SH2 domain-containing PTP-2 (SHP2). RASopathies typically affect components of the RAS/MAPK pathway, yet it remains unclear how PTPN11 mutations alter cellular signaling to produce LS phenotypes. We therefore generated knockin mice harboring the Ptpn11 mutation Y279C, one of the most common LS alleles. Ptpn11 Y279C/+ (LS/) mice recapitulated the human disorder, with short stature, craniofacial dysmorphism, and morphologic, histologic, echocardiographic, and molecular evidence of hypertrophic cardiomyopathy (HCM). Heart and/or cardiomyocyte lysates from LS/+ mice showed enhanced binding of Shp2 to Irs1, decreased Shp2 catalytic activity, and abrogated agonist-evoked Erk/Mapk signaling. LS/+ mice also exhibited increased basal and agonist-induced Akt and mTor activity. The cardiac defects in LS/+ mice were completely reversed by treatment with rapamycin, an inhibitor of mTOR. Our results demonstrate that LS mutations have dominant-negative effects in vivo, identify enhanced mTOR activity as critical for causing LS-associated HCM, and suggest that TOR inhibitors be considered for treatment of HCM in LS patients.

Introduction

With approximately 1 per 100 babies affected each year, congenital heart diseases (CHDs) are the most common type of birth defect and the number 1 cause of birth-related deaths (1). Though numerous CHD phenotypes of various etiologies exist, the majority of patients present with abnormal valves, membranous septa, and/or myocardial defects (2). Abnormalities in signaling molecules and/or pathways involved in cardiac development are implicated in CHD pathogenesis; however, the underlying mechanisms remain poorly understood and/or unknown.

Primary hypertrophic cardiomyopathy (HCM), which affects the cardiac muscle wall, is a common cause of mortality and morbidity in CHD patients (3–5). Although hypertrophy may initially be a compensatory response to cardiac stress, over time, HCM can decompensate to dilation and end-stage heart failure. Mutations in genes that encode sarcomeric proteins, such as the myosin-binding protein C, β-MHC, and troponin T, and that alter sarcomeric structure and function constitute approximately 75% of cases of primary HCM (6–9). The remaining approximately 25% are caused by mutations in other genes, most of which remain undefined. The ultimate effect of all of these mutations is to impose mechanical, biochemical and/or bioenergetic stresses on the heart. These stresses activate cardiac signaling pathways, including the RAS/MAPK pathway, other MAPK (e.g., p38, JUN N terminal kinase [JNK]) pathways, the PI3K/AKT pathway, and in some cases the RHOA, STAT3, and/or calcineurin/nuclear factor of activated T cells pathways, to mediate the hypertrophic phenotype (10).

One non-sarcomeric protein involved in the pathogenesis of CHDs is SH2 domain-containing PTP-2 (SHP2), which is encoded by the non-receptor protein tyrosine phosphatase (PTP) type 11 (PTPN11) gene. SHP2 is a ubiquitously expressed protein that contains 2 N terminal SH2 domains, a catalytic (PTP) domain, and a C terminal tail with 2 tyrosine phosphorylation sites and a proline-rich motif (11, 12). SHP2 is regulated by an elegant molecular switch mechanism that couples its recruitment to appropriate locations in the cell with its catalytic activation (13, 14). In the basal state, the backside loop of the N-SH2 of SHP2 is wedged into the PTP domain, rendering the PTP domain physically and chemically inactive. Binding of a phosphotyrosyl...
peptide alters the conformation of the N-SH2 domain, preventing interaction of the backside loop with the PTP domain, unfolding the enzyme, and resulting in phosphatase activation (13–15).

Essential for development and the first PTP known to have a functional role in adult myocardium (16, 17), SHP2 plays a key role in RAS/MAPK activation in response to most, if not all, receptor tyrosine kinase (RTK), cytokine receptor, GPCR, and integrin signaling pathways (18). Moreover, germline PTPN11 mutations cause 2 related, but distinguishable, syndromes that include congenital heart defects among their features. Essentially all cases of LEOPARD syndrome (LS) (MIM151100), a rare autosomal dominant, multisystemic disease, are caused by mutations in PTPN11 (19). LS is named for its presenting manifestations: multiple lentigines, electrocardiographic conduction abnormalities, ocular hypertelorism, pulmonic stenosis, abnormal genitalia, retardation of growth, and sensorineural deafness (20). PTPN11 mutations also cause more than 45% of cases of Noonan syndrome (NS) (MIM163950) (21), the more common disorder (~1/2,000 births), with the remaining cases resulting from mutations in SOS1 (22, 23), KRAS (24), NRAS (25), SHOC2 (26), RAF1 (27, 28), or as yet unknown genes.

NS and LS are 2 of several autosomal dominant “RASopathies,” disorders caused by mutations in various RAS/MAPK pathway components (29, 30). Not surprisingly, many of the phenotypic abnormalities in NS and LS (and in other RASopathies) are quite similar: for example, both are characterized by proportionate short stature, facial dysmorphism, and skeletal anomalies (21, 31). However, their cardiac phenotypes are quite distinct. Pulmonary valve stenosis with dysplastic leaflets and atrial/ventricular septal defects are the most prevalent cardiac defects in NS caused by PTPN11 mutations (32, 33). By contrast, despite the fact that pulmonic stenosis is part of the LS acronym, the most common cardiac manifestation of this disorder is HCM (34–38).

We and others previously showed that the biochemical properties of LS and NS alleles are also quite distinct (39–41), suggesting different mechanisms for NS and LS pathogenesis. Whereas NS mutants primarily perturb the N-SH2/PTP interface to preferentially “open” the structure to an activated state (39), LS mutations typically affect conserved residues important for PTP catalysis (e.g., of the 2 most common sites for mutation in LS, Y279 sets the depth of the catalytic cleft and T468 lies close to the PTP domain “signature motif”). Almost all LS mutants tested behave as gain-of-function mutations of SHP2 and act primarily, if not exclusively, to potentiate RAS/MAPK pathway activation (40, 42–46). By contrast, LS mutants are catalytically impaired and act as dominant-negative mutants, impairing ERK activation in transient and stable transfection assays (39–41).

Together, these findings raise an interesting question: how can PTPN11 mutations that result in SHP2 proteins with opposite catalytic functions give rise to such similar disease phenotypes? Drosophila (47) and Zebrafish (48, 49) models of LS have provided some insights; however, these data are conflicting. Oishi et al. reported that LS mutants enhance Ras/MAPK pathway activity in Drosophila (47), whereas in Zebrafish studies, Jopling et al. and Stewart et al. found that LS mutants have dominant-negative effects on this pathway (48, 49). To resolve this paradox and to address the above question in a potentially more relevant mammalian system, we generated an inducible “knockin” mouse model expressing the LS-associated Ptpn11 Y279C mutation (Ptpn11<sup>Y279C/+</sup> mice). Remarkably, our mice recapitulated nearly all major aspects of the LS phenotype. Furthermore, biochemical analyses of hearts and primary cardiomyocytes from these mice identify the molecular basis for HCM in LS and a pharmacological intervention that reverses the cardiac defects associated with LS in vivo.

**Results**

**Generation of mice expressing an inducible Ptpn11 Y279C allele.** To assess the functional consequences of LS mutations, we generated knockin mice harboring an inducible, floxed Y279C allele of Ptpn11, Ptpn11<sup>Y279C/+/</sup> mice, hereafter termed ilS/+ mice (Figure 1). We chose this allele because Ptpn11<sup>Y279C</sup> is one of the 2 most common LS mutations (40, 50). The targeting construct was generated using recombination-mediated genetic engineering (recombineering) (51). Briefly, a fragment of the mouse Ptpn11 gene containing exons 7–9 was subcloned from a bacterial artificial chromosome clone into a plasmid containing a thymidine kinase (TK) selection cassette (for negative selection). The targeting vector itself included a loxP site, a Ptpn11 genomic fragment encoding WT exon 7, a loxpS11 site, an inverted mutant Ptpn11 exon 7 fragment containing the Y279C mutation, an inverted loxp site, an inverted loxpS11 site, a neo selection cassette flanked by FRT sites, and the Ptpn11 genomic fragment encoding WT exons 8 and 9 (Figure 1A). The inverted mutant Y279C exon 7 also introduced 2 HpyCH4 restriction sites which we believe to be novel in the sequence to be used for screening (Figure 1).

This construct, when recombined appropriately into the endogenous Ptpn11 locus, directs expression of WT Ptpn11 in the absence of Cre recombinase (Cre); these mice are termed ilS/+ mice. Upon exposure to Cre, unidirectional recombination (as a consequence of the mutant loxp sites) results in expression of the mutant Y279C allele; these mice are designated LS/+ mice (Figure 1, A–C).

The targeting construct was electroporated into TC1 (129S6/SvEv) ES cells and selected with G418 and FIAU. Resistant colonies were expanded, and homologous recombinants were identified by long-range PCR (Figure 1D and Supplemental Table 1; supplemental material available online with this article; doi:10.1172/JCI4972DS1). Correctly targeted ES cell clones were injected into blastocysts and implanted into pseudopregnant mice. Germline transmission was achieved, as verified by PCR for the neo gene (Figure 1E and Supplemental Table 1). The neo cassette was then removed by crossing ilS/+ chimeras to Flp-recombinase–expressing mice (Figure 1B), and ubiquitous expression of the LS mutant was achieved by mating appropriate progeny from this cross with El1a-Cre (C57BL6/J) mice (Figure 1C). These mice were subsequently crossed to WT C57BL6/J mice to generate mice with global LS expression (LS/+ mice). Two PCR strategies were used to distinguish LS/+ mice from WT mice using tail DNA (Figure 1F and Supplemental Table 1). Moreover, expression of the mutant allele (at levels comparable to that of WT Ptpn11 mRNA) was detected by RT-PCR, and the expected products were observed upon HpyCH4 digestion (Figure 1G and Supplemental Table 1). LS/+ mice also expressed comparable levels of Shp2 protein as compared to those of WT mice (data not shown). LS/+ mice were obtained at the expected Mendelian ratio at weaning, indicating that on this background, LS expression was compatible with embryonic development. All experiments herein were performed using LS/+ mice (and their WT littermates) crossed for at least 4–5 generations on C57BL6/J background.

LS/+ mice demonstrate phenotypic abnormalities similar to those in human LS. It was immediately apparent that, compared with WT littermates, LS/+ mice had abnormal faces, with distinctly smaller, more slanted eyes (Figure 2A, top) and a planar nasal bridge
Microcomputed tomography (\(\mu\)CT) scans showed an increased skull width-to-length ratio in LS/+ mice, compared with that in WT controls (Table 1). Together, these features gave LS/+ mice the appearance of hypertelorism, even though inner canthal distance, while trending wider in LS/+ mice, was not statistically different.

LS/+ mice also had skeletal/chest abnormalities, with pectus carinatum superiorly and pectus excavatum inferiorly (Figure 2B), a common feature of LS patients. Although their size was normal at birth (data not shown), by weaning, LS/+ mice were significantly smaller than their WT littermates, and they remained so throughout their lives (Figure 2, C and D). \(\mu\)CT scans showed that femur length also was decreased significantly in LS/+ mice (Table 1). Histological examination revealed abnormal genitalia and substantial macrophage accumulation in the organ of Corti (inner ear) in the LS/+ mice, which might cause (or indicate) sensorineural defects (data not shown). No other phenotypic/organ abnormalities were observed.

Somatic mutations in PTPN11 occur in several types of hematologic malignancies, most notably, juvenile myelomonocytic leukemia, and, more rarely, in solid tumors. Furthermore, approximately 20%–50% of NS patients have some hematologic abnormality (52–54). We collected peripheral blood, bone marrow, spleen, and thymus from a small cohort of either WT or LS/+ mice. Notably, in contrast to mice with NS-associated Ptpn11 mutations (43), we observed no apparent abnormalities in any hematological parameter in LS/+ mice (data not shown). Indeed, LS patients also are not reported to have any highly penetrant hematological abnormalities. Taken together, these data indicate that the gross morphologic features in LS/+ mice closely recapitulate those in LS patients (20, 31, 55).

LS/+ mice have pathological cardiac hypertrophy that transitions to dilation. Over 80% of LS patients develop severe HCM (38, 55–57). Therefore, we focused on the cardiac effects of the Y279C mutation in our mice. Although normally sized at birth, LS/+ hearts became...
progressively larger than WT hearts, becoming statistically different by 12 weeks of age (Figure 3, A and B, and data not shown). Analysis of H&E-stained transverse sections of 16-week-old hearts revealed dramatic thickening of the left ventricular free wall and septum (Figure 3B). Consistent with these observations, heart weight to body weight ratios were significantly elevated in hearts from 12- and 16-week-old \( \text{LS}^+ /\text{+} \) mice (Figure 3C). Morphometric analysis of individual cardiomyocytes in reticulin-stained heart sections from 16-week-old mice (Figure 3D), or that of isolated primary adult cardiomyocytes from 8- to 10-week-old \( \text{LS}^+ /\text{+} \) or WT mice (Figure 3E), indicated that the LS mutation did not affect overall cardiomyocyte number but rather significantly increased individual cardiomyocyte area (by \( \approx 30\% \)), as compared with that of controls. Isolated cardiomyocytes also had significantly increased cell width as opposed to length (Figure 3E), consistent with concentric HCM (58).

Further indicative of pathological hypertrophy in \( \text{LS}^+ /\text{+} \) hearts, we observed markedly enlarged nuclei, myofiber disarray, and inflammatory cell accumulation in the interstitial spaces between myofibers of \( \text{LS}^+ /\text{+} \) hearts (Figure 3F, indicated by arrows and magnified in inset). Electron microscopy of 12-week-old \( \text{LS}^+ /\text{+} \) hearts confirmed the increase in myofibril size but showed no overt effects on sarcomeric structure or mitochondrial number or size (Figure 3G).

Table 1
\( \mu \text{CT} \) morphometric values from WT and \( \text{LS}^+ /\text{+} \) mice

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Femur length (mm)</th>
<th>Tibia length (mm)</th>
<th>Skull width/skull length (mm)</th>
<th>Inner canthal distance/skull width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT mice</td>
<td>15.66 ± 0.16</td>
<td>17.19 ± 0.14</td>
<td>0.447 ± 0.002</td>
<td>0.635 ± 0.003</td>
</tr>
<tr>
<td>( \text{LS}^+ /\text{+} ) mice</td>
<td>15.07 ± 0.14\textsuperscript A</td>
<td>17.02 ± 0.24</td>
<td>0.457 ± 0.004\textsuperscript A</td>
<td>0.642 ± 0.010</td>
</tr>
</tbody>
</table>

Note significantly decreased femur length and increased skull width-to-length ratio. Data represent mean ± SEM (\( n = 5–10 \) mice/group); \( \textsuperscript A P < 0.05 \), 2-tailed Student's \( t \) test.
By 52 weeks, we noted a significantly increased number of deaths in the \( \text{LS}^+ \) mouse cohort (Figure 4A). Hearts from the older \( \text{LS}^+ \) mice displayed increased myofiber disarray, enlarged nuclei (Figure 4B), and marked fibrosis (Figure 4C), yet their cardiomyocytes remained larger than those of WT (Figure 4D). Although the precise reason(s) of excess mortality in \( \text{LS}^+ \) mice cannot be ascertained with certainty, these pathologic features strongly implicate cardiac causes (e.g., end-stage heart failure or arrhythmia).

To assess cardiac function and morphology more quantitatively, we obtained echocardiographs of \( \text{LS}^+ \) and WT littermates at 6, 12, 16, 20, and 52 weeks (Figure 5 and Supplemental Figure 1). No differences in cardiac size or function were observed at 4 to 6 weeks of age. By 12 weeks, however, \( \text{LS}^+ \) mice had significant left ventricular hypertrophy, as indicated by decreased chamber dimension and increased posterior wall thickness compared with those of littermate controls. Furthermore, \( \text{LS}^+ \) mice did indeed transition to dilated cardiomyopathy by 52 weeks, with

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**Figure 3**

\( \text{LS}^+ \) mice have pathological cardiac hypertrophy. (A) Representative hearts from 16-week-old WT and \( \text{LS}^+ \) mice. (B) Transverse sections of WT and \( \text{LS}^+ \) hearts stained with H&E (original magnification, \( \times 100 \)). (C) Heart weight to body weight (HW/BW) ratios of WT and \( \text{LS}^+ \) mice at indicated ages (n = 5–10 mice/group at each age measured). Data represent mean ± SEM; \(^*P < 0.05, \) 2-tailed Student’s t test. (D) Paraffin-embedded heart sections from 16-week-old WT and \( \text{LS}^+ \) mice stained with reticulin (original magnification, \( \times 400 \); scale bar: 100 μm). The average area of WT cardiomyocytes is 2,038 ± 98.5 μm\(^2 \)/cardiomyocyte and that of \( \text{LS}^+ \) cardiomyocytes is 2,578 ± 115.9 μm\(^2 \)/cardiomyocyte (\( P < 0.001, \) 2-tailed Student’s t test). Data represent mean ± SEM (200–500 cardiomyocytes/group). (E) Cardiomyocytes from 8- to 10-week-old WT and \( \text{LS}^+ \) hearts (original magnification, \( \times 200 \)). Cardiomyocyte length for WT hearts is 108.4 ± 2.6 μm and for \( \text{LS}^+ \) hearts is 113.5 ± 2.9 μm; cardiomyocyte width for WT hearts is 18.9 ± 0.8 μm and for \( \text{LS}^+ \) hearts is 22.4 ± 0.7 μm (\( P < 0.05, \) 2-tailed Student’s t test). Data represent mean ± SEM (200–500 cardiomyocytes; n = 4 mice each.). (F) H&E staining (original magnification, \( \times 400 \); white bar: 100 μm) of paraffin-embedded longitudinal heart sections from 16-week-old WT and \( \text{LS}^+ \) mice. Note the myofiber disarray and increased inflammatory cells (indicated by white arrows and magnified in inset) in the interstitial spaces. (G) Scanning electron microscopy of cardiomyocytes (original magnification, \( \times 4,800 \)) from 12-week-old mice. Double arrowhead: 1 μm.
increased diastolic dimensions and thinning of their posterior walls (Figure 5 and Table 2). Left ventricular function in LS/+ mice, as measured by ejection fraction and fractional shortening, also became impaired over time and was statistically different from WT controls at 52 weeks (Table 2).

Cardiac hypertrophy can be secondary to pressure overload caused by stenotic valves. Notably, many NS and some LS patients have valvuloseptal abnormalities (19, 59, 60). However, LS/+ hearts have increased chamber dimensions and have dominant-negative effects in vitro (39–41). To examine the effect of Shp2-Y279C in vivo, we performed immune complex phosphatase assays using whole heart lysates isolated from WT or LS/+ mice that were either treated for 10 minutes with PBS or insulin (10 mU/g body weight). As an additional (positive) control for the sensitivity of our PTP assay, we included lysates from similarly treated D61G/+ mice (43), which express a catalytically active Shp2 allele (Figure 7A). Whereas WT hearts had low basal activity that could be induced by insulin stimulation, LS/+ hearts compared with that in WT hearts (Figure 6). In addition, there was increased expression of other fetal genes, including atrial natriuretic factor (ANF), brain natriuretic peptide (BNP), and phospholamban (PLN), and decreased expression of the calcium pump, SERCA2A (Figure 6), all of which are consistent with remodeling of the heart and HCM (61, 62).

**LS mutants are catalytically impaired and show increased association with Shp2-binding proteins.** Previously, we and others reported that LS mutations in SHP2, including Y279C, are catalytically defective and have dominant-negative effects in vitro (39–41). To examine the effect of Shp2-Y279C in vivo, we performed immune complex phosphatase assays using whole heart lysates isolated from WT or LS/+ mice that were either treated for 10 minutes with PBS or insulin (10 mU/g body weight). As an additional (positive) control for the sensitivity of our PTP assay, we included lysates from similarly treated D61G/+ mice (43), which express a catalytically activated, NS-associated Ptpn11 allele (Figure 7A). Whereas WT hearts had low basal activity that could be induced by insulin stimulation, LS/+ hearts had an approximately 50% reduction in Shp2 activity. The decreased survival in LS/+ mice (n = 5–8 per group at each age point) was significant by the log-rank test. (B) H&E-stained sections (original magnification, ×400; scale bar: 100 μm) depicting myofiber disarray and enlarged nuclei in 52-week-old LS/+ hearts compared with WT hearts. (C) Masson-Trichrome stain of paraffin-embedded longitudinal heart sections from WT and LS/+ mice reveals marked fibrosis in LS/+ hearts at 52 weeks of age (original magnification, ×400). Fibrous tissue is stained in blue and magnified in inset. (D) Reticulin stain of paraffin-embedded heart sections from 52-week-old WT and LS/+ mice (original magnification, ×400), showing enlarged LS/+ cardiomyocytes.

**Figure 4**

**Figure 5**

LS/+ mice have HCM that progresses to chamber dilation. Representative echocardiographs of WT and LS/+ mice at 12 to 14 weeks of age and 52 weeks of age, respectively. Two-headed arrows indicate left ventricle chamber size. Note that at 12 weeks, LS/+ hearts have small chamber dimensions compared with those of WT controls; at 52 weeks, LS/+ hearts have increased chamber dimensions and have dilated/decompensated compared with those of WT controls.
phosphatase activity, in accord with the heterozygous expression of the Ptpn11Y279C allele. Also, there was no increase in Shp2 activity after insulin stimulation, consistent with a dominant-negative effect of the LS mutant. By contrast, D61G/+ heart lysates had dramatically enhanced basal and insulin-stimulated Shp2 activity. Similar results were obtained when liver lysates were used as the source for Shp2 (data not shown). Together, these data confirm that Shp2 LS mutations are catalytically defective and have dominant-negative effects in vivo.

Previous in vitro data suggest that LS mutations preferentially adopt the open conformation (39, 41). Consistent with this notion, we observed increased basal as well as IGF-1–induced association of Shp2 with IRS-1 (Figure 7B) and Gab1 (data not shown) in LS/+ cardiomyocytes compared with that in WT cells. These data validate our previous results (39) and suggest how LS mutations might function as dominant negatives.

Agonist-evoked Erk activation is impaired in LS/+ mice. Multiple types of receptors contribute to the survival and growth of cardiomyocytes, and Shp2 is required for normal activation of the RAS/MAPK pathway downstream of most, if not all, RTKs, cytokine receptors, GPCRs, and integrins. To assess the functional consequences of LS mutations on Erk activation, we isolated whole hearts from LS/+ or WT mice before or 10 minutes after i.p. injection of PBS (vehicle) or insulin. Although we observed no significant difference in basal Erk1/2 activity between the LS/+ and WT hearts, there was significant attenuation in Erk1/2 activation after insulin stimulation in LS/+ hearts, compared with WT controls (Figure 8, A and B). Consistent with these data, Erk1/2 activation also was decreased in isolated primary cardiomyocytes from 8-week-old LS/+ mice stimulated with RTK (IGF-1, EGF-1), GPCR (angiotensin II), or cytokine (IL-6) agonists (Figure 8C). Together, these data reveal an intrinsic defect in Erk pathway activation in LS/+ cardiomyocytes. Moreover, these findings contrast with the effects of an NS-associated, kinase-activating Raf1 mutation in mice, which, as illustrated in the accompanying manuscript (63), develop cardiac hypertrophy due to excessive Ras/Mapk activity (see Discussion).

The Akt/mTor pathway is hyperactivated in LS/+ hearts. Shp2 also plays a significant, although complex, role in PI3K/AKT pathway regulation (64–66). Notably, basal as well as insulin-induced Akt phosphorylation was increased in LS/+ hearts (Figure 9, A and B). Basal and agonist-induced Akt phosphorylation also was enhanced in IGF-1–stimulated (Figure 9, C and D) or IL–6–stimulated (data not shown) primary cardiomyocytes from LS/+ mice, compared with

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**Table 2**

| Anatomic and functional parameters, as assessed by echocardiography, in WT and LS/+ mice at the indicated ages |
|---|---|---|
| **4–6 weeks** | **12–14 weeks** | **52 weeks** |
| | WT | LS/+ | WT | LS/+ | WT | LS/+ |
| BW (g) | 19.9 ± 1.0 | 18.9 ± 0.7 | 24.9 ± 0.5 | 22.6 ± 1.1*A | 35.5 ± 4.5 | 32.7 ± 1.8 |
| HR (bpm) | 668 ± 21.1 | 691 ± 26.9 | 672 ± 25.2 | 648 ± 25.3 | 715 ± 29.1 | 668 ± 27.8 |
| LV PW-th (mm) | 0.93 ± 1.07 | 1.15 ± 0.13 | 1.04 ± 0.09 | 1.58 ± 0.07*A | 0.85 ± 0.04 | 0.61 ± 0.06*A |
| LVID-d (mm) | 2.34 ± 0.16 | 2.16 ± 0.10 | 2.70 ± 0.23 | 1.86 ± 0.24*A | 2.83 ± 0.86 | 3.68 ± 0.15*A |
| FS% | 56.6 ± 2.29 | 55.23 ± 2.28 | 56.37 ± 2.33 | 61.40 ± 2.35 | 50.99 ± 0.23 | 36.69 ± 1.94*A |
| n | 8 | 8 | 8 | 8 | 5 | 5 |

Note the increased posterior wall thickness, smaller left ventricular chamber dimension, and increased fractional shortening (consistent with enhanced contractility) in 12- to 14-week-old LS/+ hearts compared with that in WT hearts. By 52 weeks, LS/+ hearts have thinned and dilated, with functional compensation, as indicated by decreased fractional shortening. Note that the fractional shortening calculation includes the papillary muscle. No significant differences were seen in any parameters in 4- to 6-week-old LS/+ mice compared with WT littermates. Data represent mean ± SEM; *P < 0.05, 2-tailed Student’s t test. Hr, heart rate; LVID-d, left ventricular chamber dimension in diastole; FS%, fractional shortening.

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**Figure 6**

LS/+ mice upregulate expression of cardiac fetal genes. Total RNA from WT and LS/+ mice (n = 4–6 of each genotype) of the indicated ages was used to perform quantitative RT-PCR (each sample in triplicate). The ratio of ΔΔCt was analyzed using GAPDH as a control. Data represent mean ± SEM; *P < 0.01, 2-tailed Student’s t test. Note the significant difference in cardiac fetal gene expression in LS/+ and WT hearts of the same age.
that in WT controls. The mTor pathway, a downstream target of Akt, was hyperactivated in LS/+ hearts, even under basal conditions, as indicated by elevated levels of Tsc2 phosphorylation at S1462, an Akt phosphorylation site, and enhanced p70S6K phosphorylation as indicated by elevated levels of Tsc2 phosphorylation at S1462, an Akt phosphorylation site, and enhanced p70S6K phosphorylation (68, 69) and the ability of Y279C mutant to enhance Akt/mTor activity, suggested that this pathway might be required for HCM pathogenesis in LS/+ mice. To begin to test this possibility, we first asked whether reduction of mTor1 activity could ameliorate the cellular abnormalities in LS/+ cardiomyocytes. Primary cardiomyocytes from WT or LS/+ mice were treated with rapamycin (0.02 M) for 12 hours. After this treatment, the size of the LS/+ cardiomyocytes was indeed significantly reduced (Supplemental Figure 2). By contrast, there was no effect of Jnk or Stat inhibitors on overall LS/+ cardiomyocyte cell surface area (Supplemental Figure 2). These data suggested that, while multiple signaling abnormalities might contribute to the cardiac phenotype in LS/+ mice, excessive Akt/mTOR signaling is an essential contributor to pathologic cardiac hypertrophy.

We next asked whether we could normalize the cardiomyocyte defects in vivo. We administered daily i.p. injections of either vehicle or rapamycin (2 mg/kg body weight) to 8-week-old WT or LS/+ mice for 4 weeks. At the onset of this treatment period, LS/+ heart size was not significantly different from that of WT heart size (data not shown, but see Supplemental Figure 1 for reference). When the mice reached 12 weeks of age (a time at which significant hypertrophy is evident in LS/+ mice; see Figure 3), we isolated primary cardiomyocytes from vehicle- and rapamycin-treated mice and quantified their area 2 hours after plating. Remarkably, cardiomyocytes

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isolated from rapamycin-treated LS/+ mice had significantly decreased cell size as compared with that of vehicle-treated LS/+ cells (Figure 11A). By contrast, rapamycin (at least at this dose) had little/no effect on the size of WT cardiomyocytes; consequently, the sizes of rapamycin-treated LS/+ and WT (untreated or rapamycin-treated) cardiomyocytes were similar (Figure 11B).

As expected, rapamycin treatment reduced the phosphorylation of the downstream mTorc1 target, p70S6 kinase (Figure 11C), but did not affect Erk, JNK, or Stat3 activation (Supplemental Figure 3). The phosphorylation of Akt on S473, an mTorc2 phosphorylation site, also was reduced, as was the phosphorylation of GSK-3β on its Akt site, Ser21. Although rapamycin only inhibits mTorc1 directly, chronic rapamycin administration has been reported to sequester Tor into the (inhibited) mTorc1 complex, resulting in inhibition of both mTor complexes (70). Notably, when we discontinued our daily injections of rapamycin (see below) and administered only a once a week dose of rapamycin, we reversed this effect and normalized Akt activity (data not shown).

**Rapamycin treatment normalizes HCM in LS/+ mice.** After 4 weeks of treatment, hearts from rapamycin-treated LS/+ mice but not vehicle-treated LS/+ mice showed a trend toward decreased size, as measured by heart weight to body weight ratios, but this difference did not reach statistical significance (data not shown). Compared with vehicle-treated LS/+ mice, rapamycin-treated mice did show a substantial reduction in left ventricular posterior wall thickness (LVPW-th) to values indistinguishable from their WT littermates. However, chamber dimensions remained abnormally small in rapamycin- and vehicle-treated LS/+ mice.

These findings indicated that even short-term rapamycin treatment had some therapeutic efficacy for LS-associated HCM and suggested that prolonging the treatment period might be even more beneficial. Therefore, we treated another cohort of WT and LS/+ mice daily with either vehicle or rapamycin (2 mg/kg body weight i.p.) for 4 weeks, followed by an additional 4 weeks of weekly injections of the same dose. A similar protocol has been used to analyze the effects of mTor inhibition in mouse models of polycystic kidney disease (71) and tuberous sclerosis complex disorder (72). Remarkably, after 8 weeks of rapamycin treatment, the gross size of LS/+ hearts appeared normal (Figure 12A). LS/+ cardiomyocyte area was reduced, compared with that of vehicle-treated LS/+ cells (Figure 12, B and C), to a level comparable to that of WT control cardiomyocytes. Heart weight to body weight ratios of rapamycin-treated LS/+ mice decreased significantly, also becoming indistinguishable from control values (Figure 12D).

**Rapamycin treatment reverses HCM in LS/+ mice.** The above experiments indicated that rapamycin treatment could prevent the development of HCM in LS/+ mice. To test whether rapamycin also could reverse established hypertrophy, we treated a new cohort of LS/+ mice with rapamycin, beginning at 12 weeks of age, when these mice already have apparent HCM (see Figure 3). WT or LS/+ mice were treated daily with vehicle or rapamycin (2 mg/kg body weight i.p.) for 4 weeks, followed by an additional 4 weeks of weekly injections of the same dose. Serial echocardiographic analysis at the 4- and 8-week time points (16- and 20-week-old mice, respectively) showed normalization of LVPW-th and left ventricular chamber diameter (Figure 13, A and B). Furthermore, there was a substantial reduction in left ventricular posterior wall thickness (LVPW-th) to values indistinguishable from their WT littermates. However, chamber dimensions remained abnormally small in rapamycin- and vehicle-treated LS/+ mice.

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The efficacy of rapamycin should be evaluated in LS patients. Akt/mTor activity in LS pathogenesis and suggest that therapeutic efficacy of rapamycin should be evaluated in LS patients.

To study LS pathogenesis, we generated inducible knockin mice harboring the Ptpn11 mutation Y279C. Similar to the human LS phenotype, LS/+ mice have short stature, craniofacial dysmorphism, and skeletal abnormalities (20, 31, 55). In addition, several lines of evidence indicate that LS/+ mice have pathological cardiac hypertrophy: (a) their hearts are enlarged, and they show increased heart weight to body weight ratios; (b) LS/+ cardiomyocytes show myofiber disarray, inflammatory cells within the myocardial interstitium, and fibrosis; (c) cardiac fetal gene expression is reactivated in LS/+ mice, including a shift from α-MHC to β-MHC gene expression; (d) LS/+ cohorts have an increased death rate compared with that of WT mice; and (e) LS/+ mice transition from hypertrophy to dilation by 52 weeks of age, and cardiac function declines concomitantly. Biochemically, LS/+ mutant hearts and/or cardiomyocytes show enhanced binding of Shp2 to IRS-1, decreased phosphatase activity, and abrogated agonist-evoked Erk activation, consistent with previous reports that LS mutants have dominant-negative effects in vitro (39–41). By contrast, Akt/mTor signaling is enhanced significantly in LS/+ hearts, as well as in cardiomyocytes, consistent with recent findings on fibroblasts isolated from LS patients (73), and there is increased phosphorylation of Stat3 and Jnk1/2, 2 other signaling molecules implicated in cardiomyopathy (74, 75). Although we cannot exclude the possibility that these other signaling pathways contribute to HCM in vivo (i.e., in LS/+ mice themselves), inhibiting the mTor pathway by rapamycin treatment completely normalized and reversed the LS cardiac defects, both in vitro and in vivo. Together, these data directly implicate excessive Akt/mTor activity in LS pathogenesis and suggest that therapeutic efficacy of rapamycin should be evaluated in LS patients.

Some features in LS/+ mice are reminiscent of the phenotype of mice expressing NS-associated gain-of-function Ptpn11 mutations (43, 76, 77) and of the abnormalities seen in NS patients (78). Germ-line PTPN11 mutations cause NS and LS, and both NS and LS are part of the family of autosomal dominant RASopathies caused by mutations in different components of the RAS/RAF/MEK/ERK MAPK pathway (29, 30). Not surprisingly, each of these disorders shares some phenotypes, albeit with varying degrees of penetrance. Yet, each RASopathy also has clinically distinguishable features. Mouse models recapitulated some of these differences. For example, 2 parallel studies on knockin mice expressing the NS-associated Sos1-E846K (79) and Raf1-L613V (63) mutations, respectively, show that mutations in different genes along the same pathway yield different phenotypes: Sos1-E846K/+ mice develop HCM with incompletely penetrant aortic stenosis, whereas the Raf1-L613V/+ mice develop HCM with normal valvuloseptal development. Even distinct mutations in the same RASopathy gene can result in distinguishable phenotypes, as shown for Ptpn11 mutations with different degrees of Shp2 activation (43, 76, 77). Indeed, differential expression of the individual causal mutants, and/or their activity, localization, and feedback regulation in different cell/tissue types, probably accounts for the variable severity and/or phenotype in each RASopathy.

Mutations associated with different RASopathies also have distinct effects in mice. Biochemical, cell biological, and genetic studies indicate that the PTPN11 alleles associated with NS are hypermorphs that enhance Erk pathway activation (44). Given that knockin models of activated Sos1 (79) and Raf1 (63) each show HCM, whereas absence of Ptpn11 in cardiomyocytes causes dilated cardiomyopathy (16), one might expect NS-associated PTPN11...
mutations to cause HCM. Yet, HCM is rare in NS patients with PTPN11 mutations (80–82). Moreover, knockin mice for the NS allele Ptpn11 D61G exhibit valvuloseptal defects similar to those in NS but no evidence of HCM (43). On the other hand, LS is caused almost exclusively by catalytically impaired PTPN11 mutations (39, 40), and HCM is the most common cardiac abnormality in this syndrome (34, 37, 83). Our Ptpn11 Y279C knockin mice show that the predominant cardiac manifestation of LS, HCM, is a direct and specific consequence of expression of catalytically impaired mutants of Ptpn11 (rather than, for example, the effects of different modifiers in the human population).

The molecular basis for the events that lead to hypertrophic responses in the heart are confounding and complex. As Shp2 is a critical upstream regulator in multiple RTK, cytokine, GPCR, and integrin-mediated signaling pathways (84), Shp2 mutations might be expected to have several effects in the heart. Indeed, LS/+ cardiac lysates show enhanced binding of Shp2 to IRS-1, decreased phosphatase activity, and abrogated agonist-evoked Erk activation, consistent with our previous findings that LS mutants have dominant-negative effects on the Erk/Mapk pathway (39). Notably, 2 previous studies reported that LS mutants evoke increased Erk activation. Expression of the LS mutants Y279C or T468M in Drosophila resulted in ectopic wing veins and a rough eye phenotype, characteristic of increased Erk activity in these tissues, and genetic analysis of enhancers and suppressors also was consistent with hypermorphism of the Erk pathway in these mutant flies (47). Furthermore, in a very recent study, induced pluripotent stem cells (iPSCs) from LS patient-derived fibroblasts showed higher basal p-ERK levels compared with those of control iPSCs (85). By contrast, LS mutants of shp2 were found to have dominant-negative effects when expressed in Zebrafish (48, 49), consistent with our findings that basal Erk activation is unchanged and agonist-evoked activation is abrogated in LS/+ mice. The reasons for these discrepancies are unclear but might relate to species differences, cell-type specificity, and/or the effects of overexpression.

Regardless, our data are inconsistent with the hypothesis that excessive Erk activity causes HCM in LS/+ mice (and, by inference, in humans). Instead, our results suggest that the excessive Akt/mTor pathway activity is critical for the cardiac pathogenesis in LS (Supplemental Figure 4). Our biochemical studies, which are consistent with recent work on fibroblasts isolated from LS patients (73), showed increased Akt activation, as exemplified by increased Akt3 phosphorylation and, more importantly, increased phosphorylation of Tsc2 and GSK-3a on known Akt phosphorylation sites. This, in turn, leads to increased mTor activity, as indicated by increased phosphorylation of the mTor substrate, p70S6K (Supplemental Figure 4).

Previous pharmacological studies have shown that treatment of cardiomyocytes with rapamycin could inhibit the hypertrophic response evoked by stimulation with various agonists (86–89). Rapamycin also attenuates or reverses pressure overload- or constitutively active Akt-induced cardiac hypertrophy (87, 90, 91), supporting our findings that there is a potential regulatory role for mTor in HCM. By contrast, a recent study of transgenic mice with cardiomyocyte-specific expression of constitutively active or kinase-dead mutants of mTor, respectively, showed no overt cardiac phenotype (92). There are several possible explanations for this apparent discrepancy with our findings. First, in the above study, the transgenes were expressed only in cardiomyocytes, whereas in LS/+ mice, mutant Ptpn11 was expressed ubiquitously. Recent data indicate the cardiac fibroblasts can also contribute to HCM (93–96), and it is conceivable that both cardiomyocyte and cardiac fibroblast signaling abnormalities contribute to HCM in our model. Second, transgene expression of the kinase-active and kinase-dead mTor was induced by cMHC-Cre expression, which expresses postnatally in the mouse (97); conceivably, aberrant mTor signaling must occur during development to cause HCM. Third, the extent to which transgenes that drive expression of kinase-dead and kinase-active mTor represent endogenous activation/inactivation of the mTor pathway, as in our LS/+ mice, is unclear. For example, kinase-active or kinase-dead mTor would affect mTorc1 and mTorc2. Rapamycin, by contrast, inhibits only mTorc1. Last, as discussed further below, although our experiments using primary cardiomyocytes argue against roles for elevated JNK and/or Stat3 in cardiac hypertrophy in LS/+ mice (Supplemental Figure 3), we cannot (and do not) exclude roles for these other signaling pathways in the whole animal context. Overall, we believe that our system, in which the mTor pathway is activated under endogenous promoter control by the mouse analog of a human disease-associated PTPN11 mutant, is a more physiologically relevant system for analyzing the role of the mTor pathway elevation in LS.

Most importantly, our data indicate that the biochemical abnormalities in LS/+ hearts have functional consequences, as illustrated by the dramatic effects of rapamycin on the cardiac phenotype of LS/+ mice. After 8 weeks of rapamycin treatment, the gross size
argue strongly that clinical trials of rapamycin or related rapamycin analogs for the treatment of renal cancer (105). Taken together, our data from in vivo animal models and humans lend credence to the idea that rapamycin also has proven beneficial for treatment of polycystic kidney disease in mice (101, 102), a therapy that has moved to clinical trials (103, 104) and likely human trials (105). Furthermore, our work demonstrably supports the use of rapamycin in a variety of cardiac-related conditions, including cardiac hypertrophy and heart failure. Nevertheless, it also has been used for other purposes, both in animal models and humans. For example, previous studies have demonstrated its efficacy in the treatment of cardiac hypertrophy in spontaneously hypertensive rats (99) and in reducing pressure overload-induced hypertrophy in mice (91, 100). Rapamycin also has proven beneficial for treatment of polycystic kidney disease in mice (101, 102), a therapy that has moved to clinical trials (103, 104), and a rapamycin analog is now approved for the treatment of renal cancer (105). Taken together, our data strongly support the idea that clinical trials of rapamycin or a rapamycin analog be considered for the treatment of LS-associated HCM.

Figure 11

LS/+ cardiomyocytes respond to rapamycin treatment. (A) Photomicrograph of primary cardiomyocytes isolated from vehicle-injected WT, vehicle-injected LS/+, or rapamycin-injected LS/+ mice after 4 weeks of daily injections. Original magnification, ×200. (B) Quantification of the differences in area between vehicle- or rapamycin-treated WT and LS/+ cardiomyocytes (200–500 cells per group). Note the significant difference in total area between WT and LS/+ cardiomyocytes. Rapamycin had little/no effect on WT cardiomyocyte cell size. Results are the mean ± SEM. *P < 0.001, 2-tailed Student’s t test. (C) Inhibiting mTor activity rescues aberrant LS/+ signaling. Whole heart lysates from vehicle-treated WT, vehicle-treated LS/+, and rapamycin-treated LS/+ mice after 4 weeks of daily injections were harvested, lysed, and immunoblotted with anti-phospho–Akt(Ser473), –GSK-3α (Ser21), –Tsc2 (Ser21), and –p70S6K antibodies, followed by anti-Akt antibodies to control for loading, respectively. Note that rapamycin treatment reversed the Akt/mTor pathway signaling defects associated with LS/+ mutation. rapa, rapamycin.

Excessive Akt/mTor activity in LS/+ mice is most likely due to increased PI3K activation; indeed, Shp2 can have positive (or negative) effects on the PI3K/Akt pathway, depending on the specific upstream pathway and/or the cellular context (66). There are at least 2 potential ways in which LS mutants might cause increased PI3K activation. First, previous work has suggested that Shp2 can dephosphorylate the binding sites for PI3K on Gab1 (66, 106). Recent studies of the effects of Ptpn11 deletion in the liver suggest that Shp2 also dephosphorylates the PI3K binding sites on IRS-1/2 (107). Alternatively, or in addition, excessive Fak activity may also play a role in increased PI3K activation in LS/+ hearts. A recent study showed that Fak is associated with Shp2 in NRVMs. Moreover, depletion of Shp2 by siRNA increased phosphorylation of Fak, Akt, Tsc2, and S6 kinase and induced hypertrophy of NRVMs (67). Indeed, heart lysates from our LS/+ mice had elevated Fak phosphorylation as well. Further studies will be required to determine whether, in fact, LS/+ hearts/cardiomyocytes have increased PI3K activity and, if so, whether either (or both) of the above mechanisms is responsible for this increase.

While it is true that the PI3K/Akt pathway plays an important role in regulating cardiac homeostasis/adaptive hypertrophy (108), the mechanisms are controversial. Mice expressing a cardiac-specific constitutively active mutant of the PI3K p110α subunit developed substantial physiological hypertrophy but did not transition into pathological hypertrophy (109). Conversely, cardiac expression of a dominant-negative PI3K p110α catalytic subunit impaired physiological hypertrophy (110, 111), whereas the PI3K p110γ subunit was shown to be required for maladaptive hypertrophy (111, 112). On the other hand, short-term activation of Akt1 promotes cardiomyocyte viability and reverses hypertrophy, while...
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Chronic Akt1 activation induces extensive cardiac hypertrophy, with severe contractile dysfunction and massive interstitial fibrosis (113, 114). These findings indicate that the PI3K/Akt pathway is highly complex, with differential roles in regulating cardiac hypertrophy. Clearly, further studies are needed to better elucidate the mechanism(s) for these signaling-specific differences.

Figure 12
Rapamycin normalizes HCM in LS/+ mice. (A) H&E-stained longitudinal sections of hearts from WT and LS/+ mice. Note normalization of hypertrophy in LS/+ hearts after rapamycin treatment (original magnification, ×100). (B) Reticulin stain of paraffin-embedded heart sections from 16-week-old WT and LS/+ mice (original magnification, ×400). (C) Quantification of average area (in μm²) of cardiomyocytes (200–500 cells counted/group) from WT or LS/+ cardiomyocytes isolated from mice that were either vehicle- or rapamycin-treated (2 mg/kg body weight) daily by i.p. injection for 4 weeks, then weekly for 4 weeks; see Results and Methods for details. Results are shown as the mean ± SEM. *P < 0.05, †P < 0.05. (D) Heart weight to body weight ratios of WT and LS/+ mice with vehicle- or rapamycin-treatment, as indicated. *P < 0.05, †P < 0.001. (E) Representative echocardiographs from 16-week-old vehicle-treated WT, vehicle-treated LS/+, or rapamycin-treated LS/+ mice. Two-headed arrows indicate left ventricle chamber size. (F) Anatomic and functional parameters of 12- and 16-week-old WT, LS/+ and LS/+ rapamycin-treated mice, as assessed by echocardiography, either after 4 weeks (measured at 12 weeks of age) or after 4 weeks of daily i.p. injections, followed by 4 weeks of weekly (measured at 16 weeks of age) i.p. injections. LVID-d, left ventricular chamber dimension in diastole. *P < 0.001 denotes significance between the vehicle-treated 16-week-old LS/+ mice and the LS/+ rapamycin-treated mice. All P values in C, D, and F were derived from ANOVA and Bonferroni post-test when ANOVA was significant.

Indeed, although our data clearly implicate excessive Akt/mTor activity in LS cardiac pathogenesis, we cannot and do not exclude the possibility that other signaling abnormalities contribute either to the initial hypertrophic phase or to the ultimate dilation of LS hearts. For example, the inability of LS mutants to activate Erk in response to agonist stimula-
tion might contribute to the eventual transition to dilation in the LS/+ mice, perhaps in tandem or in parallel with increased Jnk and/or Stat3 activities. Jnk and/or Stat3 themselves might be important contributors to hypertrophy in LS; increased Jnk activity is associated with development of cardiac hypertrophy (74), and Stat3 phosphorylation is significantly upregulated in the failing heart with dilated cardiomyopathy (75). Interestingly, however, inhibition of Jnk and Stat3 had little effect on overall cardiomyocyte cell surface area in vitro (Supplemental Figure 2). Given that these inhibitors lack specificity and have poor bioavailability, evaluation of the overall contribution of aberrant Jnk and Stat activity to HCM in LS/+ mice (in vivo) will require genetic approaches. However, it will be important to clarify the role of these other signaling abnormalities in LS pathogenesis, as they may provide additional targets for therapeutic intervention.

In summary, our data support the conclusion that excessive Akt/mTOR activity is essential for the development and maintenance of HCM in LS, and we identify a potential effective treatment for the reversal of HCM in LS/+ mice (in vivo) will require genetic approaches. However, it will be important to clarify the role of these other signaling abnormalities in LS pathogenesis, as they may provide additional targets for therapeutic intervention.

In summary, our data support the conclusion that excessive Akt/mTOR activity is essential for the development and maintenance of HCM in LS, and we identify a potential effective treatment for the reversal of HCM in LS patients. Attention has naturally focused on the ERK/MAPK pathway in explaining the pathogenesis of RASopathies. However, our data argue that different RASopathies can have complex and distinct effects on cellular signaling pathways. Knowledge of the detailed effects of these mutations on molecular and cellular signaling is essential for a more rational and personalized approach to therapy for these disorders.

**Methods**

**Generation of LS/+ mice**

The targeting construct was generated using recombineering methodology as developed by Liu et al. (51). Our strategy used unidirectional Cre-mediated inversion of a duplicated mutant (Y279C) exon, permitting expression of the WT protein in the absence of Cre and the mutant product after Cre exposure. Briefly, a 9.3-kb fragment (based on the C57BL/6 genome, build NCBIM37) of the mouse *Ptpn11* gene containing exons 7–9 (extending 4,871 bp upstream of exon 7 and 2,148 bp downstream of exon 9) was subcloned by recombineering from the bacterial artificial chromosome, bMQ-311k06 (Geneservice), into a plasmid containing a TK selection cassette. A loxP site was inserted by recombination 371 bp upstream of exon 7. Exon 7 was amplified by PCR (761-bp fragment extending 371 bp upstream and 294 bp downstream), and a single base change (A>C) was introduced into the codon for amino acid 279 (Y279C) by site-directed mutagenesis. The point mutation and surrounding region were sequenced to verify the mutation and the fidelity of the amplification and then were subcloned into a modified neo cassette, consisting of a loxP511 site, the inverted mutant exon fragment, an inverted loxP site, an inverted loxP511 site, and a neo selection cassette flanked by FRT sites. This cassette was inserted by recombineering 294 bp downstream of exon 7 to generate final targeting construct.
for blastocyst injection. Chimeras were generated (Brigham and Women’s Transgenic Core Facility), and germline transmission of ILS/+ mice was obtained. ILS/+ (129S6/SvEv × C57BL6/J) mice were crossed to Frt-Flp (C57BL6/J) mice (The Jackson Laboratory) to excise the neo cassette. ILS/+ mice with excised neo cassette were then crossed to EIIA-Cre (C57BL6/J) mice (The Jackson Laboratory), which express Cre ubiquitously, and then to WT (C57BL6/J) mice to generate mice with global LS Y279C expression (LS/+ mice). Subsequent generations of LS/+ mice were crossed to WT C57BL6/J mice, thereby maintaining the line on a global LS Y279C background; these mice were used for all experiments. Genotyping was carried out by PCR using tail DNA (see Supplemental Table 1). Unless otherwise indicated, WT C57BL6/J littermates were used as controls.

All animal studies were approved by the Beth Israel Deaconess Medical Center IACUC Committee and performed in accordance with IACUC standards. μCT scans (conducted at the Ontario Cancer Institute) were analyzed using at least 3 mice per group, and each sample was measured in triplicate. Data were quantified by using the comparative C_{T} method, with Gapdh expression as a control. Note that rapamycin-treated LS/+ heart lysates have normalized fetal gene expression profiles as compared with those of WT heart lysates. Data represent mean ± SEM. *P < 0.01, †P < 0.001, 2-tailed Student’s t test.

**Electron microscopy**

Electron microscopy was performed at the Harvard Medical School Facility. Briefly, mouse hearts were perfused in PBS and fixed with a mixture of paraformaldehyde (2%) and glutaraldehyde (1.5%) in cacodylate buffer (0.1 M Na cacodylate, pH 7.4). Pieces (1 mm^3) were dissected from the left ventricle, postfixed in 1% OsO_4, dehydrated in a series of alcohols, and embedded in Epon Araldite (SPI Supplies). Ultrathin sections (silver to gold) were obtained with a Reichert Ultracut E microtome, stained with uranyl acetate and lead citrate, and observed in a Tecnai G^2 Spirit BioTWIN (Tecnai), with an AMT 2k charge-coupled device camera.

**Quantitative real-time PCR**

RNA was isolated from whole hearts with TRIzol (Invitrogen) or using the RNeasy Mini Kit (QIAGEN). Quantitative real-time PCR was performed with SYBR Green (Applied Biosystems), using an Applied Biosystems 7900. Gene expression analyses for α-MHC, β-MHC, Anf, Bnp, SERCA2A, and Phn were carried out according to the manufacturer’s instructions. Primer sequences and conditions are listed (Supplemental Table 2). Each measurement was obtained using at least 3 mice per group, and each sample was measured in triplicate. Data were quantified by using the comparative C_{T} method, with Gapdh expression as a control.

**Echocardiography**

Transthoracic echocardiography was conducted on nonanesthetized animals as described previously (115), with a 13-MHz probe (Vivid 7, GE Medical Systems) or VisualSonics Vevo 770 high-frequency ultrasound rodent imaging system. GE Medical Systems or VisualSonics Vevo 770 software was used for data acquisition and subsequent analysis. Hearts were imaged in the 2-dimensional parasternal short-axis view, and an
M-mode echocardiogram of the midventricular region was recorded at the level of the papillary muscles. Calculations of cardiac anatomic and functional parameters were carried out as described previously (115).

**Hemodynamic studies**

Cardiac function was evaluated by measuring the maximum rate of increase (dP/dtmax) and decline (dP/dtmin) in left ventricular pressure with a micro-manometer catheter (Millar 1.4F, SPR 671, Millar Instruments) positioned in the left ventricle via a right common carotid artery cannulation.

**Biochemical analyses**

Whole hearts from WT or LS/+ mice were dissected, perfused in PBS, and immediately frozen in liquid N2. Whole-cell lysates were prepared by homogenizing the tissue in radioimmunoprecipitation (RIPA) buffer (25 mmol/l Tris-HCl [pH 7.4], 150 mmol/l NaCl, 0.1% SDS, 1% NP-40, 0.5% sodium deoxycholate, 5 mmol/l EDTA, 1 mmol/l NaF, 1 mmol/l sodium orthovanadate, and a protease cocktail) at 4°C, followed by clarification at 14,000 g.

Primary cardiomyocytes were isolated and cultured as previously described (116). Briefly, hearts were placed in a Langendorff apparatus, and adult cardiomyocytes were obtained by perfusion with Ca2+-free Tyrode buffer (135 mmol/l NaCl, 4 mmol/l KCl, 1 mmol/l MgCl2, 0.33 mmol/l NaH2PO4, 10 mmol/l HEPES) (pH 7.4) and 10 mmol/l glucose, 10 mmol/l 2,3-butanedioine monoxide (Sigma-Aldrich), and 5 mmol/l Taurine (Sigma-Aldrich) for 3 to 5 minutes. Perfusion was continued for an additional 7 to 10 minutes with recirculating Tyrode buffer, containing a mixture of collagenase D (0.3 mg/g body weight), Roche, collagenase B (0.4 mg/g body weight; Roche), and proteinase XIV (0.05 mg/g body weight; Sigma-Aldrich). Ventricular tissue was then minced in Tyrode solution containing 2% bovine serum albumin (Sigma-Aldrich), incubated for 15 minutes at 37°C, and filtered through a 250-μm nylon mesh. The cell suspension was centrifuged at 420 g for 2 minutes and then gradually subjected to Tyrode buffer containing increasing concentrations of calcium and decreasing concentrations of 2,3-butanedioine monoxide (i.e., the final concentration was 1.2 mmol/l CaCl2 with no 2,3-butanedioine monoxide). Typical yields were 1.5 × 106 to 2.5 × 106 cells per heart, with 70% to 80% of the cells retaining their rod-shaped morphology. After 12 hours, cardiomyocytes were stimulated for the indicated times with the appropriate agonist (10 nmol/l IGF-1, 25 ng/ml EGF, 100 nmol/l angiotensin II, 10 ng/ml IL-6), washed, and lysed either directly in sample buffer containing SDS or in RIPA at 4°C, followed by clarification at 14,000 g.

After 12 hours, cardiomyocytes were stimulated for the indicated times with the appropriate agonist (10 nmol/l IGF-1, 25 ng/ml EGF, 100 nmol/l angiotensin II, or 10 ng/ml IL-6), washed, and lysed either in sample buffer containing SDS or in RIPA at 4°C, followed by clarification at 14,000 g, or directly in SDS-PAGE sample buffer. Proteins were resolved by SDS-PAGE and transferred to PVDF membranes. Immunoprecipitations were performed with either anti-Gab1 or anti-IRS-1 antibodies (Cell Signaling Technology). Immunoblots were performed, following the manufacturer’s directions, with anti-Akt, anti-JNK, anti-GSK-3εt, anti-phospho-FAK-297, or anti-Shp2 antibodies (all from Santa Cruz Biotechnology Inc.); anti-Stat3, anti-Erk1/2, anti-Gab1, anti-IRS-1, anti-TSC21442, or anti-p70S6 kinase antibodies (all from Cell Signaling Technology); or anti-phospho-Akt173, anti-phospho-Erk1/2, anti-phospho-Stat3, anti-phospho-JNK, anti-phospho-TSC21442, anti-phospho-p70S6 kinase, or anti-phospho-GSK-3εt antibodies (all from Cell Signaling Technology). Bands were visualized with enhanced chemiluminescence and quantified by densitometry (developed by Wayne Rasband; ImageJ 1.41i software, http://rsbweb.nih.gov/ij/).

**Immune complex PTP assays**

PTP assays were conducted as previously described (39) using para-nitrophenyl phosphate (pNPP, obtained from Sigma-Aldrich) as substrate. WT or LS/+ whole heart lysates were homogenized and lysed in RIPA buffer (but without sodium orthovanadate), and Shp2 was immunoprecipitated by using anti-Shp2 polyclonal antibodies (Santa Cruz Biotechnology Inc.) coupled to protein A-Sepharose. Immune complexes were washed 3 times in RIPA buffer without sodium orthovanadate and once in wash buffer (30 mmol/l HEPES [pH 7.4], 120 mmol/l NaCl without pNPP). For each sample, PTP assays were performed in triplicate at 37°C in 50 μl assay buffer (30 mmol/l HEPES [pH 7.4], 120 mmol/l NaCl, 5 mmol/l dithiothreitol, 10 mmol/l pNPP) containing 50 μl of the Shp2 beads. Reactions were terminated with 0.2 N NaOH, and phosphate release was determined by measuring A405. After the assays, immune complexes were recovered by centrifugation, boiled in 2× SDS-PAGE sample buffer, resolved by SDS-PAGE, and immunoblotted with polyclonal Shp2 antibodies (Santa Cruz Biotechnology Inc.) to ensure that equal amounts of Shp2 had been tested for phosphatase activity.

**Rapamycin studies**

*In vitro*. When indicated, primary cardiomyocytes were treated in vitro with rapamycin (Sigma-Aldrich) dissolved in DMSO at 0.02 μM or DMSO alone for 12 hours.

*In vivo*. Rapamycin (LC Laboratories) was dissolved in ethanol at a concentration of 20 mg/ml, filter sterilized, resuspended in vehicle (0.25% PEG, 0.25% Tween-80) at a concentration of 1 mg/ml, and injected i.p. (2 mg/kg body weight), either daily for 4 weeks or daily for 4 weeks followed by weekly injections for an additional 4 weeks. Injections began at either 8 weeks (prior to onset of hypertrophy) or 12 weeks (after established hypertrophy was indicated) of age, and mice were assessed after 4 weeks of treatment or after 8 weeks of treatment, as detailed in the Results and figure legends. As controls, WT and LS/+ mice were treated with vehicle alone.

*In vitro Jnk and Stat3 inhibition experiments*. When indicated, similarly to rapamycin treatment, primary cardiomyocytes were treated in vitro with either Jnk Inhibitor II (Calbiochem) or Stat Inhibitor V (Santa Cruz) dissolved in DMSO at 10 μM and 1 μM, respectively.

**Statistics**

All data are expressed as mean ± SEM. Statistical significance was determined using 2-tailed Student’s t test and 1-way ANOVA or 2-way repeated measure ANOVA, as appropriate. If ANOVA was significant, individual differences were evaluated using the Bonferroni post-test. Kaplan-Meier survival curves were analyzed using the log-rank test. For all studies, values of P < 0.05 were considered statistically significant.

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