Pten mediates Myc oncogene dependence in a conditional zebrafish model of T cell acute lymphoblastic leukemia

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The MYC oncogenic transcription factor is overexpressed in most human cases of T cell acute lymphoblastic leukemia (T-ALL), often downstream of mutational NOTCH1 activation. Genetic alterations in the PTEN–PI3K–AKT pathway are also common in T-ALL. We generated a conditional zebrafish model of T-ALL in which 4-hydroxytamoxifen (4HT) treatment induces MYC activation and disease, and withdrawal of 4HT results in T-ALL apoptosis and tumor regression. However, we found that loss-of-function mutations in zebrafish pten genes, or expression of a constitutively active Akt2 transgene, rendered tumors independent of the MYC oncogene and promoted disease progression after 4HT withdrawal. Moreover, MYC suppresses pten mRNA levels, suggesting that Akt pathway activation downstream of MYC promotes tumor progression. Our findings indicate that Akt pathway activation is sufficient for tumor maintenance in this model, even after loss of survival signals driven by the MYC oncogene.

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Abbreviations used:
4-hydroxytamoxifen, 4HT; T-ALL, T cell acute lymphoblastic leukemia.
transgenic zebrafish fusion transgene to induce T-ALL which closely resembles rag2

We previously generated a zebrafish model of T-ALL, using a promoter-driven expression of a mouse EGFP-Myc fusion transgene to induce T-ALL which closely resembles the human disease pathologically and by gene expression

RESULTS

Conditional T-ALL development in rag2:MYC-ER transgenic zebrafish

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Figure 1. Conditional T-ALL development in rag2:MYC-ER transgenic zebrafish. (A and B) Thymic fluorescence in control MYC-ER-negative lck-EGFP transgenic (A) and rag2:dsRed2 transgenic (B) zebrafish raised in the absence of 4HT. (C and D) Thymic fluorescence in the absence of 4HT treatment in rag2:MYC-ER transgenic zebrafish that also expressed lck-EGFP (C) or rag2:dsRed2 (D). For A–D, one representative zebrafish is shown from a minimum of eight fish raised in each condition. (E and F) Fully penetrant T-ALL in rag2:MYC-ER transgenic zebrafish raised in 50 µg/liter (129 nM) 4HT. A representative triple-transgenic rag2:MYC-ER, lck-EGFP, rag2:dsRed2 zebrafish is shown at the time of disseminated T-ALL development, imaged in both green and red fluorescent channels. (G and H) Thymic fluorescence in the rag2:MYC-ER transgenic zebrafish from E and F, shown 4 wk after 4HT removal. In all triple-transgenic zebrafish in which regression occurred (n = 6 of 8), T-ALL regression occurred simultaneously in both green and red fluorescent channels, with no evidence of residual EGFP-positive dsRed2-negative mature T cells, indicating that differentiation was not the primary mechanism of T-ALL regression. Bar, 1 mm. (I) After T-ALL development, zebrafish were either removed from 4HT to down-regulate the MYC transgene (−4HT) or kept in 4HT (+4HT), and tumor phenotype was assessed 8 wk after 4HT removal. Zebrafish that became moribund with leukemia before the 8-wk time point were euthanized and classified into the progression category. Number of fish analyzed per condition: −4HT, n = 8; +4HT, n = 13.

(langenau et al., 2003, 2005a). To generate a zebrafish model of T-ALL in which MYC activity could be modulated in established tumor cells, we generated stable transgenic zebrafish expressing rag2:MYC-ER, in which the zebrafish rag2 promoter drives expression of a fusion transgene consisting of human MYC fused to the ligand-binding domain of a modified

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estrogen receptor that is posttranslationally induced by 4-hydroxytamoxifen (4HT) treatment but not by endogenous estrogens (Littlewood et al., 1995). When treated with vehicle control (ethanol), rag2:MYC-ER heterozygous fish did not develop T-ALL over a 16-wk follow-up period. Thymic fluorescence in 8-wk-old rag2:MYC-ER transgenic fish co-expressing lck:EGFP and rag2:dsRed2 transgenes that were treated with vehicle control was indistinguishable from that of their rag2:MYC-ER negative siblings (Fig. 1, A–D). However, when MYC-ER was induced by treatment with 50 µg/liter (129 nM) 4HT beginning at 5 d postfertilization, rag2:MYC-ER transgenic zebrafish developed fully penetrant T-ALL starting at 5 wk of age (Fig. 1, E and F). Histological analysis of T-ALL tumors induced by rag2:MYC-ER alone revealed that these tumors consisted of sheets of monomorphic lymphoblasts characterized by regular nuclear contours, scant cytoplasm, homogeneous chromatin, and inconspicuous nucleoli (Fig. S1), morphological features which closely resemble those of human T-ALL lymphoblasts. Note that no phenotypic differences were observed between these tumor cells and those arising in zebrafish of other genotypes studied throughout this manuscript (Fig. S1).

To test whether these tumors were dependent on ongoing MYC transgene activation, zebrafish with T-ALL were removed from 4HT to down-regulate MYC activity, and tumors were monitored weekly for 8 wk by fluorescence imaging. Tumor phenotypes were then classified into four categories based on the degree of change in tumor size by the end of the 8-wk monitoring period: (1) complete regression (disappearance of all abnormal extrathymic fluorescence), (2) partial regression (reduction in tumor diameter to less than half its original size), (3) stable disease (tumors that did not meet criteria for regression or progression), and (4) progression (increase in tumor diameter to more than twice its original size). After T-ALL development, removal from 4HT induced complete tumor regression in 75% of zebrafish examined, whereas tumor regression was not seen in any of the zebrafish kept in 4HT (Fig. 1 F; P = 0.0001).

Figure 2. T-ALL regression after MYC down-regulation occurs via mitochondrial apoptosis. (A) Immunohistochemical staining for the apoptotic marker activated caspase 3 was performed in rag2:MYC-ER transgenic zebrafish with T-ALL in the presence of 4HT (+4HT) and 4 d after 4HT removal (−4HT). Number of fish analyzed = 4 per condition. Bars, 10 µm. (B) One representative rag2:MYC-ER;rag2:EGFP-bcl2;rag2:dsRed2 triple-transgenic zebrafish is shown at the time of T-ALL onset and 3 wk after removal from 4HT. Bar, 1 mm. (C) Quantitation of T-ALL phenotypes 8 wk after MYC-ER inactivation, comparing rag2:EGFP-bcl2 transgenic zebrafish versus rag2:dsRed2 controls. Number of fish analyzed per condition: rag2:MYC-ER;rag2:dsRed2, n = 12; rag2:MYC-ER;rag2:dsRed2;rag2:EGFP-bcl2, n = 20.

MYC down-regulation induces mitochondrial apoptosis in T lymphoblasts

In most experimental models of MYC-induced tumorogenesis, inactivation of MYC leads to the loss of the malignant phenotype as a result of apoptotic cell death or differentiation/senescence (Arvanitis and Felsher, 2006). To examine the fate of T-ALL cells in rag2:MYC-ER zebrafish after 4HT withdrawal, we monitored EGFP expression driven by the lck promoter, which is expressed in both immature and mature T cells, and dsRed2 expression driven by the rag2 promoter, which is expressed in immature but not mature T cells (Langenau et al., 2004, 2005a). The loss of tumor cells after removal from 4HT did not appear to predominantly represent T cell differentiation because in each fish with tumor regression we noted the simultaneous disappearance of disseminated cells expressing both EGFP and dsRed2 fluorescence, with no visible residual extrathymic EGFP-positive dsRed2-negative mature T cells (Fig. 1, E–H). Furthermore, examination of the senescence marker acidic β-galactosidase activity revealed no increase above background levels in T-ALL cells after MYC inactivation (Fig. S2). In some settings, collapse of the tumor-associated vasculature is involved in tumor regression after MYC inactivation (Giuriato et al., 2006; Sodir et al., 2011); thus, we also examined whether MYC inactivation affected the tumor vasculature, taking advantage of fli1:EGFP transgenic zebrafish in which EGFP is robustly expressed in vascular endothelium (Lawson and Weinstein, 2002). Immunohistochemistry for EGFP in rag2:MYC-ER;rag2:dsRed2;fli1:EGFP triple-transgenic zebrafish revealed no significant differences in tumor-associated microvascular density 4 d after MYC inactivation (Fig. S3).

Immunohistochemical analysis of T-ALL cells from rag2:MYC-ER transgenic zebrafish revealed increased staining for the apoptotic marker activated caspase 3 after removal from 4HT (Fig. 2 A), implicating the induction of apoptotic cell death in T-ALL cells after MYC down-regulation. We thus reasoned
that mitochondrial (intrinsic) apoptosis might be the key mediator of T-ALL regression after MYC down-regulation, a hypothesis which we tested using a rag2:EGFP-bcl2 transgene, which blocks intrinsic apoptosis in thymocytes by binding and sequestering proapoptotic BCL2 family proteins (Langenau et al., 2005b). Indeed, we found that T-ALL tumors induced in rag2:MYC-ER zebrafish that also expressed rag2:EGFP-bcl2 failed to regress after MYC down-regulation (Fig. 2, B and C; \( P < 0.0001 \)). Collectively, these findings implicate mitochondrial apoptosis as a central mediator of T-ALL regression after MYC down-regulation in this model.

### Pten inactivating mutations promote loss of MYC oncogene dependence

We have recently identified genetic alterations of PTEN and the PI3K-AKT pathway in 48% of primary T-ALL human tumor specimens, most of which (86%) were also characterized by MYC overexpression (Gutierrez et al., 2009). We thus wanted to use our model to test the hypothesis that such alterations would render T-ALLs independent of MYC oncogenic activity for tumor maintenance. Because of a partial genome duplication event during teleost evolution, zebrafish have duplicated pten genes, known as ptenA and ptenB, both of which are highly conserved with mammalian PTEN genes, demonstrate phosphatase activity toward phosphatidylinositol(3,4,5)triphosphate, and have redundant roles during zebrafish development (Faucherre et al., 2008). Complete deficiency of all zebrafish pten alleles leads to embryonic lethality, whereas compound haploinsufficiency is compatible with normal development. To test whether pten is a modulator of MYC oncogene dependence, double-transgenic rag2:MYC-ER;rag2:GFP zebrafish were mated to fish harboring loss-of-function mutations in their ptenA and/or ptenB genes (Fig. 3 A). Offspring from these matings were raised in 50 µg/liter (129 nM) 4HT beginning at 5 d postfertilization, the time at which thymic fluorescence is first visible in rag2:GFP transgenic fish, and T-ALL onset was monitored by weekly GFP fluorescence imaging beginning at 4 wk of age. After development of disseminated T-ALL, fish were removed from 4HT to down-regulate MYC activity, and tumor phenotypes after 4HT removal were assessed based on the degree of change in tumor size by the end of the 8-wk monitoring period, as described in the previous section.

![Figure 3. pten haploinsufficiency does not accelerate onset of MYC-induced T-ALL.](image)

(A) Experimental design to test the effect of pten haploinsufficiency on T-ALL onset upon MYC-ER activation and on tumor regression after 4HT removal. (B) Analysis of T-ALL onset in zebrafish from the experiment described in A. Number of fish analyzed per genotype: ptenA +/+; ptenB +/+; n = 39; ptenA +/+; ptenB +/−; n = 22; ptenA +/−; ptenB +/+; n = 12; ptenA +/−; ptenB +/−; n = 10.

![Figure 4. pten haploinsufficiency promotes loss of MYC transgene dependence.](image)

(A and C) One representative rag2:MYC-ER;rag2:GFP double-transgenic pten−wild-type zebrafish, shown at time of T-ALL onset (A) and 3 wk after removal from 4HT (C). (B and D) Representative rag2:MYC-ER;rag2:GFP double-transgenic zebrafish that harbored heterozygous mutations of both ptenA and ptenB, shown at time of T-ALL onset (B) and 3 wk after removal from 4HT (D). Bar, 1 mm. (E) Quantitation of T-ALL phenotypes after 4HT removal, based on pten genotype. Number of fish with T-ALL analyzed per genotype: ptenA +/+; ptenB +/+; n = 39; ptenA +/+; ptenB +/−; n = 12; ptenA +/−; ptenB +/−; n = 22; ptenA +/−; ptenB +/−; n = 10. (F) Western blot analysis for phosphorylation of S6 ribosomal protein, a marker of Akt pathway activation, in sorted T-ALL cells from five different rag2:MYC-ER pten−wild-type zebrafish in which T-ALL progressed despite MYC down-regulation. Units for the molecular mass markers shown are in kD.
Loss of up to two of the four zebrafish pten alleles did not measurably accelerate the onset of MYC-induced T-ALL (Fig. 3 B); however, pten haploinsufficiency significantly promoted loss of tumor dependence on MYC transgene activation (Fig. 4). The rates of complete or partial regression were 69% in pten wild-type zebrafish, 58% in fish harboring heterozygous ptenB mutations, 18% in fish harboring heterozygous ptenA mutations, and 10% in pten double-heterozygous zebrafish (Fig. 4 E). Conversely, deficiency of pten also significantly promoted tumor progression after MYC-ER inhibition, with progression rates of 13% in pten wild-type zebrafish, 33 and 36% in fish harboring a single heterozygous mutation of ptenB or ptenA, respectively, and 60% in zebrafish harboring heterozygous mutations in both ptenA and ptenB (Fig. 4 E; P = 0.001 by 4 × 4 Fisher’s exact test). Thus, pten haploinsufficiency strongly promoted the loss of MYC transgene dependence. Furthermore, Western blot analysis of the minority of T-ALL tumors from rag2:MYC-ER pten−/− wild-type zebrafish that progressed despite MYC down-regulation revealed that a subset of these tumors spontaneously acquired activation of the AKT pathway, as indicated by robust phosphorylation of S6 ribosomal protein (Fig. 4 F).

**Constitutive Akt activation promotes loss of MYC oncogene dependence**

Although PTEN is best known as a negative regulator of oncogenic signaling through the PI3K–AKT pathway, evidence also suggests that PTEN has AKT-independent functions, including regulation of p53 activity, chromosomal stability, and activity of the anaphase-promoting complex (Freeman et al., 2003; Shen et al., 2007; Song et al., 2011). To test whether pten deficiency modulates MYC dependence via Akt pathway activation, we tested whether expression of rag2:myr-mAkt2, encoding a myristoylated constitutively active mouse Akt2 transgene (Tan et al., 2008), would phenocopy the effect of pten inactivation on MYC transgene dependence. Heterozygous rag2:MYC-ER zebrafish that did not harbor a thymic fluorescent transgene were out-crossed to wild-type animals, and all resultant embryos were injected at the one-cell stage with DNA expression constructs encoding rag2:GFP alone or both rag2:GFP and rag2:myr-mAkt2. Injected fish were raised in 4HT to induce T-ALL, after which 4HT was removed and tumor regression was monitored as in the previous section. Expression of rag2:myr-mAkt2 significantly accelerated the onset of T-ALL in rag2:MYC-ER transgenic zebrafish, with a mean age at T-ALL onset of 4.3 wk in rag2:myr-mAkt2−injected fish, compared with 12.1 wk in control MYC-ER fish injected with rag2:GFP alone (Fig. 5 A; P = 0.017). Expression of rag2:myr-mAkt2 in MYC-ER−negative zebrafish also induced T-ALL development in 17% of these fish by 20 wk (Fig. 5 A), indicating that Akt activation is sufficient to induce T-ALL in the zebrafish, albeit at a relatively low penetrance.

Analysis of T-ALL regression after 4HT removal demonstrated that expression of the constitutively active myr-mAkt2 transgene was strongly associated with loss of MYC transgene dependence (Fig. 5, B and C), suggesting that the effect of pten inactivation is mediated by Akt. T-ALLs arising in rag2:MYC-ER transgenic zebrafish expressing both rag2:myr-mAkt2 and rag2:GFP showing a complete or partial regression rate of 14% after MYC-ER inhibition, compared with a regression rate of 75% in rag2:MYC-ER controls injected with rag2:GFP alone. Concomitantly, tumor progression rates were 86% in rag2:myr-mAkt2−injected zebrafish, compared with 17% of rag2:GFP-injected controls (Fig. 5 D; P = 0.0002 by 2 × 4 Fisher’s exact test).

**Akt pathway activation does not alter the transcriptional activity of Myc**

Activated Akt directly phosphorylates and inhibits GSK3 (Cross et al., 1995), which is a key regulator of Myc protein stability (Sears et al., 2000), thus we wanted to test whether Akt pathway activation might substitute for MYC transgene activation by inducing the transcriptional activity of endogenous Myc. The Ddx18 RNA helicase is a well-established direct target of Myc in human and mouse cells (Grandori et al., 1996; O’Hagan et al., 2000), and we used injection of Myc mRNA into zebrafish embryos followed by ddx18 RNA in situ
hybridization to confirm that the regulation of ddx18 by Myc is conserved in the zebrafish (Fig. 6 A). We then performed quantitative (Q) RT-PCR analysis of ddx18 mRNA levels in sorted T-ALL cells from rag2:MYC-ER;rag2:EGFP-bcl2 zebrafish that also expressed either a rag2:GFP or a rag2:myr-mAkt2 transgene. T-ALL cells were sorted from animals in 4HT (+4HT) or 4 d after 4HT removal (−4HT). β-Actin was used as the Q-RT-PCR control. Becl2-transgenic T-ALL cells were used in all conditions to avoid comparing live versus dying cells after MYC-ER inactivation. Error bars represent standard error of the mean. Number of tumors analyzed per group: 4HT+, myr-mAkt2−, n = 6; 4HT−, myr-mAkt2−, n = 7; 4HT+, myr-mAkt2+, n = 5; 4HT−, myr-mAkt2+, n = 5.

Figure 6. Expression of activated Akt does not alter the transcriptional activity of MYC. (A) Whole mount RNA in situ hybridization for ddx18, a known direct target of MYC in mammalian cells (Grandori et al., 1996; O’Hagan et al., 2000), performed at the 24-h postfertilization developmental stage in zebrafish embryos that were injected with 100 pg mCherry (control) or Myc mRNA at the one-cell stage. One representative zebrafish is shown in each condition out of a minimum of 20 embryos analyzed per condition. (B) Q-RT-PCR for ddx18 expression, performed using RNA from T-ALL cells from rag2:MYC-ER;rag2:EGFP-bcl2 zebrafish which also expressed either a rag2:GFP or a rag2:myr-mAkt2 transgene. T-ALL cells were sorted from animals in 4HT (+4HT) or 4 d after 4HT removal (−4HT). β-Actin was used as the Q-RT-PCR control. Becl2-transgenic T-ALL cells were used in all conditions to avoid comparing live versus dying cells after MYC-ER inactivation. Error bars represent standard error of the mean. Number of tumors analyzed per group: 4HT+, myr-mAkt2−, n = 6; 4HT−, myr-mAkt2−, n = 7; 4HT+, myr-mAkt2+, n = 5; 4HT−, myr-mAkt2+, n = 5.

DISCUSSION

We have demonstrated for the first time that pten is an important mediator of MYC oncogene dependence in T-ALL lymphoblasts, an effect which appears to be mediated by its role as an inhibitor of oncogenic signaling through the Akt pathway. Furthermore, we also find that Myc represses Pten mRNA levels, an effect which is likely mediated by Myc-induced micro-RNAs which have recently been shown to down-regulate Pten (Mu et al., 2009; Olive et al., 2009; Kim et al., 2010; Mavrakis et al., 2010). Our data thus support a model in which Myc dependence is mediated in part by the up-regulation of Pten which follows Myc inactivation, which then acts to inhibit AKT pathway signaling which would otherwise be sufficient to maintain the malignant phenotype.
phenotype, even in the absence of oncogenic signals mediated by Myc (Fig. 7 B).

Our findings implicate apoptotic cell death through the mitochondrial pathway as a critical mediator of Myc oncogene dependence in this model, thus indicating that inhibition of apoptosis downstream of AKT is the likely mechanism through which Pten haploinsufficiency induces loss of Myc oncogene dependence. Akt has previously been shown to inhibit mitochondrial apoptosis via multiple pathways (Manning and Cantley, 2007), including inactivation of BAD via phosphorylation (Datta et al., 1997; del Peso et al., 1997), transcriptional down-regulation of BIM downstream of its effect on FOXO proteins (Dijkers et al., 2002), inhibition of p53 via phosphorylation and activation of MDM2 (Mayo and Donner, 2001; Zhou et al., 2001), and up-regulation of the antiapoptotic MCL1 downstream of both mTOR (Wei et al., 2006; Hsieh et al., 2010) and GSK3 (Maurer et al., 2006). Our results indicate that AKT activation is one mechanism that can overcome MYC oncogene dependence in T-ALL, suggesting that PI3K–AKT inhibitors may have therapeutic utility in combination with inhibitors of MYC itself in the design of new therapeutic strategies for T-ALL.

MATERIALS AND METHODS

Transgenic and mutant zebrafish lines. The n2g2-MYC-ER construct was generated by placing a human MYC transgene fused to the ligand-binding domain of the estrogen receptor, which is posttranslationally induced by 4HT but not endogenous estrogens (Littlewood et al., 1995), downstream of the zebrafish n2g2 promoter in a modified plBluescript vector in which the n2g2-MYC-ER construct is flanked by recognition sequences for I-SceI meganuclease. This circular n2g2:MYC-ER was co-injected together with a wild-type mhta construct under its own promoter, also flanked by I-SceI recognition sequences, into one-cell stage embryos from the nacre line using a previously described I-SceI co-injection strategy (Grabher and Wittbrodt, 2008). Nacre zebrafish harbor a pigmentation defect caused by homozygous loss-of-function mutations, thus allowing rescue of the pigmentation defect by the co-injected mhta transgene to act as a transgenesis reporter in the I-SceI–modified pBluescript vector described in the first paragraph. Genotyping by genomic PCR after the completion of each experiment. PCR genotyping primers were as follows: n2g2-MYC-ER forward, 5'-AGTCCCTGAGACGATCAGCA-3', and reverse, 5'-TCATCATGGGAACCGACTT-3'; and n2g2-myrm2b forward, 5'-ATGCTAATTTGAAGCACTAGCA-3', and reverse, 5'-ATGCTAATTTGAAGCACTAGCA-3', and reverse, 5'-TTGGTCTTCTTCTCACGAG-3'. Genotyping for ptenA and ptenB was performed as previously described (Faucherre et al., 2008).

Zebrafish paraffin sectioning and immunohistochemistry. Zebrafish were euthanized in tricaine anesthetic, fixed in 4% paraformaldehyde at 4°C for 2 d, decalcified with 0.25 M EDTA, pH 8.0, for 2 d, dehydrated in alcohol, and embedded in paraffin. Slides were deparaffinized and pretreated with 10 mM citrate, pH 6.0, in a steam pressure cooker (Decloaking Chamber; BioCare Medical) according to the manufacturer’s instructions, followed by washing in distilled water. Slides were pretreated with Peroxidase Block (Dako) for 5 min, followed by serum-free protein block (Dako) for 20 min to block nonspecific binding sites. Slides were then incubated with primary rabbit anticleaved caspase-3 antibody (1:50; Cell Signaling Technology) or mouse anti-GFP antibody (1:1500; Takara Bio Inc.). Secondary detection was performed by adding horseradish peroxidase-labeled polymer (Dako) for 30 min. Immunoperoxidase staining was developed with diaminobenzidine + a CM3050 cryostat (Leica). Staining for activity of senescence-associated (Sakura), and snap-frozen in isobutane precooled in dry ice. 14-μm frozen sections were cut onto slides using a CM3050 cryostat (Leica). Staining for activity of senescence-associated β-galactosidase was performed using the Senescence β-Galactosidase Staining kit (Cell Signaling Technology) according to the manufacturer’s instructions.

Zebrafish cryosectioning and β-galactosidase staining. Zebrafish were euthanized in tricaine anesthetic, embedded in a 1:1 mixture of 30% sucrose and Tissue-Tek O.C.T. compound (Sakura), and snap-frozen in isobutane precooled in dry ice. 14-μm frozen sections were cut onto slides using a CM3050 cryostat (Leica). Staining for activity of senescence-associated β-galactosidase was performed using the Senescence β-Galactosidase Staining kit (Cell Signaling Technology) according to the manufacturer’s instructions.

Western blotting. DsRed2–sorted T-ALL cells were lysed in RIPA buffer (Millipore) supplemented with Complete Mini protease inhibitor (1 tablet/10 ml; Roche) and PhosSTOP phosphatase inhibitor (1 tablet/10 ml; Roche). 20 μg protein lysate was mixed with Laemmli 4× SDS sample buffer (Boston Bioproducts) and β-mercaptoethanol (Sigma-Aldrich) in appropriate
proportions and incubated at 100°C for 3 min before being run on a 4–12% Novex bis-tris polyacrylamide gel (Invitroge) at 160V for 1 h. Blots were then transferred to a nitrocellulose membrane (Millipore) at 380 mA for 1 h, blocked with 5% milk in tris-buffered saline with 0.1% tween, and probed with anti-phospho-S6 ribosomal protein (Ser240/244) antibody (1:1,000; Cell Signaling Technology), anti-S6 ribosomal protein antibody (1:1,000; Cell Signaling Technology), and anti-α-tubulin antibody (1:1000; Cell Signaling Technology). Secondary detection was with HRP-linked antibodies (Cell Signaling Technology). HRP substrate was SuperSignal West Dura (Thermo Fisher Scientific), and Western blot images were captured using an ImageQuant LAS4000 chemiluminescent image analyzer (GE Healthcare).

RNA extraction and Q-RT-PCR. Total RNA was extracted from fluorochrome-sorted T-ALL cells using Trizol reagent according to the manufacturer’s instructions (Invitroge). cDNA was synthesized from total RNA using the SuperScript III First-Strand Synthesis System for RT-PCR according to the manufacturer’s instructions (Invitroge). 3% of the cDNA reaction volume was then taken for each Q-RT-PCR reaction, performed with the SYBR green PCR Core Reagents kit (Applied Biosystems) and a 7300 Real Time PCR System instrument (Applied Biosystems) according to the manufacturer’s instructions. All Q-RT-PCR were performed in triplicate, and β-actin1 was used as the control for all Q-RT-PCR reactions. Q-RT-PCR primer sequences were as follows: ddx18 forward, 5′-CGCT- CAGAGGAGATGTAGT-G3′ and reverse, 5′-ACGCACCTGCTGCAC-CAGAAG-3′; npm1a forward, 5′-ACAAAGGGCGAAGAAAGACAG-3′ and reverse, 5′-CGCTTAAAGTCCTGGTTGT- TGT-3′; ptenA forward, 5′-ATCCCCAGGGCTCTAGAAAG-3′ and reverse, 5′-TGGGATCTT- TACCTCAACGTGATA-3′; ptenB forward, 5′-GGGTTGTCATGATTGTTGCTG-3′ and reverse, 5′-TGCTCGTACGTGCTAGTC-3′; β-actin1 forward, 5′-TACAATGAGCTCCGGTTGCT-3′ and reverse, 5′-ACATACTACGGAGGGTGTT-3′.

Myc RNA injection into zebrafish embryos and ddx18 in situ hybridization. Mouse Myc was cloned into the pCS2+ vector and linearized by NotI digestion. Myc mRNA was then transcribed in vitro using the Ambion SP6 mMessage mMachine kit (Applied Biosystems). Zebrafish embryos were injected at the one-cell stage with 100 pg of Myc or control mCherry mRNA. At the 24-h postfertilization developmental stage, injected embryos were fixed overnight in 4% paraformaldehyde, and ddx18 RNA in situ hybridization was performed as previously described (Payne et al., 2011).

Statistical analyses. Differences in tumor-free survival were assessed by the log-rank test, and time-to-event distributions were estimated via the Kaplan-Meier method. Differences in categorical data were assessed via Fisher’s exact test, and differences in continuous data were assessed via the Mann-Whitney (rank-sum) test.

Online supplemental material. Fig. S1 shows histological morphology of T-ALL lymphoblasts of various genotypes analyzed in this study. Fig. S2 shows analysis of the senescence marker acidic β-galactosidase activity in sectioned nsq2:MYC-ER; nsq2:dsRed2 double-transgenic zebrafish with T-ALL before and after 4HT withdrawal. Fig. S3 shows analysis of microvascular density in T-ALL tumors before and after 4HT withdrawal. Fig. S4 shows the effect of 4HT treatment versus withdrawal, and of expression of activated Akt2 versus control, on mRNA expression of the Myc target npm1a. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20101691/DC1.

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