BET Bromodomain Inhibition as a Therapeutic Strategy to Target c-Myc


SUMMARY

MYC contributes to the pathogenesis of a majority of human cancers, yet strategies to modulate the function of the c-Myc oncoprotein do not exist. Toward this objective, we have targeted MYC transcription by interfering with chromatin-dependent signal transduction to RNA polymerase, specifically by inhibiting the acetyl-lysine recognition domains (bromodomains) of putative coactivator proteins implicated in transcriptional initiation and elongation. Using a selective small-molecule bromodomain inhibitor, JQ1, we identify BET bromodomain proteins as regulatory factors for c-Myc. BET inhibition by JQ1 downregulates MYC transcription, followed by genome-wide downregulation of Myc-dependent target genes. In experimental models of multiple myeloma, a Myc-dependent hematologic malignancy, JQ1 produces a potent antiproliferative effect associated with cell-cycle arrest and cellular senescence. Efficacy of JQ1 in three murine models of multiple myeloma establishes the therapeutic rationale for BET bromodomain inhibition in this disease and other malignancies characterized by pathologic activation of c-Myc.

INTRODUCTION

c-Myc is a master regulatory factor of cell proliferation (Dang et al., 2009). In cancer, pathologic activation of c-Myc plays a central role in disease pathogenesis by the coordinated upregulation of a transcriptional program influencing cell division, metabolic adaptation, and survival (Dang, 2008). Amplification of MYC is among the most common genetic alterations observed in cancer genomes (Beroukhim et al., 2010). Validation of c-Myc as a therapeutic target is supported by numerous lines of experimental evidence. Murine models of diverse malignancies have been devised by introducing genetic constructs overexpressing MYC (Harris et al., 1988; Leder et al., 1986; Stewart et al., 1984). In addition, conditional transgenic models featuring tunable transcriptional suppression have shown that even transient inactivation of MYC is capable of promoting tumor regression (Jain et al., 2002; Soucek et al., 1998; Soucek et al., 2002). Elegant studies of systemic induction of a dominant-negative MYC allele within an aggressive, KRAS-dependent murine model of lung adenocarcinoma have further suggested the putative therapeutic benefit of c-Myc inhibition (Fukazawa et al., 2010). Importantly, these studies establish the feasibility of c-Myc inhibition within an acceptable therapeutic window of tolerability.

Nevertheless, a therapeutic approach to target c-Myc has remained elusive. The absence of a clear ligand-binding domain establishes a formidable obstacle toward direct inhibition, which is a challenging feature shared among many compelling transcriptional targets in cancer (Darnell, 2002). c-Myc functions as a DNA-binding transcriptional activator upon heterodimerization with another basic-helix-loop-helix leucine zipper (bHLH-LZ) transcription factor, Max (Amati et al., 1993; Blackwood and Eisenman, 1991). High-resolution structures of the complex fail to identify a hydrophobic involution compatible with the positioning of an organic small molecule (Nair and Burley, 2003). Therefore, we have targeted c-Myc transcriptional function by another means, namely the disruption of chromatin-dependent signal transduction (Schreiber and Bernstein, 2002). c-Myc transcription is associated locally and globally with increases in histone lysine side-chain acetylation, a covalent modification of chromatin that is regionally associated with transcriptional...
activation (Frank et al., 2003; Vervoorts et al., 2003). Histone acetylation templates the assembly of higher-ordered transcriptional complexes by recruiting proteins with one or more acetyl-lysine-binding modules or bromodomains (Dhalluin et al., 1999; Haynes et al., 1992). Members of the bromodomain and extraterminal (BET) subfamily of human bromodomain proteins (BRD2, BRD3, and BRD4) associate with acetylated chromatin and facilitate transcriptional activation by increasing the effective molarity of recruited transcriptional activators (Rahman et al., 2011). Notably, BRD4 has been shown to mark select M/G1 genes in mitotic chromatin as transcriptional memory and direct postmitotic transcription (Dey et al., 2009) via direct interaction with the positive transcription elongation factor complex b (P-TEFb) (Bisgrove et al., 2007). The discovery that c-Myc regulates promoter-proximal pause release of Pol II, also through the recruitment of P-TEFb (Rahl et al., 2010), established a rationale for targeting BET bromodomains to inhibit c-Myc-dependent transcription.

Recently, we reported the development and biochemical characterization of a potent, selective small-molecule inhibitor of BET bromodomains, IQ1 (Figure 1A) (Filippakopoulos et al., 2010). IQ1 is a thieno-triazolo-1,4-diazepine that displaces BET bromodomains from chromatin by competitively binding to the acetyl-lysine recognition pocket. In the present study, we leverage the properties of IQ1 as a chemical probe (Frye, 2010) to interrogate the role of BET bromodomains in Myc-dependent transcription and to explore the role of BET bromodomains as cancer dependencies.

Multiple myeloma (MM) represents an ideal model system for these mechanistic and translational questions, given the known role of MYC in disease pathophysiology. MM is an incurable hematologic malignancy that is typified by the accumulation of malignant plasma cells harboring diverse genetic lesions (Chapman et al., 2011). Dysregulation of transcription factors features prominently in the biology of MM, including NFκB (Keats et al., 2007), c-Maf (Hurt et al., 2004), XBP1 (Claudio et al., 2002), HSF1 (Mitsiades et al., 2002), GR (Gomi et al., 2011), IRF4 (Shaffer et al., 2008), Myb (Palumbo et al., 1989), and, notably, c-Myc (Dean et al., 1983). Rearrangement or translocation of MYC are among the most common somatic events in early- and late-stage MM (Shou et al., 2000), and transcriptional profiling identifies Myc pathway activation in more than 60% of patient-derived MM cells (Chng et al., 2011). Experimental support for the central role of c-Myc in the pathogenesis of MM is contributed by an informative, genetically engineered murine model of MM. Lineage-specific and stochastic activation of MYC and, notably, c-Myc (Dean et al., 1983). Rearrangement or translocation of MYC is frequently identified in MM patient samples (Figure 1D). The majority of patient samples exhibit broad amplification of chromosome 19p, but focal amplification at the BRD4 locus is observed (Figure S1 available online). Among 45 established MM cell lines, expression of BRD4 was pronounced and did not correlate with disease stage (data not shown). BRD4 is a testis-specific bromodomain-containing protein, is not expressed in MM.

Analysis of copy number polymorphism (CNP) data collected on 254 MM patients by the Multiple Myeloma Research Consortium (MMRC) revealed that the BRD4 locus is frequently amplified in MM patient samples (Figure 1D). The majority of patient samples exhibit broad amplification of chromosome 19p, but focal amplification at the BRD4 locus is observed (Figure S1 available online). Among 45 established MM cell lines, expression of BRD4 was pronounced and did not correlate with amplification status (Figure 1E).

Human MM cells are highly osteotropic in vivo, and interaction with bone marrow stromal cells (BMSCs) induces proliferation and contributes to drug resistance (McMillin et al., 2010). Analysis of BET bromodomain expression, as influenced by MM cell binding to BMSCs (McMillin et al., 2010), revealed marked upregulation of BRD4 in the INA-6 human MM cell line upon interaction with HSS stromal cells (Figure 1F), suggesting a plausible role for BRD4 function in MM cells within the bone marrow microenvironment.

To explore the function of BET bromodomains in MM, we examined the effect on proliferation of small hairpin RNAs (shRNAs) targeting each of the four BET proteins in comparison to shRNAs targeting 1011 kinases, phosphatases, and oncogenes in a lentivirally delivered, arrayed shRNA screen in INA-6 cells. As illustrated in Figures 1G and 1H, shRNA constructs targeting each of the expressed BET bromodomains are identified as reducing INA-6 proliferation as shown by normalized B scores (Malo et al., 2006). Together, these data establish
Figure 1. Integrated Genomic Rationale for BET Bromodomains as Therapeutic Targets in MM

(A) Structures of the BET bromodomain inhibitors JQ1 and iBET.

(B and C) Expression levels (log2 transformed, median-centered values) for BRD4 transcripts were evaluated in oligonucleotide microarray data from normal plasma cells (NPCs) from healthy donors, individuals with MGUS, or SMM patients (B, data set GSE5900; Zhan et al., 2007) and in plasma cells from MGUS, MM, and PCL patients (C, data set GSE2113; Mattioli et al., 2005). Increased BRD4 expression is observed in SMM (or MGUS) compared to NPCs (B) and in PCL compared to MM (C) (nonparametric Kruskal-Wallis one-way analysis of variance; p < 0.001 and p = 0.0123, respectively; Dunn's Multiple Comparison post-hoc tests; p < 0.05 in both cases). For each box plot, the whiskers represent minimum and maximum values, the lower and upper boundaries denote the 25th and 75th percentile, respectively, and the horizontal line represents the median value for each group.

(D) Copy number analysis of the BRD4 locus at human chromosome 19p13.1 in primary samples from 254 MM patients. Chromosome 19p amplifications are common in MM. See also Figure S1.
a rationale for the study of BET bromodomains, and BRD4 in particular, as tumor dependencies in MM.

**BET Inhibition with JQ1 Arrests c-Myc Transcriptional Programs**

To test the hypothesis that BET inhibition will specifically abrogate Myc-dependent transcription, we utilized global transcriptional profiling and unbiased gene set enrichment analysis (GSEA). We first characterized the transcriptional consequences of BET inhibition in three MM cell lines with genetically distinct activating lesions at the MYC locus (KMS11, MM.1S, and OPM1) (Dib et al., 2008). Unsupervised hierarchical clustering segregated samples based on treatment assignment, suggesting a common transcriptional consequence in response to JQ1 (Figure 2A). Acute JQ1 treatment did not prompt global, nonspecific transcriptional silencing but instead produced significant changes in a finite number of genes (88 down- and 25 upregulated genes by 2-fold or greater in all three MM lines).

To examine higher-order influences on biological networks regulated by c-Myc, we evaluated four canonical transcriptional signatures of MYC-dependent genes (Kim et al., 2006; Schlosser et al., 2005; Schuhmacher et al., 2001; Zeller et al., 2002). All four signatures were strongly correlated with downregulation of expression by JQ1 (Figure 2B). As a measure of the specificity of this effect, an open-ended enrichment analysis was performed on the entire set of transcription factor target gene signatures available from the Molecular Signatures Database (MSigDB). Gene sets defined by adjacency to Myc-binding motifs were in almost all cases significantly enriched in JQ1-suppressed genes (Figures 2C and 2D). In marked contrast, JQ1 treatment did not exert significant suppression of gene sets for other transcription factors with established roles in MM pathophysiology. Immunoblotting analyses confirmed the JQ1 suppression of c-Myc protein expression in a further expanded panel of Myc-dependent MM cell lines (Figure 3). Despite the intriguing potential effect on E2F transcriptional function and MYB gene expression, JQ1 did not influence E2F or MYB protein abundance through 24 hr of drug exposure (Figure 3F). Together, these data support the general observation that BET inhibition specifically suppresses MYC transcription across MM cells with different genetic lesions affecting the MYC locus and with striking selectivity in comparison to other oncogenic transcription factors with established roles in MM pathophysiology.

**BRD4 Binds IgH Enhancers, Regulating MYC Expression and Function**

Based on the integrated, functional genomic analysis of BET bromodomains in MM (Figure 1), we pursued further mechanistic studies of BRD4. Silencing of BRD4 using directed shRNAs (Figure 3A). Excellent concordance was observed between replicate measurements of expressed genes (Figure 3A). Unsupervised hierarchical clustering segregated replicate data correctly into early- and late-treatment time points. Surprisingly, we observed immediate, progressive, and profound downregulation of MYC transcription itself, a unique finding among all transcripts studied (p < 0.05).

Downregulation of MYC was further confirmed by RT-PCR and immunoblot (Figures 3B and 3C). This effect was BET bromodomain specific, supported by the nearly comparable activity of an analogous BET inhibitor subsequently published by Glaxo SmithKline (iBET) (Figure 1A) (Nicodeme et al., 2010) and the lack of activity of the inactive (-) JQ1 enantiomer, which we previously characterized as structurally incapable of inhibiting BET bromodomains (Filippakopoulos et al., 2010) (Figure 3C). Inhibition of MYC transcription by JQ1 was observed to be dose and time dependent, with peak inhibition at submicromolar concentrations (Figures 3D and 3E). Rapid depletion of chromatin-bound c-Myc was confirmed by nuclear ELISA transcription factor-binding assays (Figure 3F). In contrast, NF-kB and AP-1 chromatin-binding assays failed to reveal any decrease in DNA binding within 8 hr of JQ1 treatment (Figure 3G and Figure S4A).

To assess the breadth of these findings in MM, we expanded gene expression studies to three MM cells with distinct lesions at the MYC locus. MM.1S cells have a complex MYC rearrangement involving an IgH insertion at the breakpoint of a derivative chromosome der3t(3;8); KMS-11 cells have both MYC duplication and inversion; and OPM1 cells feature a der8t(1;18) (Dib et al., 2008). Among 230 genes studied, MYC was one of only four genes downregulated by treatment with JQ1, along with MYB, TYRO3, and TERT (Figure 3H and Figure S4B). Immunoblotting analyses confirmed the JQ1 suppression of c-Myc protein expression in a further expanded panel of Myc-dependent MM cell lines (Figure 3).丝当的肿瘤依赖性MM细胞系的转录表达分析(Bradford et al., 2011) (Nicodeme et al., 2010) and the lack of activity of the inactive (-) JQ1 enantiomer, which we previously characterized as structurally incapable of inhibiting BET bromodomains (Filippakopoulos et al., 2010) (Figure 3C). Inhibition of MYC transcription by JQ1 was observed to be dose and time dependent, with peak inhibition at submicromolar concentrations (Figures 3D and 3E). Rapid depletion of chromatin-bound c-Myc was confirmed by nuclear ELISA transcription factor-binding assays (Figure 3F). In contrast, NF-kB and AP-1 chromatin-binding assays failed to reveal any decrease in DNA binding within 8 hr of JQ1 treatment (Figure 3G and Figure S4A).

To assess the breadth of these findings in MM, we expanded gene expression studies to three MM cells with distinct lesions at the MYC locus. MM.1S cells have a complex MYC rearrangement involving an IgH insertion at the breakpoint of a derivative chromosome der3t(3;8); KMS-11 cells have both MYC duplication and inversion; and OPM1 cells feature a der8t(1;18) (Dib et al., 2008). Among 230 genes studied, MYC was one of only four genes downregulated by treatment with JQ1, along with MYB, TYRO3, and TERT (Figure 3H and Figure S4B). Immunoblotting analyses confirmed the JQ1 suppression of c-Myc protein expression in a further expanded panel of Myc-dependent MM cell lines (Figure 3).丝当的肿瘤依赖性MM细胞系的转录表达分析(Bradford et al., 2011) (Nicodeme et al., 2010) and the lack of activity of the inactive (-) JQ1 enantiomer, which we previously characterized as structurally incapable of inhibiting BET bromodomains (Filippakopoulos et al., 2010) (Figure 3C). Inhibition of MYC transcription by JQ1 was observed to be dose and time dependent, with peak inhibition at submicromolar concentrations (Figures 3D and 3E). Rapid depletion of chromatin-bound c-Myc was confirmed by nuclear ELISA transcription factor-binding assays (Figure 3F). In contrast, NF-kB and AP-1 chromatin-binding assays failed to reveal any decrease in DNA binding within 8 hr of JQ1 treatment (Figure 3G and Figure S4A).

To assess the breadth of these findings in MM, we expanded gene expression studies to three MM cells with distinct lesions at the MYC locus. MM.1S cells have a complex MYC rearrangement involving an IgH insertion at the breakpoint of a derivative chromosome der3t(3;8); KMS-11 cells have both MYC duplication and inversion; and OPM1 cells feature a der8t(1;18) (Dib et al., 2008). Among 230 genes studied, MYC was one of only four genes downregulated by treatment with JQ1, along with MYB, TYRO3, and TERT (Figure 3H and Figure S4B). Immunoblotting analyses confirmed the JQ1 suppression of c-Myc protein expression in a further expanded panel of Myc-dependent MM cell lines (Figure 3).丝当的肿瘤依赖性MM细胞系的转录表达分析(Bradford et al., 2011) (Nicodeme et al., 2010) and the lack of activity of the inactive (-) JQ1 enantiomer, which we previously characterized as structurally incapable of inhibiting BET bromodomains (Filippakopoulos et al., 2010) (Figure 3C). Inhibition of MYC transcription by JQ1 was observed to be dose and time dependent, with peak inhibition at submicromolar concentrations (Figures 3D and 3E). Rapid depletion of chromatin-bound c-Myc was confirmed by nuclear ELISA transcription factor-binding assays (Figure 3F). In contrast, NF-kB and AP-1 chromatin-binding assays failed to reveal any decrease in DNA binding within 8 hr of JQ1 treatment (Figure 3G and Figure S4A).

To assess the breadth of these findings in MM, we expanded gene expression studies to three MM cells with distinct lesions at the MYC locus. MM.1S cells have a complex MYC rearrangement involving an IgH insertion at the breakpoint of a derivative chromosome der3t(3;8); KMS-11 cells have both MYC duplication and inversion; and OPM1 cells feature a der8t(1;18) (Dib et al., 2008). Among 230 genes studied, MYC was one of only four genes downregulated by treatment with JQ1, along with MYB, TYRO3, and TERT (Figure 3H and Figure S4B). Immunoblotting analyses confirmed the JQ1 suppression of c-Myc protein expression in a further expanded panel of Myc-dependent MM cell lines (Figure 3).丝当的肿瘤依赖性MM细胞系的转录表达分析(Bradford et al., 2011) (Nicodeme et al., 2010) and the lack of activity of the inactive (-) JQ1 enantiomer, which we previously characterized as structurally incapable of inhibiting BET bromodomains (Filippakopoulos et al., 2010) (Figure 3C). Inhibition of MYC transcription by JQ1 was observed to be dose and time dependent, with peak inhibition at submicromolar concentrations (Figures 3D and 3E). Rapid depletion of chromatin-bound c-Myc was confirmed by nuclear ELISA transcription factor-binding assays (Figure 3F). In contrast, NF-kB and AP-1 chromatin-binding assays failed to reveal any decrease in DNA binding within 8 hr of JQ1 treatment (Figure 3G and Figure S4A).

To assess the breadth of these findings in MM, we expanded gene expression studies to three MM cells with distinct lesions at the MYC locus. MM.1S cells have a complex MYC rearrangement involving an IgH insertion at the breakpoint of a derivative chromosome der3t(3;8); KMS-11 cells have both MYC duplication and inversion; and OPM1 cells feature a der8t(1;18) (Dib et al., 2008). Among 230 genes studied, MYC was one of only four genes downregulated by treatment with JQ1, along with MYB, TYRO3, and TERT (Figure 3H and Figure S4B). Immunoblotting analyses confirmed the JQ1 suppression of c-Myc protein expression in a further expanded panel of Myc-dependent MM cell lines (Figure 3).丝当的肿瘤依赖性MM细胞系的转录表达分析(Bradford et al., 2011) (Nicodeme et al., 2010) and the lack of activity of the inactive (-) JQ1 enantiomer, which we previously characterized as structurally incapable of inhibiting BET bromodomains (Filippakopoulos et al., 2010) (Figure 3C). Inhibition of MYC transcription by JQ1 was observed to be dose and time dependent, with peak inhibition at submicromolar concentrations (Figures 3D and 3E). Rapid depletion of chromatin-bound c-Myc was confirmed by nuclear ELISA transcription factor-binding assays (Figure 3F). In contrast, NF-kB and AP-1 chromatin-binding assays failed to reveal any decrease in DNA binding within 8 hr of JQ1 treatment (Figure 3G and Figure S4A).
Figure 2. Inhibition of Myc-Dependent Transcription by the JQ1 BET Bromodomain Inhibitor

(A) Heatmap representation of the top 50 down- and upregulated genes (p < 0.001) following JQ1 treatment in MM cell lines. Data are presented row normalized (range from −3 to 3 standard deviations from median in expression). MYC (arrow) is downregulated by JQ1 treatment.

(B) GSEA of four Myc-dependent gene sets (Kim et al., 2006; Schlosser et al., 2005; Schuhmacher et al., 2001; Zeller et al., 2003) in transcriptional profiles of MM cells treated (left) or untreated (right) with JQ1.

(E) Gene Set n NES FDR q-val

<table>
<thead>
<tr>
<th>Gene Set</th>
<th>n</th>
<th>NES</th>
<th>FDR q-val</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCHUHMACHER_MYC_TARGETS_UP</td>
<td>67</td>
<td>-2.61</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>DANG_MYC_TARGETS_UP</td>
<td>127</td>
<td>-2.29</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>SCHLOSSER_MYC_TARGETS_AND_SERUM_RESPONSE_UP</td>
<td>47</td>
<td>-2.29</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>KIM_MYC_AMPLIFICATION_TARGETS_UP</td>
<td>153</td>
<td>-2.27</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>MORIEMU_MYC_LYMPHOMA_BY_ONSET_TIME_UP</td>
<td>96</td>
<td>-1.953</td>
<td>0.0001</td>
</tr>
<tr>
<td>RIBOSOME_BIOGENESIS_AND_ASSEMBLY</td>
<td>14</td>
<td>-1.78</td>
<td>0.0006</td>
</tr>
<tr>
<td>YU_MYC_TARGETS_UP</td>
<td>37</td>
<td>-1.65</td>
<td>0.004</td>
</tr>
<tr>
<td>MOOTHA_GLYCOLYSIS</td>
<td>21</td>
<td>-1.42</td>
<td>0.045</td>
</tr>
<tr>
<td>V$MYCMAX_01</td>
<td>192</td>
<td>-2.078</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>V$MYCMAX_02</td>
<td>200</td>
<td>-1.72</td>
<td>0.0018</td>
</tr>
<tr>
<td>V$NKPPAB65</td>
<td>190</td>
<td>-1.13</td>
<td>NS</td>
</tr>
<tr>
<td>V$AP1_Q4</td>
<td>214</td>
<td>-1.11</td>
<td>NS</td>
</tr>
<tr>
<td>V$STAT3_0</td>
<td>111</td>
<td>-1.04</td>
<td>NS</td>
</tr>
<tr>
<td>V$MYB_Q3</td>
<td>176</td>
<td>-0.92</td>
<td>NS</td>
</tr>
<tr>
<td>V$HSF1_01</td>
<td>197</td>
<td>-0.92</td>
<td>NS</td>
</tr>
<tr>
<td>V$GR_01</td>
<td>155</td>
<td>-0.88</td>
<td>NS</td>
</tr>
<tr>
<td>V$XBP1_01</td>
<td>107</td>
<td>-0.89</td>
<td>NS</td>
</tr>
</tbody>
</table>
validated by RT-PCR analysis (Figure 4A) elicited a marked decrease in MYC transcription (Figure 4B) accompanied by G1 cell-cycle arrest in JQ1-sensitive MM cells (OPM-1) (Figure 4B and Figure S5A). We reasoned that early and sustained JQ1-induced suppression of MYC transcription can be mechanistically explained by physical interaction of BRD4 with regulatory elements influencing MYC expression. Indeed, avid binding of BRD4 to established IgH enhancers was observed by chromatin immunoprecipitation (ChIP) in MM.1S cells (Figure 4C and Figure S6), which harbor an IgH insertion proximal to the MYC transcriptional start site (TSS). BRD4 binding was not observed at five characterized enhancer regions adjacent to the MYC gene (Pomerantz et al., 2009a, 2009b). JQ1 treatment (500 nM) for 24 hr significantly depleted BRD4 binding to IgH enhancers and the TSS, supporting direct regulation of MYC transcription by BET bromodomains and a model whereby BRD4 acts as a coactivator of MYC transcription potentially through long-range interactions with distal enhancer elements. Forced overexpression of c-Myc in MM cells (OPM1) by retroviral infection rescues, in part, the cell-cycle arrest observed with JQ1 treatment (Figures 4D and 4E), arguing that MYC downregulation by JQ1 contributes functionally to cell physiology in MM.

**Therapeutic Implications of BET Inhibition in MM**

Based on this mechanistic rationale, we evaluated the therapeutic opportunity of MYC transcriptional inhibition using established translational models of MM. Antiproliferative activity of JQ1 was assessed using a panel of 25 MM cell lines or isogenic derivative lines (Figure 5A). MM cell proliferation was uniformly inhibited by JQ1 (Figure 5A), including several MM cell lines selected for resistance to FDA-approved agents (dexamethasone-resistant MM.1R and melaphalan-resistant LR5). As expected, MM cells possessing diverse genetic lesions involving MYC (Dib et al., 2008) were comparably sensitive to JQ1 (Figure 5B).

As interaction of MM cells with BMSCs is widely recognized to confer resistance to numerous therapeutic agents (Hideshima et al., 2007; McMillin et al., 2010), we sought to characterize the effect of BMSCs on MM cell sensitivity to BET inhibition. Using compartment-specific bioluminescence imaging assays (CS-BLI), we observed that the sensitivity of MM cell lines to JQ1 is largely unchanged by the presence of HS-5 bone marrow stroma cells (Figure 5C). This pattern of broad activity in MM without evident stroma-mediated chemoresistance has been associated with efficacy of FDA-approved agents bortezomib and lenalidomide.

MM cells were then further phenotyped for Myc-specific biological effects of BET inhibition. Flow cytometry of JQ1-treated MM.1S cells revealed a pronounced decrease in the proportion of cells in S phase, with a concomitant increase in cells arrested in G0/G1 (Figure 6A). Only a modest induction of apoptosis was observed after 48 hr of JQ1 treatment (Figure 6B), in contrast to the nonselective cytotoxic kinase inhibitor staurosporine (Figure S5B). Transcripts previously associated with induction of cellular senescence were enriched following treatment with JQ1, by GSEA (Figure 6C). Experimentally, treatment with JQ1 resulted in pronounced cellular senescence by β-galactosidase staining (Figure 6D). Overall, these phenotypes of arrested proliferation, G1 cell-cycle arrest, and cellular senescence are highly specific to anticipated effects of inhibiting cellular c-Myc function (Wu et al., 2007).

We next extended the study of JQ1 in MM cells to primary MM samples. JQ1 exposure led to a significant reduction in cell viability among the majority of CD138+ patient-derived MM samples tested (Figure 7A). In primary cells isolated from a patient with relapsed/refractory MM, JQ1 treatment ex vivo conferred a time-dependent suppression of c-Myc expression (Figure 7B). In contrast, JQ1 treatment of phytohemaglutinin (PHA)-stimulated peripheral blood mononuclear cells (PBMCs) suppressed PHA-induced proliferation but did not adversely influence cell viability, indicating that the anti-MM effect of JQ1 is not accompanied by a nonspecific, toxic effect on all hematopoietic cells (Figure S7A).

To model the therapeutic effect of JQ1 in vivo, we evaluated anti-MM efficacy in multiple orthotopic models of advanced disease. First, JQ1 was studied using an established, bioluminescent MM model (MM.1S-luc), which recapitulates the clinical sequelae, anatomic distribution of MM lesions, and hallmark bone pathophysiology observed in MM patients (Mitsiades et al., 2004). Tumor-bearing mice were treated with JQ1 administered by intraperitoneal injection (50 mg/kg daily) or vehicle control. JQ1 treatment significantly decreased the burden of disease measured by serial, whole-body, noninvasive bioluminescence imaging (Figures 7C and 7D). Importantly, treatment with JQ1 resulted in a significant prolongation in overall survival compared to vehicle-treated animals (Figure 7E).

As interaction of MM cells with BMSCs is widely recognized to confer resistance to numerous therapeutic agents (Hideshima et al., 2007; McMillin et al., 2010), we sought to characterize the effect of BMSCs on MM cell sensitivity to BET inhibition. Using compartment-specific bioluminescence imaging assays (CS-BLI), we observed that the sensitivity of MM cell lines to JQ1 is largely unchanged by the presence of HS-5 bone marrow stroma cells (Figure 5C). This pattern of broad activity in MM without evident stroma-mediated chemoresistance has been associated with efficacy of FDA-approved agents bortezomib and lenalidomide.

MM cells were then further phenotyped for Myc-specific biological effects of BET inhibition. Flow cytometry of JQ1-treated MM.1S cells revealed a pronounced decrease in the proportion of cells in S phase, with a concomitant increase in cells arrested in G0/G1 (Figure 6A). Only a modest induction of apoptosis was observed after 48 hr of JQ1 treatment (Figure 6B), in contrast to the nonselective cytotoxic kinase inhibitor staurosporine (Figure S5B). Transcripts previously associated with induction of cellular senescence were enriched following treatment with JQ1, by GSEA (Figure 6C). Experimentally, treatment with JQ1 resulted in pronounced cellular senescence by β-galactosidase staining (Figure 6D). Overall, these phenotypes of arrested proliferation, G1 cell-cycle arrest, and cellular senescence are highly specific to anticipated effects of inhibiting cellular c-Myc function (Wu et al., 2007).

We next extended the study of JQ1 in MM cells to primary MM samples. JQ1 exposure led to a significant reduction in cell viability among the majority of CD138+ patient-derived MM samples tested (Figure 7A). In primary cells isolated from a patient with relapsed/refractory MM, JQ1 treatment ex vivo conferred a time-dependent suppression of c-Myc expression (Figure 7B). In contrast, JQ1 treatment of phytohemaglutinin (PHA)-stimulated peripheral blood mononuclear cells (PBMCs) suppressed PHA-induced proliferation but did not adversely influence cell viability, indicating that the anti-MM effect of JQ1 is not accompanied by a nonspecific, toxic effect on all hematopoietic cells (Figure S7A).

To model the therapeutic effect of JQ1 in vivo, we evaluated anti-MM efficacy in multiple orthotopic models of advanced disease. First, JQ1 was studied using an established, bioluminescent MM model (MM.1S-luc), which recapitulates the clinical sequelae, anatomic distribution of MM lesions, and hallmark bone pathophysiology observed in MM patients (Mitsiades et al., 2004). Tumor-bearing mice were treated with JQ1 administered by intraperitoneal injection (50 mg/kg daily) or vehicle control. JQ1 treatment significantly decreased the burden of disease measured by serial, whole-body, noninvasive bioluminescence imaging (Figures 7C and 7D). Importantly, treatment with JQ1 resulted in a significant prolongation in overall survival compared to vehicle-treated animals (Figure 7E). In a second plasmacytoma xenograft that more accurately models extramedullary disease, JQ1 also exhibited a significant disease-modifying response (Figure S7B). Finally, the effect of JQ1 was explored in the genetically engineered model of MYC-dependent MM (Chesi et al., 2008). To date, two Vk*MYC mice with established disease and measurable M-protein have completed 14 days of JQ1 treatment (25 mg/kg daily, adjusted to tolerability). Both animals reveal objective evidence of response assessed by reduction of serum immunoglobulins, including a complete response (CR) in the second animal (Figure 7F and Figure S7C). In this faithful orthotopic and nonproliferative model, the only FDA-approved agents, bortezomib, melphanal and cyclophosphamide, have previously prompted a CR (Chesi et al., 2008). These results establish in vivo proof of concept.
Figure 3. BET Inhibition Suppresses MYC Transcription in MM

(A) Heatmap of cancer-related genes expressed in MM cells (MM.1S), treated with JQ1 (500 nM over 1, 4, and 8 hr). MYC (red) is downregulated by JQ1 in a time-dependent manner, uniquely among all oncogenes studied (230 total). MYC was identified as the only statistically significant decrease in transcription at all four time points analyzed (p < 0.05). See also Figure S3.

(B) Quantitative RT-PCR analysis for MYC levels in JQ1-treated MM.1S cells (500 nM, 0–8 hr). Data are presented as ratio of MYC expression at each time point compared to baseline MYC expression (mean ± SD). Asterisks denote the level of statistical significance (*p < 0.01, **p < 0.0002, ***p < 0.006; paired Student’s t test each relative to t = 0 hr).

(D and E) Immunoblotting analyses of the (D) dose- and (E) time-dependent effects of JQ1 treatment on c-Myc expression in MM.1S cells.

(F and G) Selective depletion of nuclear c-Myc following JQ1 treatment (500 nM) as measured by ELISA-based DNA-binding assays for the activity of (F) c-Myc (depleted after 1–2 hr) and (G) NF-κB family members (unaffected). Data represent mean ± SEM. See also Figure S4.
for the investigational study of BET bromodomain inhibitors in the treatment of MM.

**DISCUSSION**

Despite the centrality of Myc in the pathogenesis of cancer, conventional approaches toward direct Myc inhibition have not proven successful. To date, efforts to target c-Myc have identified only a small number of molecules with low biochemical potency and limited biological characterization (Bidwell et al., 2009; Hammoudeh et al., 2009; Jeong et al., 2010), underscoring both the challenge of targeting c-Myc as well as the enduring need for chemical probes of c-Myc transcriptional function. Considering chromatin as a platform for signal transduction (H) Heatmap of clustered gene expression data from multiplexed measurement (Nanostring) of cancer-associated genes in three human MM cell lines treated with JQ1 or vehicle control. Among 230 genes studied (Figure S4), four genes (MYC, TERT, TYRO3, and MYB) exhibited statistically significant (p < 0.05) downregulation. Replicate expression measurements exhibited high concordance among low and highly expressed genes (Figure S3B).

(I) Immunoblotting study of four MM lines (KMS11, LR5, OPM1, and INA-6) identifies a JQ1-induced decrease in c-Myc expression (500 nM, 24 hr).
we have undertaken to inhibit Myc transcription and function through displacement of chromatin-bound, coactivator proteins using competitive small molecules. Using a first-in-class, small-molecule bromodomain inhibitor developed by our laboratories, JQ1, we validate BET bromodomains as determinants of c-Myc transcription and as therapeutic targets in MM, an ideal model system for the mechanistic and translational study of Myc pathway inhibitors. Most importantly, we illustrate the feasibility of selectively downregulating transcription of MYC itself via the molecular action of a selective, small molecule. The ensuing suppression of c-Myc protein levels, depletion of chromatin-bound c-Myc, and concomitant downregulation of the Myc-dependent transcriptional network lead to growth-inhibitory effects sharing the specificity of phenotypes associated with prior genetic models of Myc inhibition. These are notable observations that distinguish the transcriptional consequences of BET inhibition from other nonselective transcriptional inhibitors, such as actinomycin D, α-amanitin, and flavopiridol.

A compelling finding is the observed, direct interaction of BRD4 with IgH enhancers in MM cells possessing IgH rearrangement into the MYC locus and the depletion of BRD4 binding by JQ1. This suggests BET inhibition as a strategy for targeting other structural rearrangements in cancer involving IgH or other
strong enhancers and has potential implications for the modulation of immunoglobulin gene expression in autoimmune diseases.

An unexpected finding was the pronounced and concordant suppression of multiple E2F-dependent transcriptional signatures. In this instance, E2F1 protein and transcript levels were not affected by BET inhibition, suggesting either an unrecognized function of BET bromodomains in E2F transcriptional complexes or a dominant effect of Myc downregulation causing cell-cycle arrest in G1 leading to silencing of E2F. These observations are also compatible with the known role of Myc and E2F1 as transcriptional collaborators in cell-cycle progression and tumor cell survival (Matsumura et al., 2003; Trimarchi and Lees, 2002).

Insights provided by our study identify rational strategies for combination therapeutic approaches warranting exploration in MM. MYC activation is commonly accompanied by antiapoptotic signaling in human cancer. In MM, constitutive or microenvironment-inducible activation of antiapoptotic Bcl-2 proteins has been reported (Harada et al., 1998; Legartova et al., 2009). Thus, Myc pathway inhibition by JQ1 may demonstrate synergism with targeted proapoptotic agents (e.g., ABT-737) (Oltersdorf et al., 2005; Trudel et al., 2007). Additionally, the selective effect of JQ1 on Myc and E2F1 transcriptional programs provides an opportunity to combine BET inhibitors with pathway-directed antagonists of the NF-κB, STAT3, XBP1, or HSF1 transcriptional programs.

Direct inhibition of c-Myc remains a central challenge in the discipline of ligand discovery. Inhibition of MYC expression and function, demonstrated herein, presents an immediate opportunity to study and translate the concept of c-Myc inhibition more
broadly in human cancer. During the course of this research, a collaborative effort with the laboratories of Christopher Vakoc and Scott Lowe revealed *BRD4* as a tumor dependency in acute myeloid leukemia. Consistent with our observations described here in MM, leukemia cells similarly require BRD4 to sustain MYC expression to enforce aberrant self-renewal (Zuber et al., 2011). Collectively, these findings highlight a broad role for BRD4 in maintaining MYC expression in diverse hematopoietic malignancies and suggest the utility of drug-like BET bromodomain inhibitors as therapeutic agents in these diseases.

Figure 7. Translational Implications of BET Bromodomain Inhibition in MM
(A) JQ1 arrests the proliferation of primary, patient-derived CD138+ MM cells (Cell TiterGlo; Promega). Data represent the mean ± SD of four replicates per condition.
(B) c-Myc immunoblot shows JQ1-induced downregulation in short-term culture of primary, patient-derived MM cells (500 nM, duration as indicated).
(C) Representative whole-body bioluminescence images of SCID-beige mice orthotopically xenografted after intravenous injection with MM.1S-luc+ cells and treated with JQ1 (50 mg/kg IP daily) or vehicle control.
(D) Tumor burden of SCID-beige mice orthotopically xenografted after intravenous injection with MM.1S-luc+ cells. Upon detection of MM lesions diffusely engrafted in the skeleton, mice were randomly assigned to receive JQ1 (50 mg/kg IP daily) or vehicle control. Data are presented as mean ± SEM (n = 10/group).
(E) Survival curves (Kaplan-Meier) of mice with orthotopic diffuse MM lesions show prolongation of overall survival with JQ1 treatment compared to vehicle control (log-rank test, p < 0.0001).
(F) Serum protein electrophoresis to detect monoclonal, tumor-derived immunoglobulin (M-protein) in two MM-bearing Vk*myc* mice before or after 7 and 14 days of JQ1 treatment. JQ1 treatment induced partial and complete responses, respectively, in mouse 1 and mouse 2.

See also Figure S7.
EXPERIMENTAL PROCEDURES

Gene Expression Analysis

MM cells treated with JQ1 (500 nM, 24 h) were processed for transcriptional profiling using Affymetrix Human Gene 1.0 ST microarrays. Expression of individual genes was assessed in the context of dose- and time-ranging experiments by real-time quantitative polymerase chain reaction, multiplexed direct detection (Nanostring), and immunoblotting using antibodies as described in the Extended Experimental Procedures.

Chromatin Immunoprecipitation

ChiP was performed on MM.1S cells cultured in the presence or absence of JQ1 (500 nM, 24 hr). Specific antibodies, detailed methods, and primer sequences for MYC and IgH enhancers, as well as the MYC TSS, are described in the Extended Experimental Procedures.

In Vitro and In Vivo MM Studies

The impact of JQ1 on cell viability, proliferation, and cell cycle was assessed in human MM cells as documented in the Extended Experimental Procedures. In vivo efficacy studies were performed with protocols approved by Institutional Animal Care and Use Committees at the DFCI or Mayo Clinic Arizona. JQ1 was administered by intraperitoneal injection into SCID-beige mice with MM lesions established after subcutaneous or intravenous injections and in nonimmunocompromised tumor-bearing Vk*myc mice. Tumor burden in these models was quantified by caliper measurement, whole-body bioluminescence imaging, and serum protein electrophoresis, respectively, as detailed in the Extended Experimental Procedures.

ACCESSION NUMBERS

Oligonucleotide microarray data have been deposited in the Gene Expression Omnibus under the accession number GSE31365.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Extended Experimental Procedures, seven figures, and one table and can be found with this article online at doi:10.1016/j.cell.2011.08.017.

ACKNOWLEDGMENTS

We are grateful to S. Lowe for sharing unpublished information; A. Azab, D. McMillin, C. Ott, and A. Ruccaro for technical support; E. Fox for microarray data; J. Daley and S. Lazo-Kallanian for flow cytometry; the MMRF, MMRCC, and Broad Institute for establishing the MM Genomics Portal (http://www. broadinstitute.org/mmpg/). This research was supported by NIH: K08CA128972 (J.E.B.), NIH-R01CA650947 (C.S.M.), NIH-R01HG002668 (R.A.Y.); and NIH-R01CA146545 (R.A.Y.); the Chambers Medical Foundation (P.G.R., C.S.M.); the Stepanian Fund for Myeloma Research (P.G.R., C.S.M.); and the Richard J. Corman Foundation (P.G.R., C.S.M.); an American Cancer Society Postdoctoral Fellowship, 120272-PF-11-042-01-DMC (P.B.R.); the Burroughs-Wellcome Fund, the Smith Family Award, the Damon-Runyon Cancer Research Foundation, and the MMRF (to J.E.B.). J.E.B. and C.S.M. designed the study, analyzed data, and prepared the manuscript. J.E.D., H.M.J., and E.K. assayed MM drug sensitivity. J.E.D., H.M.J., and E.K. assayed MM drug sensitivity. J.E.B. and C.S.M. supervised the research. All authors edited the manuscript.

Received: July 19, 2011
Revised: August 13, 2011
Accepted: August 15, 2011
Published online: September 1, 2011

REFERENCES


