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BVES regulates c-Myc stability via PP2A and suppresses colitis-induced tumorigenesis

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Abstract

Objective—*Blood vessel epicardial substance* (BVES) is a tight junction-associated protein that regulates epithelial-mesenchymal states and is underexpressed in epithelial malignancy. However, the functional impact of BVES loss on tumorigenesis is unknown. Here we define the *in vivo* role of BVES in colitis-associated cancer (CAC), its cellular function, and its relevance to inflammatory bowel disease (IBD) patients.

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Design—We determined *BVES* promoter methylation status using an Infinium HumanMethylation450 array screen of patients with ulcerative colitis with and without CAC. We also measured *BVES* mRNA levels in a tissue microarray consisting of normal colons and CAC samples. *Bves*$^{-/-}$ and wild-type mice (controls) were administered azoxymethane (AOM) and dextran sodium sulfate (DSS) to induce tumor formation. Lastly, we utilized a yeast two-hybrid screen to identify BVES interactors and performed mechanistic studies in multiple cell lines to define how BVES reduces c-Myc levels.

Results—*BVES* mRNA was reduced in tumors from patients with CAC via promoter hypermethylation. Importantly, *BVES* promoter hypermethylation was concurrently present in distant non-malignant appearing mucosa. As seen in human patients, *Bves* was underexpressed in experimental inflammatory carcinogenesis, and *Bves*$^{-/-}$ mice had increased tumor multiplicity and degree of dysplasia after AOM/DSS administration. Molecular analysis of *Bves*$^{-/-}$ tumors revealed Wnt activation and increased c-Myc levels. Mechanistically, we identified a new signaling pathway whereby BVES interacts with PR61α, a PP2A regulatory subunit, to mediate c-Myc destruction.

Conclusions—Loss of BVES promotes inflammatory tumorigenesis through dysregulation of Wnt signaling and the oncogene c-Myc. *BVES* promoter methylation status may serve as a CAC biomarker.

Keywords

Cancer; IBD; Ulcerative colitis; Colonic neoplasms; Colorectal cancer

INTRODUCTION

Chronic inflammation promotes the development of colorectal cancer **(CRC)**[1,2]. Patients with inflammatory bowel disease (**IBD**), for example, have an elevated risk of developing CRC[3], particularly those who have extensive disease or long disease duration[4]. Although the pathogenesis of inflammatory carcinogenesis remains unclear, at least one component of malignant degeneration is thought to be disruption of intestinal epithelial function as a consequence of chronic inflammation[5,6]. Indeed, pathologic changes in adherens and tight junction proteins have been described in colitis and colitis-associated cancer (**CAC**)[6–8]. In addition to providing junctional integrity between cells, adherens and tight junctional complexes also transduce extracellular signals to direct intracellular programs (“outside-in” signaling[9]), such as those controlling cellular proliferation and differentiation. For example, E-cadherin can sequester β-catenin at the cell membrane, preventing its nuclear localization and transcriptional activity[10]. Given that dysregulation of junctional proteins commonly occurs in CAC, understanding their function in normal biology may yield clues to how their dysfunction promotes carcinogenesis.

Blood vessel epicardial substance (**BVES/POPDC1**) is a tight junction-associated protein often silenced in carcinomas secondary to promoter hypermethylation[11–13]. Restoring *BVES* expression in CRC cell lines promotes epithelial-like morphology and decreases proliferation, migration, invasion, xenograft tumor growth, and metastasis, together indicating broad regulatory capabilities[11]. Conversely, knockdown of *BVES* in epithelial-

like cells induces a mesenchymal-like phenotype characterized by increased proliferation, altered morphology, and disorganized cell-cell contacts[11]. Yet how BVES regulates these phenotypes is incompletely understood. Indeed, while several BVES interacting proteins have been identified[11], their known functions do not explain fully the role of BVES in maintaining epithelial phenotypes. Moreover, how BVES contributes to tumor development has not been tested using genetic approaches.

The transcription factor c-Myc is commonly overexpressed in cancer[14,15] and regulates proliferation, differentiation, apoptosis, and epithelial-to-mesenchymal transition[16]. In mouse models of sporadic CRC, decreased c-Myc levels reduce *Apc*-driven tumorigenesis[17]. In IBD, c-Myc is overexpressed in both inflamed tissues and CAC tumors[18], and network analysis of CAC samples indicated that c-Myc dysregulation functionally contributes to CAC progression[19]. c-Myc levels are also increased in experimental models of inflammatory carcinogenesis, such as the azoxymethane (**AOM**)/dextran sodium sulfate (**DSS**) mouse model of CAC[20]. Yet the processes responsible for c-Myc dysregulation in inflammatory carcinogenesis remain unidentified. To date, a complex network of proteins—including protein phosphatase 2A (PP2A), Axin1, and GSK3β—has been identified that regulates c-Myc protein levels by modifying the phosphorylation status of c-Myc at two residues, threonine 58 (**T58**) and serine 62 (**S62**)[21]. Ubiquitylation of c-Myc is initiated by phosphorylation at T58, leading to its ultimate degradation. Given the prominent role of c-Myc in driving oncogenic programs, understanding mechanisms that control PP2A dephosphorylation of c-Myc may identify new therapeutic targets in inflammatory carcinogenesis.

Here we report that BVES is an important regulator of inflammatory carcinogenesis programs and promotes c-Myc degradation through an interaction with the PR61α-PP2A complex. We observed that *BVES* is reduced in human CAC samples, and further that the *BVES* promoter was hypermethylated within the tumors and at distant unaffected mucosa, suggesting a field effect. Using the AOM/DSS inflammatory carcinogenesis model, we determined that *Bves*$^{-/-}$ mice demonstrate greater tumor incidence and multiplicity as well as a higher degree of dysplasia and intratumoral proliferation. Furthermore, molecular analysis of *Bves*$^{-/-}$ tumors revealed increased c-Myc protein and signaling activity. c-Myc protein was also elevated in intestinal crypts from *Bves*$^{-/-}$ mice. In line with *in vivo* results, knockdown of BVES *in vitro* increased c-Myc stability and consequently increased expression of key c-Myc targets *ODC* and *CAD*. Conversely, BVES overexpression reduced c-Myc stability and increased c-Myc ubiquitylation. Using a yeast two-hybrid (**Y2H**) screen, we identified PR61α, the PP2A regulatory subunit critical for c-Myc degradation, as a BVES-interacting protein, and show that this interaction is required for BVES to modulate cellular c-Myc levels. Thus, we demonstrate that BVES coordinates PR61α-containing PP2A phosphatase complexes to restrict c-Myc protein levels and that BVES is a key suppressor of inflammatory carcinogenesis whose promoter methylation status may define patients with ulcerative colitis (**UC**) at risk for colon cancer.

MATERIALS AND METHODS

Mice, treatments, and analysis

AOM and DSS were prepared as previously described[22]. *Bves*$^{-/-}$ mice have been previously described[23]. Detailed protocols can be found in the **Supplementary Materials and Methods Section**.

BVES promoter methylation analysis

Tissue samples were obtained from colectomy specimens from individuals without UC, individuals with UC but without dysplasia or cancer, and UC patients with high-grade dysplasia and/or colon cancer. Clinical information is described in online **supplementary table 1.** Detailed protocols regarding epithelial isolation, methylation array, and pyrosequencing can be found in the **Supplementary Materials and Methods Section.**

See **Supplementary Materials and Methods** for detailed methods regarding cell culture experiments, RNA scope, promoter methylation analyses, and mouse analysis.

RESULTS

BVES is downregulated and its promoter is hypermethylated in CAC

As *BVES* is underexpressed via promoter hypermethylation in CRC[11], we asked whether the *BVES* promoter was also hypermethylated in CAC. Therefore, we analyzed *BVES* methylation status in an Infinium HumanMethylation450 array screen of IBD samples. The samples consisted of control patients (**Control—No UC**), patients with UC who did not have cancer (**UC—no HGD/CAC**), and two different types of samples from patients with UC who had colon cancer: the remote, non-malignant tissue (**UC— concurrent HGD/CAC**) and tissue with high-grade dysplasia and/or cancer (**HGD/CAC**). These analyses demonstrated that the *BVES* promoter was unmethylated in the controls–No UC (0.1% + 0.016%), moderately methylated in UC–no HGD/CAC (16% + 4.7%), and hypermethylated in the HGD/CAC among patients with colitis-associated carcinoma (HGD/CAC, 53% + 2.6%) (**figure 1A**). Furthermore, remote nonneoplastic, mucosal samples (UC-Concurrent HGD/CAC) from the same patients who had CAC (HGD/CAC) were hypermethylated (50% + 2.6%) to a similar degree as that observed in cancerous tissue. Interestingly, these results suggest that *BVES* promoter methylation may represent a field effect in CAC and that *BVES* promoter methylation status may identify UC patients with concurrent malignancy. To confirm the results derived from the HM450 methylation array studies, we pyrosequenced the *BVES* promoter in the same samples and again demonstrated low levels of methylation in the UC—no HGD/CAC cases, and higher methylation in both the UC—concurrent HGD/CAC and HGD/CAC cases (**figure 1B**).

It is possible that *BVES* promoter methylation, while increased, may not be sufficient to silence its expression. To determine whether *BVES* promoter methylation indeed reduced its transcription, we tested whether *BVES* mRNA was downregulated in CAC using high resolution *in situ* hybridization (RNAScope[24]) in a tissue microarray consisting of normal, UC, and CAC samples. *BVES* mRNA levels were low, but consistently present in normal

colonic epithelial cells (**figure 1C**). In UC and CAC samples, however, *BVES* message was rarely detected and quantification of epithelial staining indicated a 5-fold decrease ($p<0.001$). Taken together, *BVES* RNA expression is downregulated in both UC and CAC, most likely due to promoter hypermethylation. Furthermore, as the *BVES* promoter is hypermethylated in both tumor and non-malignant mucosa in patients with CAC, *BVES* promoter methylation may serve as a biomarker associated with dysplasia or neoplasia in patients with IBD.

Bves loss promotes CAC development—While *BVES* underexpression was consistently observed in human CAC, these studies do not establish whether BVES loss actively promotes tumorigenesis. Therefore, we used mouse genetic approaches combined with the AOM/DSS model (**figure 2A**) to determine if BVES loss contributed to inflammatory tumorigenesis. While *Bves* was expressed at baseline in the murine colon at both the RNA and protein levels (see online **supplementary figure 1**), transcriptome profiling of AOM/DSS-induced tumors in WT mice showed a 5-fold decrease in *Bves* transcripts (**figure 2B**), mirroring the results observed in human CAC. As expected, we also observed changes in other tight junction constituents, supporting previous reports of tight junctional dysregulation in colitis and CAC[25]. We confirmed that *Bves* message was decreased in AOM/DSS tumor tissue by qPCR in an independent sample set (**figure 2B**). Interestingly, *Bves* message also decreased in AOM/DSS treated non-malignant tissue compared to normal colons (**figure 2B**), again suggesting a field effect in inflammatory carcinogenesis. As a result, we hypothesized that complete loss of *Bves* might promote inflammatory carcinogenesis.

To test the effect of *Bves* loss in CAC, we compared WT and $Bves^{-/-}$ mice subjected to the same inflammatory carcinogenesis protocol. We first observed that $Bves^{-/-}$ mice lost a greater fraction of body weight compared to WT mice, most notably during cycle 3 (**figure 2C**), suggesting increased sensitivity to AOM/DSS treatment. Indeed, endoscopy one-week prior to sacrifice demonstrated increased tumor multiplicity in $Bves^{-/-}$ mice (**figure 2D)** and this was confirmed at necropsy where we observed 100% tumor penetrance in $Bves^{-/-}$ mice compared to 60% in WT mice (**figure 2E**). $Bves^{-/-}$ mice also demonstrated increased tumor multiplicity (6.5 ± 0.6 tumors per $Bves^{-/-}$ mouse vs. 2.2 ± 0.5 tumors per WT mouse, $p<0.001$), and tumor size (**figure 2E**). Furthermore, $Bves^{-/-}$ tumors exhibit more advanced dysplasia compared to WT tumors (**figure 2F**). Control mice treated with three cycles of DSS-only or a single AOM injection did not develop tumors during this time-frame (data not shown). Taken together, these results suggest that BVES underexpression in CAC functionally contributes to inflammatory carcinogenesis.

Increased proliferation and enhanced Wnt activation in $Bves^{-/-}$ tumors

To identify BVES-directed mechanisms responsible for modifying tumorigenesis, we examined proliferation and apoptosis in the tumors of AOM/DSS treated $Bves^{-/-}$ mice. Proliferation, as measured by phospho-histone H3 staining, was increased in $Bves^{-/-}$ tumors (**figure 3A)**. Conversely, staining for cleaved caspase-3 indicated no difference in intratumoral apoptosis between $Bves^{-/-}$ and WT mice (**see online supplementary figure 2**). As Wnt activation can drive proliferation, we postulated that Wnt signaling might be

perturbed in *Bves*$^{-/-}$ tumors. β-catenin dysregulation is a key indicator of hyperactive Wnt signaling[26], and β-catenin is also a mutational target in DMH/DSS inflammatory carcinogenesis, resulting in increased levels and altered subcellular distribution[27]. Therefore, we analyzed β-catenin by immunohistochemistry and observed excessive cytoplasmic and nuclear β-catenin localization in *Bves*$^{-/-}$ tumors compared to WT tumors(**figure 3B**). While these results suggested hyperactive Wnt signaling in *Bves*$^{-/-}$ tumors, we confirmed this by RNA-seq analysis, which indicated upregulation of established Wnt targets, such as *Mmp7, Wisp2,* and *Rspo4* (**figure 3C**), in *Bves*$^{-/-}$ tumors. Ingenuity Pathway Analysis (**IPA**)[28] of the RNA-seq data set also indicated hyperactive Wnt networks, such as β-*catenin* and *Tcf*. Finally, immunoblotting demonstrated greater expression of cyclin D1 and c-jun, two well-characterized Wnt target genes[29,30], in *Bves*$^{-/-}$ tumors (**figure 3D**). While previous experiments demonstrated that BVES could regulate Wnt signaling using *in vitro*, cell-based assays[11], these findings provide the first *in vivo* and genetic evidence supporting the hypothesis that BVES regulates Wnt activity.

BVES regulates c-Myc degradation

As c-Myc is a *bona-fide* Wnt transcriptional target[17], has been identified as a potential biomarker in patients with IBD at risk for CAC[19], and is overexpressed in AOM/DSS tumors[20], we postulated that c-Myc was dysregulated in *Bves*$^{-/-}$ tumors. Indeed, IPA analysis of intratumoral transcriptomes identified causal dysregulation[28] of c-Myc networks (**see online supplementary figure 3A**). While analysis of RNA-seq datasets showed only a modest increase in c-Myc transcripts in *Bves*$^{-/-}$ tumors compared to WT tumors (see online **supplementary figure 3B**), immunohistochemical staining for c-Myc demonstrated an increase in both total c-Myc protein (**figure 4A**) and transcriptionally active, phosphorylated serine 62 c-Myc species in *Bves*$^{-/-}$ tumors (see online **supplementary figure 4**). Interestingly, immunoblotting in tumor-adjacent mucosa also showed higher c-Myc levels in *Bves*$^{-/-}$ colons, which suggested c-Myc was increased prior to tumor formation and that BVES might regulate c-Myc levels in the gut at baseline (**figure 4B**). To test this, we isolated crypts from untreated *Bves*$^{-/-}$ and WT mice and observed greater c-Myc protein in *Bves*$^{-/-}$ samples (**figure 4C**). Consistent with elevated c-Myc, qPCR for *Ornithine decarboxylase (Odc)*, a c-Myc transcriptional target, indicated a 4-fold increase in *Bves*$^{-/-}$ colons (see online **supplementary figure 5**). We also observed increased mRNA of c-Myc targets *Odc* and *E2f transcription factor 2 (E2f2)* (**figure 4D**) in “mini-gut” 3D cultures, demonstrating that BVES regulation of c-Myc activity was epithelial cell-autonomous.

As we observed increased c-Myc protein in *Bves*$^{-/-}$ tumors, we postulated that BVES could regulate c-Myc protein stability. Three cell lines—HEK 293T (non-malignant cell line), Caco2 (CRC cell line that can form a polarized epithelium), and HCE (Human Corneal Epithelial)—which all express BVES **(supplementary figure 6)**[11] were used for BVES knockdown experiments. In all three cell lines, *BVES* RNAi increased c-Myc protein levels (**figure 5A and supplementary figure 7**). In addition to increasing total c-Myc protein, we also observed that *BVES* knockdown reduced T58 phosphorylation, a key post-translational modification which signals for c-Myc degradation by the ubiquitin-proteasome system (**figure 5A**). This increase in c-Myc was functionally relevant as transcript levels of c-Myc targets *ODC* and Carbamoyl-Phosphate Synthetase 2 Aspartate Transcarbamylase and

Dihydroorotase (*CAD*) were increased with *BVES* knockdown (**figure 5B**). Furthermore, knockdown of BVES doubled c-Myc half-life compared to non-targeting control samples (**figure 5C**). Conversely, overexpressing BVES reduced c-Myc protein levels, increased T58 c-Myc species (**figure 5D**), dampened c-Myc transcriptional activation of the c-Myc responsive E2F2 reporter (**see online supplementary figure 8**), and decreased c-Myc protein half-life (**figure 5E**, lower panel). We then tested whether BVES could regulate c-Myc ubiquitylation, a central post-translational event targeting its destruction. Indeed, by overexpressing BVES we observed increased c-Myc polyubiquitylation (**figure 5F**).Moreover, inhibiting the proteasome using MG132 blocked BVES-induced reduction of c-Myc (**figure 5F**). Hence, our results suggest that BVES promotes the post-translational degradation of c-Myc.

BVES interacts with PR61α, PP2Ac, and c-Myc

To identify a molecular mechanism by which BVES orchestrates c-Myc degradation, we conducted a Y2H screen to define the BVES interactome. Characterization of this interactome using the PANTHER (Protein ANalysis THrough Evolutionary Relationships) Classification System[31] identified a number of biologic processes influenced by BVES (**figure 6A)**. Interestingly, the screen identified that BVES interacted with four of the five members of the B' family of PP2A regulatory subunits (PPP2R5A, PPP2R5B, PPP2R5D, and PPP2R5E). PPP2R5A, also known as PR61α, is a key regulator of PP2A mediated c-Myc dephosphorylation. PR61α directs the heterotrimeric PP2A complex, consisting of a regulatory, catalytic, and structural subunit, to associate with doubly phosphorylated (T58/S62) c-Myc and dephosphorylate S62, resulting in increased levels of monophosphorylated T58 c-Myc species, which signals c-Myc to be degraded by the proteaosome[32].

The BVES:PR61α interaction was then confirmed by directed Y2H (**figure 6A**) and by exogenous and endogenous co-immunoprecipitation in HEK 293T cells (**figure 6B and C)**. If BVES were interacting with PR61α to promote c-Myc degradation, we hypothesized that BVES would complex with both the PP2A catalytic subunit (PP2Ac) and c-Myc, which we then demonstrated by co-immunoprecipitation (figure 6D and E and see online supplementary figure 9). We further used the proximity ligation assay (PLA) and confirmed interaction of both exogenous and endogenous BVES with endogenous PR61α and c-Myc (**figure 6F).** Overall, these data indicate that BVES complexes with c-Myc, PR61α, and the PP2A catalytic subunit.

BVES is essential for PR61α-mediated c-Myc degradation

PP2A dephosphorylation of S62 requires c-Myc to be phosphorylated at residue T58[33]. If BVES reduces c-Myc through PP2A, we reasoned c-Myc^{T58A}, a c-Myc mutant resistant to T58 phosphorylation, would escape BVES-induced degradation. Indeed, BVES expression consistently reduced c-Myc^{WT} but had no effect on c-Myc^{T58A} (**figure 7A**). We next hypothesized that knockdown of BVES would ablate PR61α-PP2A induced c-Myc degradation. Overexpression of PR61α reduced c-Myc protein subtly but consistently as previously reported[32] (**figure 7B**; compare lane 1 and 3). Knocking down BVES, however, rescued PR61α-induced degradation (**figure 7B**; compare lanes 3 and 4). We then tested whether BVES could enhance PR61α-mediated c-Myc degradation, and indeed,

overexpression of BVES and PR61α substantially reduced c-Myc protein compared to PR61α or BVES alone (**figure 7C**; compare lane 4 to 2 or 3).

We then sought to determine whether BVES requires PR61α to degrade c-Myc. For these experiments we first mapped the BVES:PR61α interaction domain by serial deletions to the carboxy-terminus of BVES. Deleting the carboxy-terminal 30 residues, but not the last 15 residues, disrupted the BVES:PR61α interaction as demonstrated by Y2H and by co-IP, thus mapping the interaction domain to residues 330-345 (**figure 7D**). Importantly, this uncoupling mutant (BVES-330) demonstrated reduced affinity for c-Myc (**figure 7E**) and was unable to reduce c-Myc levels (**figure 7F**), indicating BVES indeed requires interaction with PR61α to regulate c-Myc. Overall, our results demonstrate that BVES, through PR61α, promotes c-Myc dephosphorylation, destabilization, and destruction, and thus provides mechanistic insight into one manner by which BVES may contribute to inflammatory carcinogenesis.

DISCUSSION

We, and others, have shown that BVES is underexpressed in gastrointestinal cancers and that restoration of BVES in cancer cell lines induces epithelial features. Here we provide the first genetic evidence that BVES modifies cancer phenotypes, as we demonstrate that mice lacking *Bves* have increased tumor multiplicity and dysplasia after establishment of inflammatory carcinogenesis. Further, we show $Bves^{-/-}$ tumors have increased c-Myc protein resulting in activation of c-Myc regulated networks. Moreover, we identify that BVES interacts with PR61α, a key regulatory subunit of the PP2A phosphatase complex, and promotes PP2A-mediated c-Myc dephosphorylation leading to c-Myc degradation. Uncoupling the BVES:PR61α interaction blocks BVES-dependent reduction of cellular c-Myc levels. To our knowledge, this is the first junctional-associated protein identified that regulates post-translational c-Myc status. The potential clinical relevance is demonstrated as we observed that *BVES* is downregulated in CAC likely secondary to promoter methylation. However, perhaps more importantly, we establish that the *BVES* promoter is also aberrantly methylated in distant, normal appearing tissues in patients with CAC/HGD—suggesting a field effect. Thus, our findings not only reveal that deletion of BVES promotes CAC, but also that *BVES* promoter methylation status may be a clinically important surrogate marker of colitis-associated dysplasia or CAC in IBD patients.

Chronic colitis has been shown to accelerate genome-wide methylation changes[34]; it has been hypothesized that this greater rate of methylation contributes to the increased cancer risk in patients with colitis by silencing tumor suppressors. Understanding how methylation broadly affects inflammatory tumorigenesis is important to design therapies and screening strategies for IBD patients. Our report specifically identifies that the *BVES* promoter is hypermethylated in UC patients who have CAC. Interestingly, *BVES* promoter hypermethylation is observed not only in the cancerous tissue, but also in the non-malignant mucosa in these patients. Currently, the standard method of cancer screening in IBD patients, who are at up to a 10-fold elevated risk of developing CAC[1], is surveillance colonoscopy performed with the hope that cancer will be detected at an early, treatable stage. Yet the detection of neoplasia in the colon can be challenging in individuals with IBD, as the

lesions are frequently flat and difficult to detect in a background of acute and chronic inflammatory changes. Our data suggest that aberrant *BVES* promoter methylation may be a useful biomarker for the presence of CAC, or even dysplasia, and that measuring *BVES* promoter methylation status could serve as a clinically useful tool to identify patients at risk for colon dysplasia or cancer.

While the molecular pathogenesis of CAC remains incompletely understood, recent work has shown the importance of NF-κB signaling[35], the intestinal microbiota[36], the tumor microenvironment[37], and the innate immune system[38] in regulating inflammatory tumorigenesis. A growing body of evidence also supports the important role of epithelial junctional constituents in inflammation and CRC. For example, mice expressing a dominant negative N-cadherin display disrupted adherens junctions and develop severe inflammation and colitis-associated dysplasia[39]. Likewise, knocking out *Junctional adhesion molecule* (*Jam-A*) results in a dramatic increase in susceptibility to DSS-induced colitis[8]. Here we show that deletion of *Bves*, a tight junction-associated protein, augments inflammatory carcinogenesis. Indeed, loss of BVES appears to increase tumor initiation and progression. We postulate that this is likely due to dual regulation of Wnt signaling and c-Myc protein degradation. Our results further strengthen the concept that junctional constituents are important regulators of colitis-induced tumor initiation and progression.

In the last decade, BVES has been shown to regulate a variety of cellular processes. For example, a Y2H screen of a mouse heart library identified an interaction between BVES and GEFT, a guanine nucleotide exchange factor[40]. Indeed, it was shown that expression of BVES modulated cell shape and locomotion, thus linking BVES to Rho-family GTPase signaling[40]. BVES has also been shown, via an interaction with ZO-1, to regulate GEF-H1-mediated RhoA activity[11]. More recently, it was reported that BVES plays a regulatory role in cardiac pacemaking through binding of cAMP and interacting with potassium channel TREK-1[41]. Further, BVES interacts with CAV3, a caveolin expressed in the muscle tissue, and cardiac myocytes in *Bves*$^{-/-}$ mice have altered calveolar number and size[42]. Thus, BVES, through scaffolding with protein complexes, regulates a wide variety of basic, yet essential, cellular processes.

Our results now expand the known regulatory roles of BVES to include maintaining appropriate c-Myc protein levels. We show that BVES, through its interaction with the PR61α-containing PP2A phosphatase complex, can promote c-Myc degradation and that silencing BVES prevents PR61α-induced degradation of c-Myc. Moreover, mutating BVES so that it is unable to associate with PR61α renders BVES unable to initiate c-Myc destruction. The post-translational regulation of c-Myc requires coordination of numerous proteins to modify its phosphorylation and ubiquitylation status[21]. Precisely how BVES coordinates the PR61α-PP2A complex remains to be understood, but given that analysis of BVES structure shows no apparent enzymatic motifs in BVES, it is likely that BVES acts as a scaffold allowing for complex formation, similar to AXIN1[21]. Interestingly, in addition to the membranous staining of the BVES:PR61α complex, there also appears to be peri-nuclear and cytoplasmic localization (**figure 6F**), which is consistent with previous reports describing the dynamic subcellular localization of BVES and its family members[43]. The PP2A family has been associated with tight junctional complexes regulating cellular

permeability, but their exact role remains controversial[44]. BVES may bridge PP2A complexes to tight junctions and our report adds a new molecular mechanism for "outside-in" signaling in the epithelium.

Because c-Myc regulates thousands of genes, even subtle changes in c-Myc expression can have profound effects on cellular transcriptomes that promote tumorigenesis[45]. Indeed, strict regulation of c-Myc is an important component of homeostasis, and this is particularly true in the intestine. Acute expression of c-Myc, for example, dramatically expands the intestinal crypts and results in loss of differentiated cells[46]. Moreover, it has been shown that c-Myc is essential for *Apc*-mediated intestinal tumorigenesis[17]. Thus, BVES may serve as an important suppressor of inflammatory tumorigenesis via attenuating excessive c-Myc levels. More broadly, BVES could act as a regulator of c-Myc in a variety of tissues, as BVES is expressed in most epithelial tissues, such as lung, stomach, and breast, and its downregulation or promoter hypermethylation has been documented in diverse epithelium[11–13].

Taking our data together, one can envision a model in which chronic inflammation leads to *BVES* promoter hypermethylation, resulting in suppression of *BVES* transcription and reduced cellular protein levels. Loss of BVES impairs PR61α directed PP2A dephosphorylation of c-Myc, thus favoring increased cellular pools of c-Myc, a potent oncogene, likely, in cooperation with other oncogenic events, contributing to tumor progression (**figure 8**).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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SUMMARY BOX

What is already known about this subject?

- ➢ Patients with ulcerative colitis are at greater risk for developing colon cancer.
- ➢ Blood vessel epicardial substance (BVES) is a tight junction protein that regulates epithelial-to-mesenchymal transition *in vitro.*
- ➢ c-Myc is an oncogene overexpressed in 50% of all malignancies, including colitis-associated cancer (CAC).
- ➢ **What are the new findings?**
- ➢ *BVES* promoter hypermethylation is present in CAC and distant uninvolved mucosa.
- ➢ *BVES* is underexpressed in patients with CAC compared to normal colonic tissue.
- ➢ Deletion of *Bves* promotes colitis-associated tumor multiplicity and dysplasia.
- ➢ BVES directs the PR61α-PP2A complex to target c-Myc for proteasomal destruction.

How might it impact on clinical practice in the foreseeable future?

- ➢ *BVES* promoter hypermethylation status is a potential biomarker to identify UC patients at risk for cancer.
- ➢ Our studies demonstrate a new mechanism for regulation of c-Myc, an oncogene that is dysregulated in numerous malignancies.
- ➢ BVES plays a key role in maintaining the integrity of the colonic mucosa and protecting from inflammatory carcinogenesis, and may represent a therapeutic target in CAC.

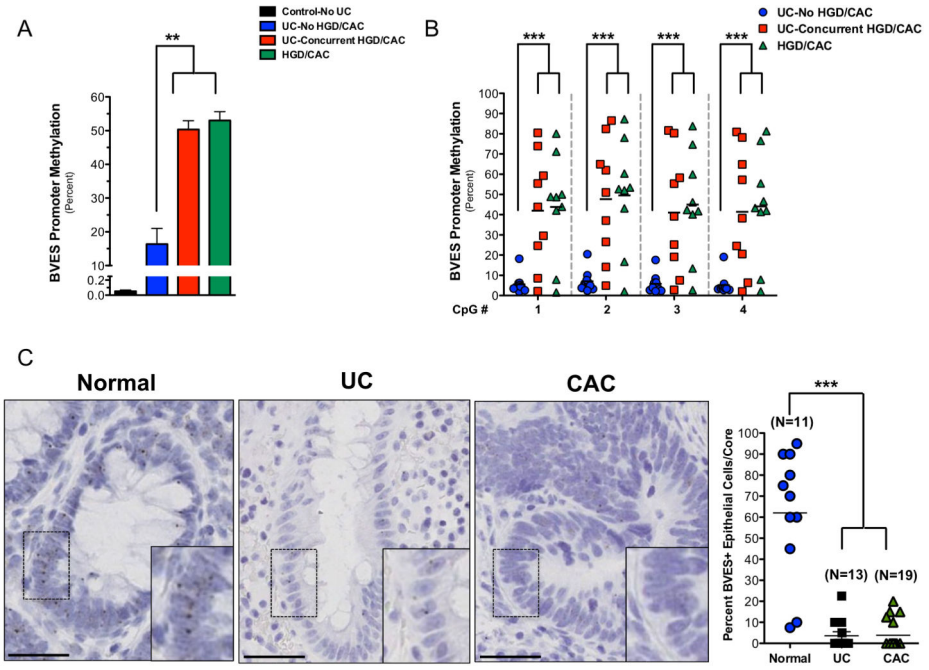

Figure 1. A field effect of *BVES* promoter hypermethylation in colitis-associated cancer

(A) Average *BVES* promoter methylation status in the indicated sample from the Infinium HumanMethylation 450 Array. Methylation was measured in four sample types: colon epithelia from patients who did not have UC (Control—No UC); colon epithelia from UC patients who did not have dysplasia or carcinoma (UC—no HGD/CAC); non-malignant colon epithelia from UC patients (UC—concurrent HGD/CAC) and malignant colon epithelia (HGD/CAC) from UC patients who had dysplasia/carcinoma. Control—No UC, n=17; UC—no HGD/CAC, n=11; UC—concurrent HGD/CAC, n=10; HGD/CAC, n=10. **p<0.01.

(B) Pyrosequencing at four sequential CpG dinucleotides in the *BVES* promoter. Each shape represents a separate individual, with mean methylation values depicted with black bars. ***p<0.001.

(C) Representative images of high-resolution in situ (RNAscope™) analysis of *BVES* message in normal colons (n=11), UC (n=13), and CAC (n=19). Right: Quantification of *BVES* expressing epithelial cells per tissue microarray core. Size standard=50 microns. ***p<0.001

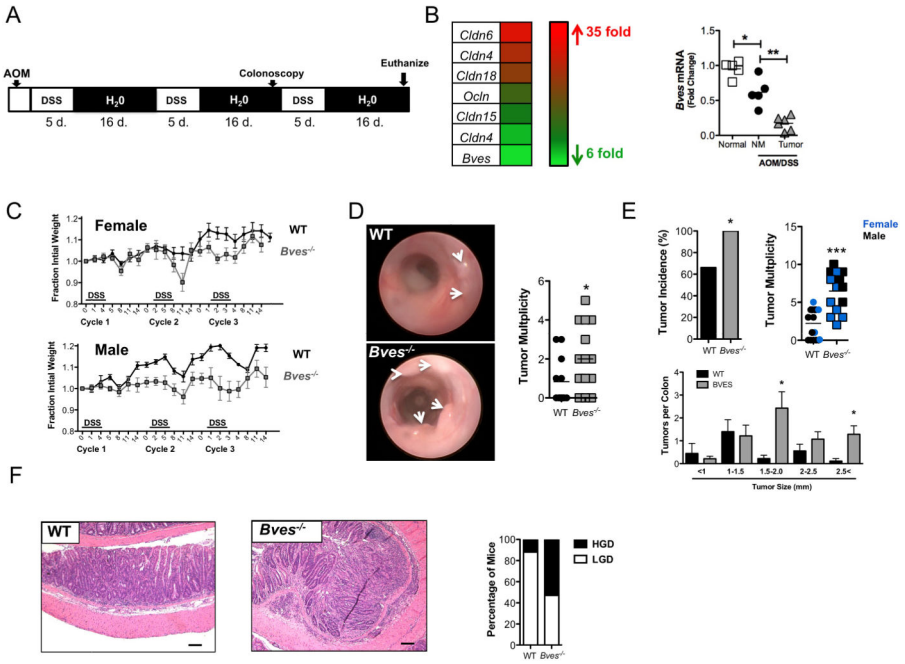

Figure 2. BVES modifies inflammatory carcinogenesis

(A) Schematic of AOM/DSS protocol and timeline. Mice were injected with 7.5 mg/kg of AOM and treated with 2.5% DSS at the indicated time.

(B) Left: Heat map of RNA-seq data derived from WT colons (n=3) and WT AOM/DSS tumors (n=3). Red indicates genes increased and green indicates genes decreased in tumors compared to normal colon. Right: qPCR of *Bves* message levels in normal colons (Normal, n=5), non-malignant AOM/DSS treated colon (NM, n=5) and AOM/DSS tumor (Tumor, n=6). Tissue harvested from WT mice after AOM/DSS treatment. ***p<0.001.

(C) Weights of *Bves*$^{-/-}$ and WT mice during AOM/DSS treatment. Weights are presented as fraction of initial weight. *Bves*$^{-/-}$ (male: n=8, female: n=7) and WT (male: n=5, female: n=10). *p<0.05, ***p<0.01, ***p<0.001.

(D) Representative colonoscopy images of WT and *Bves*$^{-/-}$ colons after the second cycle of DSS treatment. Right: Quantification of tumor multiplicity by endoscopy assessment.

(E) Tumor incidence, multiplicity, and size distribution at necropsy in WT and *Bves*$^{-/-}$ mice. Blue = female mice, black = male mice.*p<0.05, ***p<0.001.

(F) Left: Representative H&E stained sections demonstrating the histologic features of WT and *Bves*$^{-/-}$ tumors. Size standard=100 microns. Right: Blinded histological scoring of degree of dysplasia of tumors from WT and *Bves*$^{-/-}$ mice. Graph represents percentage of mice with intratumoral low or high-grade dysplasia.

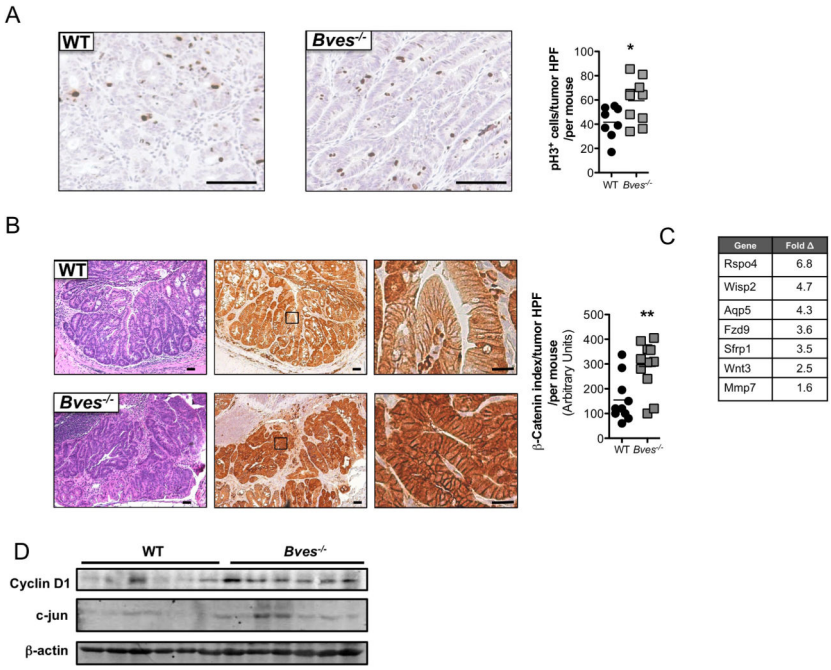

Figure 3. Dysregulated Wnt signaling in *Bves*$^{-/-}$ tumors

(A) Left: Representative images of phospho-histone H3 (pH3) immunohistochemistry in WT and *Bves*$^{-/-}$ tumors. Size standard=50 microns. Right: Quantification of pH3 positive cells per tumor high power field (HPF). Data is presented as the mean number of positive cells per tumor HPF per mouse. At least five HPF per mouse were scored. Student's t test, *$p<0.05$.

(B) Left: H&E stained sections, size standard=50 microns. Middle: Representative images of β-catenin immunohistochemistry, low magnification, size standard=50 microns. Right: β-catenin immunohistochemistry, high magnification, size standard=20 microns. Far right: Quantification of intratumoral β-catenin immunohistochemistry. An index was employed to quantify extent of nuclear and cytoplasmic β-catenin staining. This index is generated by multiplying the staining intensity (on a scale of 100-500) by percentage of the cells demonstrating nuclear staining. For example, a score of 500 indicates a field that demonstrated very intense nuclear β-catenin stain while a score of 100 indicates a field that has weak nuclear β-catenin staining. Data is presented as the mean score per tumor HPF per mouse. At least five HPF per mouse were scored.

(C) Wnt target genes upregulated in *Bves*$^{-/-}$ tumors identified in RNA-seq dataset (WT, n=3; *Bves*$^{-/-}$, n=3).

(D) Immunoblot of Cyclin D1 and c-jun in *Bves*$^{-/-}$ and WT tumors. β-actin was used as a loading control.

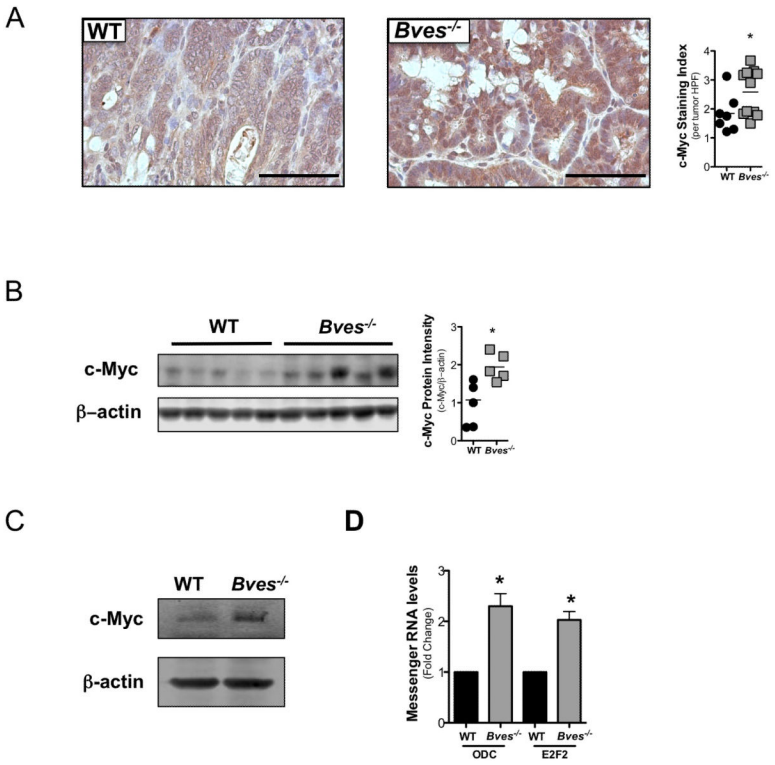

Figure 4. c-Myc signaling is dysregulated in Bves$^{-/-}$ mice in inflammatory carcinogenesis

(A) Left: Representative images of immunohistochemistry for intratumoral c-Myc. Right: quantification of c-Myc positive cells per tumor high power field (HPF). HPFs were scored according to an index from 1-4 (a score of 1 denotes less than 25% of positive cells per HPF; a score of 2 denotes 25-50%; a score of 3 denotes 50-75%; a score of 4 denotes 80-100%). Data is presented as the mean score per tumor HPF per mouse. At least five HPF per mouse were scored. Student's t test, *p<0.05. Size standard=50 microns

(B) Immunoblot of c-Myc in WT and *Bves*$^{-/-}$ normal adjacent colons. Blots were imaged using the LiCor Odyssey system and quantified using Image Studio analysis. Student's t test, p<0.05.

(C) Immunoblot of c-Myc in WT (n=3) and *Bves*$^{-/-}$ (n=3) intestinal crypts.

(D) qPCR for *Odc* and *E2f2* in enteroid cultures Student's t test, *p<0.05.

In all western blots, β-actin served as loading control.

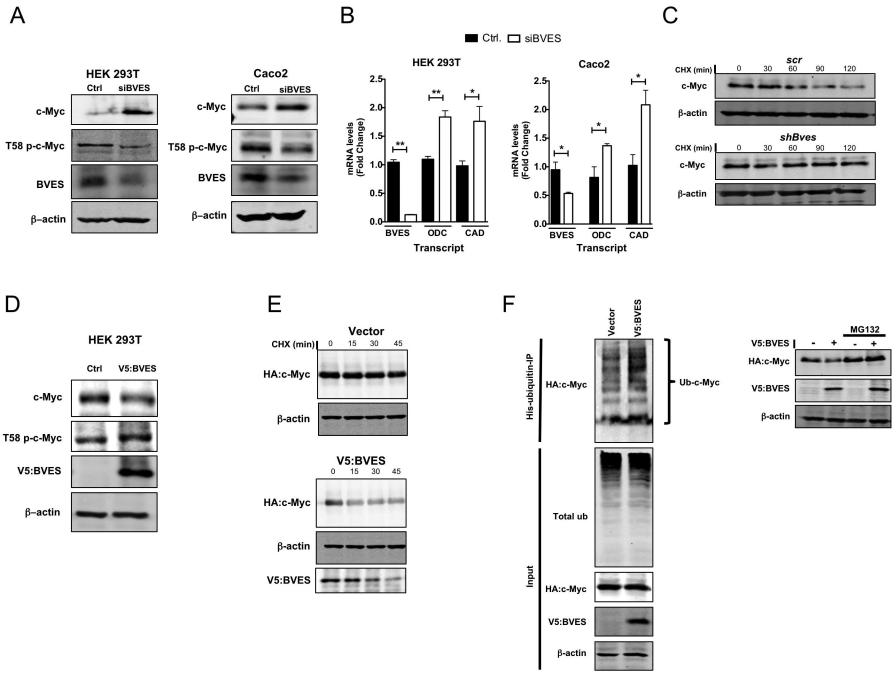

Figure 5. BVES regulates c-Myc stability and activity

(A) c-Myc and T58 phospho-c-Myc protein levels after *BVES* knockdown in HEK 293T (left) or Caco2 (right) cells after 48 hr serum starvation.

(B) qRT-PCR assay for c-Myc targets *ODC* and *CAD* following *BVES* knockdown in the indicated cell lines. Data are presented as mean ±SEM and in triplicates. *p<0.05, **p<0.01.

(C) Cycloheximide treatment (100 μg/ml) of HEK 293T cells with and without *Bves* knockdown followed by immunoblotting for c-Myc.

(D) c-Myc and T58 phospho-c-Myc protein levels after overexpression of V5:BVES in HEK 293T cells.

(E) HEK 293T cells co-transfected with HA:c-Myc and V5:BVES were then treated with cycloheximide (100 μg/ml) followed by immunoblotting for the indicated protein.

(F) Left: His:Ubiquitin and HA:c-Myc were co-transfected into HEK 293T cells along with V5:BVES. Cells were treated with proteasome inhibitor MG132 (20 μm) for 4 hours before His:Ubiquitin complexes were immunoprecipitated and resolved by SDS-PAGE. Ubiquitylated HA:c-Myc complexes were visualized by immunoblotting (Ub-c-Myc). Total ubiquitylated protein (Total ub) was examined as a control. Right: HEK 293T cells co-transfected with HA:c-Myc and V5:BVES were treated with proteasome inhibitor MG132 (20 μm) for 4 hours. Whole cell lysates were analyzed for HA:c-Myc expression. In all immunoblots, β-actin was used as a loading control. All experiments were replicated three times.

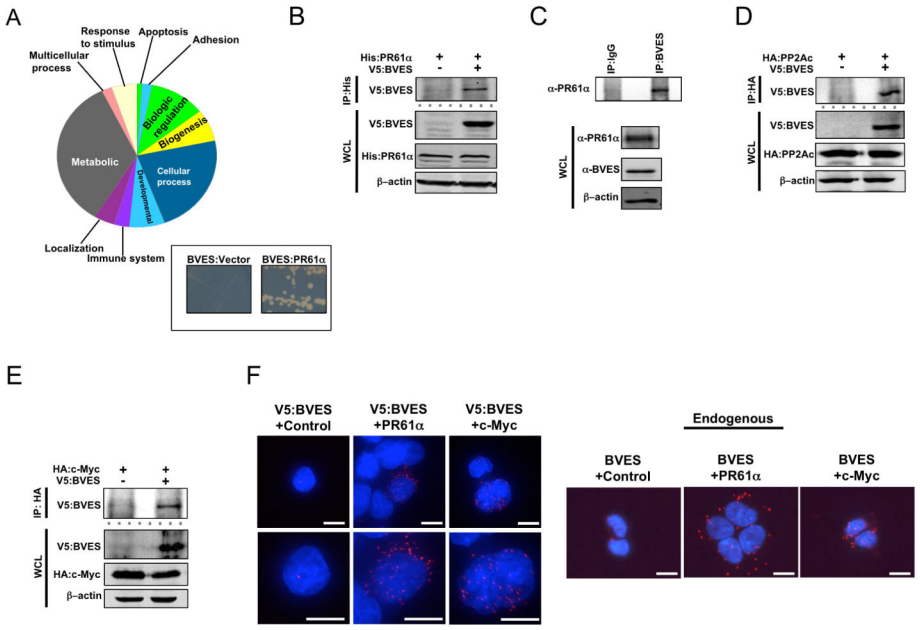

Figure 6. BVES interacts with PR61α, PP2A, and c-Myc

(A) PANTHER Biologic Process Analysis of BVES interactome. Inset: Directed yeast two-hybrid of BVES and PR61α.

(B) Co-immunoprecipitation of exogenous and (**C**) endogenous PR61α:BVES complexes in HEK 293T cells.

(D) Co-immunoprecipitation of V5:BVES and HA:PP2Ac or (**E**) HA:c-Myc.

(F) Left: Proximity ligation assay in HEK 293T cells transfected with V5:BVES. Left: control, middle: α-PR61α, right: α-c-Myc. Right: Proximity ligation assay in HEK 293T cells for endogenous protein interactions. Left: control, middle: α-PR61α, right: α-c-Myc. Anti-HA was used as a control in both exogenous and endogenous localization. Scale bar denotes 10 μm. Red staining is positive signal from the PLA interaction, and blue staining is DAPI. In all immunoblots blots, β-actin was used to ensure loading consistency. All experiments were repeated at least two times.

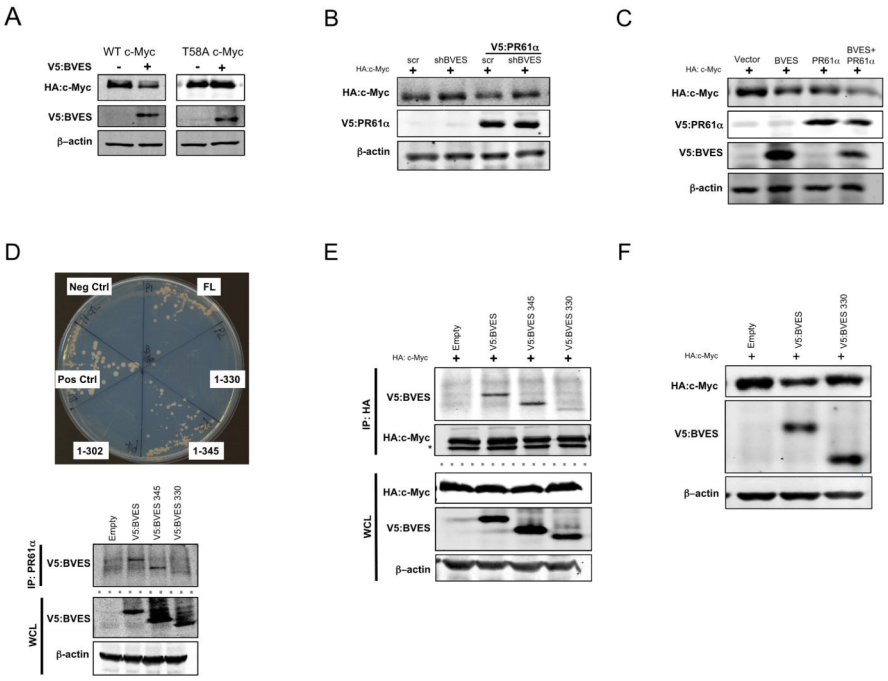

Figure 7. The BVES:PR61α interaction is required to promote c-Myc degradation

(A) WT HA:c-Myc or phospho-mutant HA:T58A c-Myc levels after either empty vector (negative control) or V5:BVES transfection in HEK 293T cells.

(B) Immunoblotting for HA:c-Myc levels following PR61α overexpression in the setting of BVES knockdown or (**C**) when both PR61α and BVES are present HEK 293T cells.

(D) Top: Mapping the PR61α BVES binding interface via directed yeast two-hybrid (Full length BVES, residues 1-345, 1-330, 1-302, negative control (Neg Ctrl), and positive control (Pos Ctrl)). Below: Co-immunoprecipitation of the indicated BVES mutants and PR61α in HEK 293T cells..

(**E**) Co-immunoprecipitation of the indicated BVES mutants and HA:c-Myc in HEK 293T cells.

(F) HA:c-Myc protein levels after transfection of the indicated BVES construct in HEK 293T cells.

In all immunoblots, β-actin was used as a loading control. All experiments were repeated at least two times.

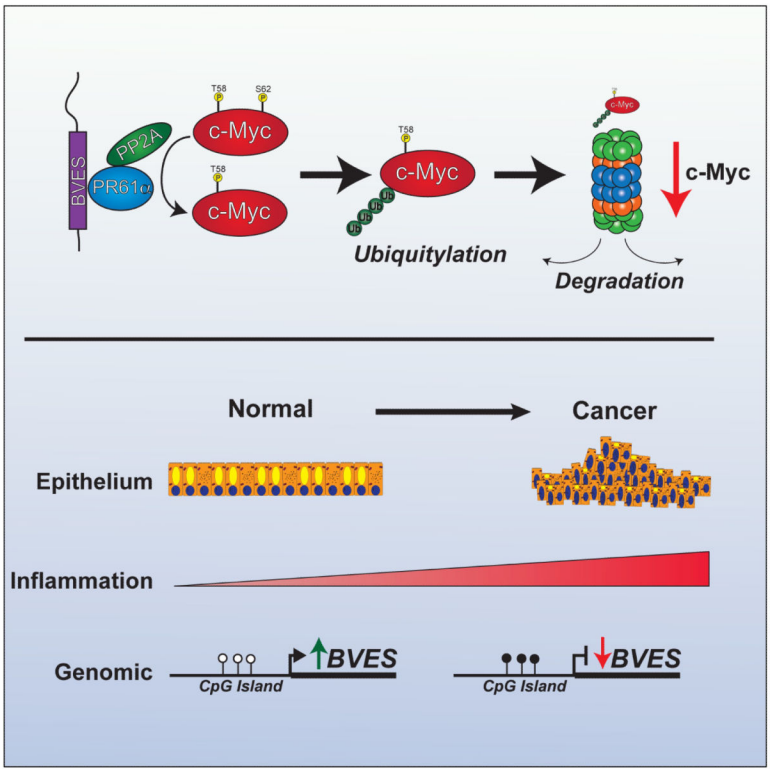

Figure 8.
Working model of the role of BVES in regulating c-Myc degradation and colitis-associated cancer development.