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(Article begins on next page)
Probiotic Yeast Inhibits VEGFR Signaling and Angiogenesis in Intestinal Inflammation

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Abstract

Background and Aims: Saccharomyces boulardii (Sb) can protect against intestinal injury and tumor formation, but how this probiotic yeast controls protective mucosal host responses is unclear. Angiogenesis is an integral process of inflammatory responses in inflammatory bowel diseases (IBD) and required for mucosal remodeling during restitution. The aim of this study was to determine whether Sb alters VEGFR (vascular endothelial growth factor receptor) signaling, a central regulator of angiogenesis.

Methods: HUVEC were used to examine the effects of Sb on signaling and on capillary tube formation (using the ECMatrix™ system). The effects of Sb on VEGF-mediated angiogenesis were examined in vivo using an adenovirus expressing VEGF-A(164) in the ears of adult nude mice (NuNu). The effects of Sb on blood vessel volume branching and density in DSS-induced colitis was quantified using VESSEL GENeration (VESGEN) software.

Results: 1) Sb treatment attenuated weight-loss (p<0.01) and histological damage (p<0.01) in DSS colitis. VESGEN analysis of angiogenesis showed significantly increased blood vessel density and volume in DSS-treated mice compared to control. Sb treatment significantly reduced the neo-vascularization associated with acute DSS colitis and accelerated mucosal recovery restoration of the lamina propria capillary network to a normal morphology. 2) Sb inhibited VEGF-induced angiogenesis in vivo in the mouse ear model. 3) Sb also significantly inhibited angiogenesis in vitro in the capillary tube assay in a dose-dependent manner (p<0.01). 4) In HUVEC, Sb reduced basal VEGFR-2 phosphorylation, VEGFR-2 phosphorylation in response to VEGF as well as activation of the downstream kinases PLCγ and Erk1/2.

Conclusions: Our findings indicate that the probiotic yeast S boulardii can modulate angiogenesis to limit intestinal inflammation and promote mucosal tissue repair by regulating VEGFR signaling.

Introduction

Saccharomyces boulardii (Sb), a nonpathogenic probiotic yeast, has been used for decades to protect against intestinal injury and inflammation [1]. Animal and in vitro studies indicate that S. boulardii can protect against severe diarrhea and enterocolitis induced by a range of bacterial enteric pathogens including Clostridium difficile, Vibrio cholerae, Salmonella typhimurium, Shigella flexneri, enterohemorrhagic E. coli and enteropathogenic E. coli [1–7]. In human studies S. boulardii treatment significantly reduced the incidence of simple antibiotic-associated diarrhea, recurrent C. difficile diarrhea, and traveler’s diarrhea [8–13]. More recent clinical studies indicate that it may also be effective in inflammatory bowel disease (IBD) [14–17]. However, the mechanisms underlying the protective actions of Sb are not well understood. Angiogenesis, the formation of new vasculature from an existing vascular network, is now recognized to play a critical role in various human disease processes, including carcinogenesis, tumor growth, and both acute and chronic inflammation [18–20]. There is considerable evidence in vivo, including clinical observations in humans, that abnormal angiogenesis is involved in many disease settings including rheumatoid arthritis and other inflammatory disorders, carcinogenesis, psoriasis, and degenerative disor-
ders including those seen in diabetes mellitus [18,19,21]. Recently, increasing clinical and experimental evidence indicates that angiogenesis also plays a crucial role in IBD [22–28]. Chronically inflamed intestinal tissues in IBD display significant alterations in microvascular physiology and function compared with healthy intestine and with uninvolved IBD intestine [27,29].

Vascular Endothelial Growth Factor (VEGF) and the associated family of tyrosine kinase VEGF receptors (VEGFRs) are key proteins modulating angiogenesis [20,30]. VEGFR types 1 and 2 (VEGFR-1 or Flt-1 and VEGFR-2 or KDR/Flk-1) are high-affinity transmembrane endothelial cell receptors for VEGF [30]. Of the primary receptors, VEGFR-2 is thought to mediate the majority of tumor angiogenic effects [19,30]. Binding of VEGF to these receptors leads to intracellular receptor phosphorylation which activates various intracellular downstream signaling path-

Figure 1. Oral administration of Sb reduced DSS-colitis induced weight loss, histological damage and neo-vascularization in mouse colon. We used the murine DSS-colitis model to assess the effect of Sb on neo-vascularization in acute colitis. We administered DSS (4% for 5 days) to mice to induce colitis. 1A) Daily administration of Sb by gavage significantly attenuated weight-loss (N = 5, *p<0.05, **p<0.01). Data points represent mean relative weight ± standard error. 1B) Histological scores for several parameters of colonic inflammation on Day 5 were evaluated [control (N = 5), DSS alone (N = 5), DSS plus Sb (N = 5)]. Data points represent mean score ± standard error, **, p<0.01. Representative H/E stained colonic images are listed. 1C) Confocal fluorescence images of the colonic microvasculature were taken 10 minutes after i.v injection of Alexa 647 WGA. Three dimensional image reconstructions were translated into two dimensional grayscale images and binarized to black-and-white vascular patterns for analysis using VESGEN software. Representative images are shown. 1D) Quantitative data are presented in Tables 1 and 2. Comparisons of vascular network and avascular space indices among control, DSS and DSS + Sb groups. Compared to control mice, the DSS group had significantly increased numbers of branch points and density of vessel endpoints (p = 0.004, p = 0.02 respectively). Sb treatment significantly reduced these DSS effects (p = 0.045, p = 0.02 respectively). The mean area per AVS (μm²) in the lamina propria was reduced in the DSS group compared to the control group (p = 0.01). Sb treatment normalized this effect (p = 0.02).

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Table 1. Vascular network results (mean ± std dev).

<table>
<thead>
<tr>
<th>Groups</th>
<th>Control</th>
<th>DSS</th>
<th>DSS+Sb</th>
</tr>
</thead>
<tbody>
<tr>
<td>vessel diameter</td>
<td>16.4±0.5</td>
<td>17.6±0.7</td>
<td>17.4±1.4</td>
</tr>
<tr>
<td>fractional vascular area</td>
<td>0.272±0.02</td>
<td>0.409±0.07</td>
<td>0.293±0.04</td>
</tr>
<tr>
<td>branch point density</td>
<td>326±32</td>
<td>981±259</td>
<td>452±25</td>
</tr>
<tr>
<td>end point density</td>
<td>134±5</td>
<td>548±101</td>
<td>266±41</td>
</tr>
</tbody>
</table>

doi:10.1371/journal.pone.0064227.t001
ways leading to endothelial cell proliferation and blood vessel formation [18,19,31,32].

We here demonstrate that Sb can regulate angiogenesis both in vitro and in vivo, by regulating the VEGFR activation and modulating capillary vessel formation during inflammatory responses thus promoting intestinal recovery from colitis.

Materials and Methods

Cells and Reagents

Human umbilical vein endothelial cells (HUVEC) were obtained from Clonetics. Cells were grown on plates coated with 30 μg/ml vitrogen in EGM-MV BulletKit (5% fetal bovine serum in endothelial basic medium (EBM) with 10 μg/ml bovine brain extract, 1 μg/ml hydrocortisone, 1 μl/ml GA-1000, and hEGF). HUVEC (passages 5 or 4) that are ~80% confluent were used for most experiments. Cells were serum-starved in 0.1% fetal bovine serum in EBM for 24 h prior to testing. Antibodies against Erk, PLCγ, VEGFR2 phosphorylated and/or non-phosphorylated forms, were purchased from Cell Signaling Technology (Beverly, MA). Preparation of Saccharomyces boulardii culture supernatant (SbS) was performed as previously described [33,34]. Briefly, lyophilized Sb (Biocodex Laboratories, France) was cultured in RPMI 1640 cell culture medium (100 mg/ml) for 24 hours in 37°C. The suspension was then centrifuged at 9000 g for 15 minutes and the supernatant collected. The supernatant was then passed through a 0.22 μm filter (Fisher Scientific) and then a 10 kDa cutoff filter (Millipore, MA).

Western Blot Analysis

HUVEC were treated with VEGF (R&D Systems) with and without SbS at different time points. Treated cells were then lysed in a lysis buffer (62.5 mM Tris-HCl, 10% glycerol, 2% SDS, 0.01% bromphenol blue, and 1% 2-mercaptoethanol). Equal amounts of cell extract were fractionated by 4% to 20% gradient SDS-PAGE, and proteins were transferred onto nitrocellulose membranes (Bio-Rad) at 300 mA for 3 h. Membranes were blocked in 5% nonfat dried milk in TBST (50 mM Tris, pH 7.5, 0.15 M NaCl, 0.05% Tween 20) and then incubated with antibodies directed against phosphorylated and non-phosphorylated forms of VEGFR2, phosphoryl/Erk1/2 and PLCγ. Membranes were washed with TBST and incubated with horseradish peroxidase-labeled secondary antibodies for 1 h. The peroxidase signal was detected by Supersignal chemiluminescent substrate (Pierce), and the image of the signal was recorded by exposure to x-ray film (Fujifilm, Tokyo, Japan).

In Vitro Tube Formation Assay

ECMatrix™ assay kit (Millipore, Inc.) was used to study the effects of SbS on HUVEC capillary tube formation in accordance with the manufacturer’s instructions. HUVEC (~1x10⁶ cells) were plated in 96-well plates previously coated with Matrigel and incubated in triplicates for 16 hours at 37°C in the absence or presence of SbS at different dilutions. Representative photomicrographs of tube formation from 10 random fields from each group were captured. Tubular structures were then counted and expressed as the mean number of tubes expressed as a percentage of that counted in the control group.

Mouse Ear Vasculature Assay

All animal protocols were approved by the BIDMC IACUC. Six-week-old, female, athymic, Nu/Nu mice (NCI, Bethesda, MD) were used in the mouse ear vasculature model as previously described [35] A non-replicating adenoviral vector (Ad-VEGF-A164) engineered to express the predominant (164 aa) murine isoform of VEGF-A was a generous gift from Dr. Harold Dvorak. 5x10⁵ pfu of Ad-VEGF-A164 (in 10 μL) were injected into the dorsal skin of both ears using a 30-gauge needle. The first SbS (or vehicle) injection was administered s.c. locally (to the ear) 1 hour after the adenovirus injection. A second SbS (or vehicle) injection was administered 24 hours later. Ears were photographed on day 16.

Angiogenesis Analysis in DSS-Colitis Model

DSS (4% for 5 days) was administered to 8-week-old female C57BL6 mice (Jackson Laboratory). Sb was given to mice daily by oral gavage at a dose of 6x10⁸ CFU. At Day 5, mice blood vessels were stained with 50 μg Alexa Fluor® 647 WGA (Molecular Probes) injected retro-orbitally. Seven minutes later, mice were sacrificed by CO2 asphyxiation. Colon tissues were immediately removed and rinsed with PBS. Tissue specimens were imaged with a Bio-Rad Radiance 2000 confocal microscope (Bio-Rad, Hercules, CA). Image acquisitions were carried out with Laser Sharp Scanning Software (Bio-Rad). Three dimensional analyses were used to assess the blood vessel volume and density in the mice colon. Three dimensional image reconstructions were translated into two dimensional grayscale images and binarized to black-and-white vascular patterns as described previously [36,37]. The image of a binary vascular pattern was input into VESsel GENeration (VESGEN) software and upon selection of the Vascular Network analysis option. VESGEN automatically mapped and quantified the vascular pattern. The mapping of networks by VESGEN excludes any avascular spaces (AVS) located at the edge of the image because representation of the AVS is incomplete in those regions and therefore the vascular density is unknown.

Histological Score Assessment of Colitis

H&E-stained colonic sections were coded for blind microscopic assessment of inflammation for DSS-induced colitis. Histological scoring includes parameters of colonic inflammation (ulceration, congestion, edema, and neutrophil infiltration) as previously reported [38].

Table 2. Avascular spaces (AVS) results (mean ± std dev).

<table>
<thead>
<tr>
<th>Groups</th>
<th>Control</th>
<th>DSS</th>
<th>DSS+Sb</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of AVS</td>
<td>100±14</td>
<td>240±79</td>
<td>104±8</td>
</tr>
<tr>
<td>mean area (μm²) per AVS</td>
<td>9692±1747</td>
<td>3214±1169</td>
<td>6717±480</td>
</tr>
<tr>
<td>avascular area fraction (reciprocal of vascular area fraction, Table 1)</td>
<td>0.728±0.02</td>
<td>0.591±0.07</td>
<td>0.707±0.04</td>
</tr>
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</table>

doi:10.1371/journal.pone.0064227.t002
Statistical Analyses

Results were expressed as mean ± SE or mean ± STDEV. Data were analyzed using the SIGMA-STAT™ professional statistics software program (Jandel Scientific Software, San Rafael, CA). Analyses of variance with protected t test were used for intergroup comparison.
To determine whether Sb could directly regulate the function of VEGF, we then went on to assess the effects of Sb on VEGF-induced angiogenesis in vivo using an adenovirus expressing VEGF-A(164) (Ad-VEGF-A(164)) in the ears of adult nude mice (N=5), an in vivo angiogenesis model as previously reported [35]. The right ears of mice (N=5) were injected with 10 μl SbS (ion-exchange chromatography enriched and DMEM diluted) and the left ears were injected with 10 μl vehicle (DMEM) as control. The first treatment was administered 1 hour after 5 x 10^6 pfu Ad-VEGF-A(164) was injected into both ears. The second SbS or vehicle injections were administered 24 hours later. As shown in Figure 2, each of the 5 mice showed an angiogenesis response to Ad-VEGF-A(164) in the control (left) ear. By day 7 an inhibitory effect of SbS was clearly evident with reduced new vessel formation in the right ear compared to the left. The effect of SbS remained evident until the end of the experiment on day 21. These results indicated that SbS mediated inhibition of vessel formation is mediated by a direct inhibition of VEGF mediated angiogenesis in vivo.

S. boulardii Inhibits VEGF-induced Angiogenesis in a Mouse Ear Neo-vascularization Model

Endothelial cell capillary tube formation is a multi-step process involving cell adhesion, migration, differentiation and growth.[21] We used the ECMatrixTM in vitro angiogenesis assay to study the effects of SbS on angiogenesis in vitro. HUVEC (~1 x 10^5 cells) were cultured as triplicates in 96-well plates previously coated with Matrigel and incubated for 16 hours at 37°C in the absence or presence of SbS. Representative photomicrographs of tube formation in the control and SbS-treated groups are shown in the lower panel of Figure 3. Tubular structures were then counted. Percentage (%) of control is the mean number of tubules expressed as a proportion of that in the control group. As shown in Figure 3, SbS significantly inhibited HUVEC tube formation in a dose-dependent manner (P<0.05 for 1/32 dilution vs control; P<0.01 for 1/16, 1/8 and 1/4 vs control) indicating that, in addition to its effects on VEGF signaling, SbS can attenuate angiogenic responses in vitro.

S. boulardii Inhibits VEGF Signaling in HUVEC

VEGFs belong to the same receptor tyrosine superfamily, as EGFR, IGF-1R, HER-2 and HER-3 which we have demonstrated to be a target of SbS in colon epithelial cells [34]. We therefore examined the activation of VEGFR-2, the most defined and major mediator of angiogenesis, in HUVEC. Near-confluent (80% confluent) HUVEC grown in complete medium were exposed to SbS for varying time periods (0–180 minutes). Cell extracts were prepared for Western blotting using antibodies against total and phopho-specific VEGFR-2. The band of phosphorylated VEGFR-2 immediately disappeared (within 1 minute) upon exposure to SbS. In contrast, the amount of total VEGFR2 remained stable. HUVEC were starved overnight and then treated with 10 ng/ml VEGF in the presence or absence of SbS for 0 to 30 minutes. Cell extracts were prepared for Western blotting with antibodies against total or phospho-specific VEGFR-2, PLCγ, or Erk1/2. VEGF induced activation of both VEGFR-2 phosphorylation sites as recognized by p-Tyr1175 and p-Tyr996 phospho-site specific antibodies. The downstream mediators PLCγ and Erk1/2 are also activated by VEGF.

The presence of SbS inhibited the phosphorylation of VEGFR-2 in response to VEGF and also reduced activation of the downstream kinases PLCγ and Erk1/2. Total protein levels were not affected.

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The downstream mediators PLCγ and Erk1/2 are also activated by VEGF. As demonstrated in Figure 4A, phosphorylated VEGFR-2 was evident under basal conditions and at 60 and 180 minutes of incubation. Phosphorylated VEGFR-2 disappeared immediately (within 1 minute) after exposure to SbS. In contrast, the amount of total VEGFR2 remained stable.

To test whether SbS inhibits ligand-induced VEGFR signaling, HUVEC (starved overnight) were treated with 10 ng/ml VEGF in the presence or absence of SbS for 0 to 30 minutes. Cell extracts were prepared for Western blotting with antibodies against total and phospho-specific VEGFR-2, PLCγ, or Erk1/2. As demonstrated in Figure 4B, VEGF induced activation of VEGFR-2 phosphorylation...
tion sites p-Tyr1175 and, less dramatically, p-Tyr996, within 2 minutes. The downstream mediators, PLC\gamma and Erk1/2 were also activated by VEGF as expected. Sb reduced VEGFR-2 phosphorylation in response to VEGF and also reduced activation of the downstream kinases PLC\gamma and Erk1/2. Total protein levels were not substantially altered. Together, these results demonstrate that Sb has the ability to inhibit VEGF 2 signaling by preventing tyrosine phosphorylation required for the activation of PLC\gamma and Erk1/2 responsible for the proliferation of endothelial cells during vessel formation.

**Discussion**

In this study, we propose a new mechanism by which *S. boulardii* regulates angiogenesis and controls mucosal inflammation. We demonstrate that Sb can inhibit VEGFR signaling and capillary tube formation in HUVEC. Sb can inhibit angiogenesis *in vivo* induced either directly by VEGF or by mucosal inflammation after epithelial barrier disruption by DSS.

For the first time, we were able to quantify vascular network structure and architecture in control and diseased intestines using several key parameters including vascular fractional area, fractional area of avascular spaces, and regularity of the geometry of avascular spaces, network morphology and the connectedness of the vascular network. Mapping and quantification by VESGEN showed that the uniform, lattice-like vascular network evident in control colonic tissues was greatly disrupted during DSS colitis. Inflammation greatly increased vessel density and disrupted the regular lattice geometry of the lamina propria microvasculature. We were also able to demonstrate that *S. boulardii* treatment substantially enhanced mucosal recovery and restored the vascular network to a significantly more normal morphology.

There is increasing evidence from experimental mouse models and from clinical observations that angiogenesis is an important component of IBD pathogenesis. For example, VEGF has been shown to be elevated in distal colonic tissue in the CD4\+/CD45RBhi colitis model as well as in intestinal tissues and sera of patients with Crohn’s disease and ulcerative colitis studies. Recent studies in experimental colitis suggest that VEGF is an important mediator of IBD through promoting intestinal angiogenesis and inflammation.  

**Probiotics on Colonic Angiogenesis**

Conceived and designed the experiments: XC HCR CPK. Performed the experiments: XC GY JHS DL JG HCR. Analyzed the data: PPW. Contributed reagents/materials/analysis tools: HZ PPW. Wrote the paper: XC CPK.

**References**