Aging reverses the role of the transient receptor potential vanilloid-1 channel in systemic inflammation from anti-inflammatory to proinflammatory

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Abbreviations: CLP, cecal ligation and puncture; LPS, lipopolysaccharide; SIRS, systemic inflammatory response syndrome; Ta, body temperature; TNF, tumor necrosis factor; TRPV1, transient receptor potential vanilloid-1

Introduction

Systemic inflammatory response syndrome (SIRS) is the leading cause of death in hospitalized patients.1,2 SIRS is considered a disease of the aged: its incidence and mortality are substantially higher in the older population.3 SIRS can be either triggered by non-infectious insults, such as blunt trauma, or associated with an infection (in which case it is called sepsis). In the laboratory, systemic administration of lipopolysaccharide (LPS, a cell-wall constituent of Gram-negative bacteria) in mice and rats is often used to induce SIRS aseptically, whereas polymicrobial sepsis is often studied in rodents subjected to cecal ligation and puncture (CLP). In either model, shock and death can occur, largely as the result of the “cytokine storm,” an overt production of proinflammatory cytokines, including TNFα, and other mediators, cumulatively referred to as the “inflammatory soup.”4-5 In both LPS-induced SIRS and CLP-induced sepsis, proinflammatory cytokine production and mortality rate are much lower in young animals.6-10 Furthermore, sepsis in young animals is much more responsive to treatment.11

Recent studies have brought attention to the role that the transient receptor potential vanilloid-1 (TRPV1) channel may play in SIRS. Abundant on small-diameter sensory nerve fibers, TRPV1 is activated by diverse stimuli, including several ingredients of the inflammatory soup.12,13 Activation of TRPV1 on sensory nerves potently inhibits LPS-induced TNFα production.14 Studies using either knockout (Trpv1–/–) mice, a pharmacological blockade with capsazepine (TRPV1 antagonist) or desensitization with resiniferatoxin (TRPV1 agonist) have shown that TRPV1 plays an anti-inflammatory role in LPS-induced SIRS by, among other mechanisms, limiting the production of TNFα, possibly via sensory nerves.15-17 However, all studies cited above were conducted...
in young rodents. Whether TRPV1 channels play a similarly prominent anti-inflammatory role in the aged is unknown.

**Results and Discussion**

Effects of a TRPV1 antagonist on LPS-induced systemic inflammation in young mice. First, we verified whether pretreatment with AMG517, a potent and selective TRPV1 antagonist, decreases the mortality of young adult (12 wk) C57BL/6 mice in LPS-induced SIRS. Mice responded to LPS (40 mg/kg, ip) with a marked, rapidly progressing SIRS (Fig. 1A). Pretreatment with AMG517 (210 μg/kg, sc) profoundly decreased the survival rate at multiple time points (e.g., from 50% to 5% at 26 h, \( p < 0.001 \)), overall (48 h) survival rate (from 15% to 5%, \( p < 0.05 \)) and increased the risk of mortality (hazard ratio of death of 0.9, \( p = 0.01 \), Table 1). AMG517 pretreatment also shortened the mean time to death from 26 ± 2 to 19 ± 1 h (\( p = 0.003 \)). All LPS-treated mice, both in this experiment and in other experiments within the present study, developed profound hypothermia: deep (abdominal) body temperature (\( T_b \)) decreased from ~36°C to ~33°C at 10 h. However, no inter-treatment differences in the hypothermic response occurred during the short time period before mice started dying (data not shown). Similar to our previous studies in references 18 and 19, AMG517 caused a short-lasting increase in \( T_b \) compared with the vehicle (\( p < 0.01 \), Fig. 1B), thus confirming an effective systemic blockade of TRPV1 channels. Overall, the results of our experiment show that pharmacological blockade of TRPV1 increases mortality of young mice in LPS-induced SIRS. Similar observations have been made in adolescent (6–8 wk) mice and in rats treated with capsazepine.16,17 It should be noted, however, that capsazepine is not a highly selective TRPV1 antagonist and has a low potency of blocking the proton mode of TRPV1 activation in the rat and mouse.20 In fact, a non-TRPV1-mediated effect of capsazepine

![Figure 1. Systemic pretreatment with AMG517 (dose indicated) decreases survival of young mice in LPS-induced SIRS (A). Confirming an effective blockade of TRPV1 channels, the AMG517 pretreatment increases deep \( T_b \) in young mice (B).](image)

**Table 1. Effects of age and TRPV1 antagonism on mortality in LPS-induced SIRS and CLP-induced sepsis**

<table>
<thead>
<tr>
<th>Model</th>
<th>Variable</th>
<th>Cox survival regression analysis</th>
<th>Logrank test</th>
<th>Time to death</th>
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<td></td>
<td></td>
<td>Hazard ratio of death</td>
<td>95% confidence interval</td>
<td>p</td>
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<td>LPS</td>
<td>Aged vs. young</td>
<td>2.2</td>
<td>1.3 ± 3.1</td>
<td>&lt;0.001</td>
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<td>LPS in young</td>
<td>AMG517 vs. vehicle</td>
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<td>0.2 ± 1.6</td>
<td>&lt;0.010</td>
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<tr>
<td>LPS in aged</td>
<td>AMG517 vs. vehicle</td>
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<td>-1.8 ± 0.2</td>
<td>&lt;0.015</td>
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<td>LPS in aged</td>
<td>( \text{Trpv1}^{-/-} ) vs. ( \text{Trpv1}^{+/+} )</td>
<td>-1.3</td>
<td>-2.4 ± 0.2</td>
<td>&lt;0.020</td>
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<tr>
<td>CLP in aged</td>
<td>( \text{Trpv1}^{-/-} ) vs. ( \text{Trpv1}^{+/+} )</td>
<td>0.7</td>
<td>-0.5 ± 1.9</td>
<td>0.239</td>
</tr>
</tbody>
</table>
on the outcome of systemic inflammation has been proposed recently in reference 17. The present results also agree with the exaggerated symptoms of LPS-induced shock found in young mature (13–20 wk) Trpv1−/− mice.15

As reviewed by Steiner et al.21 and Guptill et al.17 many treatments affect mortality in LPS-induced aseptic inflammation and CLP-induced sepsis in opposite ways, confirming that the systemic inflammatory response per se can be harmful to the host, even though it is crucial for defending the host against infection.6,7 For example, mice with a dysfunctional toll-like receptor 4 are resistant to LPS but are highly susceptible to Gram-negative bacterial infection.22-24 This susceptibility to infection can be reserved by pretreating the toll-like receptor 4-deficient mice with TNF and interleukin-1α.21 Interestingly, antibiotic treatment makes sepsis less different from aseptic SIRS, as it eradicates the infectious agent. For example, acute nicotine administration increases survival of mice in LPS-induced SIRS21,25-27 and in antibiotic-treated CLP-induced sepsis,25,26 but it worsens the outcome of untreated CLP-induced sepsis in the same species.21 From this point of view, two studies of the role of TRPV1 in CLP-induced sepsis in adolescent (5–8 wk) mice27,28 agree with the effects observed in LPS SIRS. The first study27 has found that antibiotic-treated CLP-induced sepsis causes a higher mortality when TRPV1 channels are absent (Trpv1−/− mice) or desensitized (with intrathecal resiniferatoxin). The second study28 has found that capsaicin increases survival in untreated CLP-induced sepsis. Overall, prior literature data obtained in young rodents (adolescents to mature adults) and our present experiment with AMG517 in young adult mice show that the effects of TRPV1 blockade on both LPS-induced SIRS and antibiotic-treated sepsis vary from none to strong exaggeration of severity and mortality,15,27 whereas the effect of TRPV1 blockade on mortality in untreated sepsis is the opposite: attenuation.28

Effects of AMG517 on LPS-induced systemic inflammation in aged mice. To study whether the anti-inflammatory role of TRPV1 in SIRS is preserved with aging, we conducted experiments in middle-aged (44 wk) C57BL/6 mice (Fig. 2A). The outcome of LPS-induced SIRS in these older mice was more severe than in young mice (hazard ratio of 2.2, p < 0.001, Table 1). The mean time to death in vehicle-pretreated aged mice was 16 ± 1 h, and none of the vehicle-pretreated aged mice survived for longer than 24 h. Pretreatment of aged mice with AMG517 (210 μg/kg, sc) increased the survival rate (p < 0.05), delayed the mean time to death (19 ± 1 h, p < 0.05) and decreased the risk of mortality (hazard ratio of -1.0, p < 0.05)—effects directly opposite of those observed in the young. Survival rate of AMG517-pretreated aged mice at 18 h was 10 times higher than that of vehicle-pretreated aged mice (60% vs. 6%, p < 0.001). Confirming a systemic blockade of TRPV1 channels in this experiment, AMG517 increased Tb as compared with the vehicle (p < 0.05, Fig. 2B). Hence, whereas the effect of AMG517 on LPS-induced systemic inflammation in aged mice was the opposite to that found in young mice (Figs. 1A and 2A), the effect on Tb was qualitatively the same (Figs. 1B and 2B). It is possible that the role of TRPV1 in different functions changes with age in a different way. In the regulation of locomotor activity29,30 and inflammation (present results), the role of TRPV1 reverses with age. In the modulation of Tb (for mechanisms, review ref. 31), it does not. In the regulation of body mass, TRPV1 channels are either uninvolved29 or counteract obesity32 in the young but promote obesity in the aged.29,30

Effects of genetic deletion of TRPV1 channels on LPS-induced systemic inflammation in aged mice. We then
tested whether genetic deletion of TRPV1 would have the same effects on SIRS in middle-aged mice as a pharmacological blockade. Experiments were conducted in 43–44 wk-old Trpv1−/− C57BL/6 x 129 mice of both sexes and in their age- and sex-matched Trpv1+/+ littermates. LPS caused death in all Trpv1−/− mice but only in 80% of Trpv1+/+ mice (p < 0.05, Fig. 3A). Survival rate of Trpv1−/− mice at 21 h was 3.5 times higher than of wild-type controls (70% vs. 20%, p < 0.001). Genetic deletion of TRPV1 channels decreased the risk of mortality (hazard ratio of -1.3, p < 0.05) and tended to delay death (p < 0.1, Table 1). Importantly, Trpv1−/− mice exhibited a 70% suppression of the TNFα response at 12 h post-LPS (p < 0.05, Fig. 3B). It should be noted that aged Trpv1−/− mice in this study (see Materials and Methods) and in our previous studies in references 29 and 30 were overweight compared with their wild-type littermates. Obesity33–36 and hyperlipidemia37 associated with various mutations in rats do not seem to affect the febrile response to low, non-shock-inducing doses of LPS, and obesity does not seem to increase the risk of sepsis even though it increases the risk of an infection.38 Nevertheless, systemic inflammation and obesity are intimately interconnected,39,40 and we cannot rule out that obesity could have been a contributing factor to at least some of the effects found in aged Trpv1−/− mice.

Mechanisms of the age-associated reversal of the anti-inflammatory role of TRPV1 are unknown. Our TNFα data suggest that the reversal occurs at initial stages of the pathogenesis of SIRS—at or upstream of TNFα production. The TNFα response to LPS has been shown to be under suppressive control of TRPV1 channels on sensory nerves.14 Loss of TRPV1-mediated suppression of TNFα production in aged animals may reflect reduced translation of the TRPV1 protein and its reduced transport to the periphery,41 possibly due to age-associated decline in neurotrophic support to ganglionic neurons.42 Changes in TNFα production may be central to aging-related changes in the pathobiology of sepsis: elderly patients respond to infection, including septic shock, with higher TNFα,43,44 and inflammatory cytokine production in intensive-care-unit patients with sepsis is affected by TNFα-related genetic polymorphisms.45

Effects of genetic deletion of TRPV1 channels on CLP-induced sepsis in aged mice. Next, we tested whether the attenuation of aseptic SIRS (of LPS-induced TNFα response and mortality) observed in middle-aged Trpv1−/− mice would result in attenuation of the body’s defense against CLP-induced polymicrobial infection. CLP sepsis caused substantial mortality in aged mice of both genotypes (Fig. 4A). However, Trpv1−/− mice died significantly faster than their Trpv1+/+ littermates (Table 1). The mean time to death in Trpv1−/− mice was 20 ± 2 h, as compared with 52 ± 11 h in Trpv1+/+ mice (p < 0.01), and the 30 h survival rate in Trpv1−/− mice was 3.9 times higher than in Trpv1+/+ mice (86% vs. 22%, p < 0.001). Further confirming the higher severity of sepsis in Trpv1−/− mice, recovery of deep Tb after the CLP procedure (and the related anesthesia) was delayed (p < 0.001, Fig. 4B).

Conclusions. The present study shows that the anti-inflammatory role firmly established for TRPV1 channels in young rodents15–17 is reversed with aging. Whereas pharmacological or genetic TRPV1 antagonism decreases the survival rate in aseptic SIRS and in antibiotic-treated sepsis in the young, both types of TRPV1 antagonism have the opposite effect on aseptic SIRS in middle-aged mice. The age-dependent reversal of the
anti-inflammatory role of TRPV1 to proinflammatory is likely due, at least in part, to a reversal of the suppressive control of TRPV1 on TNFα production. These pathobiological changes are highly important, as evident from the decreased ability of aged Trpv1−/− mice to resist polymicrobial sepsis. The reversal of the anti-inflammatory role of TRPV1 reported in this study is another example of profound effects of aging on the pathobiology of systemic inflammation.11,46,47

**Significance.** Our findings may influence development of TRPV1 antagonists, widely viewed as new-generation painkillers.18,20,48 If what we found for murine models applies to human sepsis, anti-TRPV1 therapy may suppress the systemic inflammatory response in the previously uninfected (untreated with antibiotics) elderly and, hence, decrease their resistance to bacterial infection and sepsis. This potential side effect is especially serious, because recognition of infection is often complicated in older patients by a variety of factors, including the absence of fever, which often delays treatment.49,50

**Materials and Methods**

The study was conducted in 168 adult mice (either young or middle-aged) of both sexes, including 101 Trpv1+/+ C57BL/6 mice (Charles River Laboratories) and 67 Trpv1−/− or Trpv1+/− C57BL/6 x 129 mice (Amgen colony at Charles River Laboratories). Several phenotypic properties of Trpv1−/− mice from the Amgen colony have been characterized in our recent studies in references 29 and 30. At the time of experiments, young adult C57BL/6 mice were 12 wk-old, and their body mass was 25 ± 0 g (n = 55); middle-aged C57BL/6 mice were 44 wk-old, and their body mass was 32 ± 1 g (n = 46). The ages of C57BL/6 mice listed are approximate; the vendor filled orders for a specified age, but did not provide the date of birth for each mouse. Middle-aged Trpv1−/− C57BL/6 x 129 mice were 43 ± 1 wk-old (n = 30), and their body mass was 40 ± 1 g. Middle-aged Trpv1+/+ C57BL/6 x 129 mice were 44 ± 1 wk-old (n = 37) and significantly heavier (46 ± 1 g; p < 0.001) than their wild-type littermates. The ages of C57BL/6 x 129 mice were calculated based on the dates of birth, which were known for all mice. Mice were maintained, surgically prepared and habituated to experimental setups as described in our earlier studies.21,29 All surgeries were performed under ketamine-xylazine-acepromazine (81.7, 9.3 and 1.2 mg/kg, ip) anesthesia. Antibiotic protection (enrofloxacin, 1.1 mg/kg, sc) was provided, except for animals subjected to CLP. For deep Tb measurements, all mice were implanted intra-peritoneally with telemetry transmitters (G2 E-Mitter series, Mini Mitter). For CLP, under the same anesthesia, the cecum was pulled out of the abdominal cavity, filled with the intestinal content (by gently squeezing the content from the ascending colon) and ligated with 3-0 silk just distal to the ileocecal junction. The cecal wall was punctured through at the antimesenteric side with a 26-gauge needle. All protocols were approved by the St. Joseph’s Hospital and Medical Center Animal Care and Use Committee.

During all experiments, mice were housed singly in their home cages placed inside a climatic chamber (model 3940, Forma Scientific) with an ambient temperature maintained at 28.0°C, i.e., within the thermoneutral zone for this experimental setup.29,51 Cages were kept on top of telemetry receivers (model ER-4000, Mini Mitter). In the experiments with LPS-induced
SIRS, the survival rate and $T_s$ were monitored for 48 h. To this end, mice were periodically examined for the presence of spontaneous movements and cardiac and respiratory activities. Because deep $T_s$ decreases steeply toward the ambient temperature when an animal dies, $T_s$ curves were also examined to identify mortality events. In the experiments with CLP-induced sepsis, the same parameters were monitored for 108 h. At the end of experiments, all survivors were euthanized with sodium pentobarbital (200 mg/kg, ip).

In a separate series of experiments (under the same anesthesia as for surgery), blood (1 ml) was collected by cardiac puncture at 12 h after LPS administration, and mice were euthanized with sodium pentobarbital. The 12 h time point for blood collection was chosen because aged mice in this model start dying shortly after this point (Fig. 3A). Serum concentration of TNFα was determined by ELISA according to the manufacturer’s instructions (SA Biosciences, catalog number MEM-004A).

A suspension of E. coli 0111:B4 LPS (Sigma-Aldrich, L2630, 2.5 mg/ml) in saline was prepared in advance and stored at 4°C. To induce SIRS, LPS (40 mg/kg ip) was injected as a bolus; controls received saline.

AMG517 (gift from Amgen) was used to block TRPV1 receptors pharmacologically. This is a highly potent and selective TRPV1 antagonist that had been tested in human patients.11 Aliquots of an ethanolic solution of AMG517 (3 mg/ml) were stored at -80°C. This stock was diluted with ethanol and saline ex tempore to achieve a 21 μg/kg sc dose of AMG517 in 3.3% ethanol. AMG517 (210 μg/kg sc) or its vehicle was administered as a bolus, 1 h before the administration of LPS (or saline).

Results are reported in the format mean ± SE. A difference was considered significant at $p < 0.05$. Unpaired student’s t-test was used to compare times to death and TNFα concentrations. Deep $T_s$ values were compared across treatments and time points by two-way ANOVA; p-values for the entire duration of response are reported. A difference was considered significant at $p < 0.05$. Results are reported in the format mean ± SE.

**Disclosure of Potential Conflicts of Interest**

N.R.G. is employed by Amgen Inc. A.A.R. has consulted for TRP programs at Amgen, Inc. and several other pharmaceutical companies, and his TRP-related research has been supported by Amgen, Inc. and Abbott Laboratories.

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