Macrophage Deletion of SOCS1 Increases Sensitivity to LPS and Palmitic Acid and Results in Systemic Inflammation and Hepatic Insulin Resistance

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OBJECTIVE—Macrophage secretion of proinflammatory cytokines contributes to the pathogenesis of obesity-related insulin resistance. An important regulator of inflammation is the suppressor of cytokine signaling-1 (SOCS1), which inhibits the JAK-STAT and toll-like receptor-4 (TLR4) pathways. Despite the reported role of SOCS1 in inhibiting insulin signaling, it is surprising that a SOCS1 polymorphism that increases SOCS1 promoter activity is associated with enhanced insulin sensitivity despite obesity. In the current study, we investigated the physiological role of myeloid and lymphoid cell SOCS1 in regulating inflammation and insulin sensitivity.

RESEARCH DESIGN AND METHODS—We used mice generated by crossing SOCS1 floxed mice with mice expressing Cre recombinase under the control of the LysM-Cre promoter (SOCS1 LysM-Cre). These mice have deletion of SOCS1 in macrophages and lymphocytes. We assessed macrophage inflammation using flow cytometry and serum cytokine levels using Bioplex assays. We then measured insulin sensitivity using glucose tolerance tests and the euglycemic-hyperinsulinemic clamp. Using bone marrow–derived macrophages, we tested the effects of SOCS1 deletion in regulating responses to the TLR4 ligands: lipopolysaccharide (LPS) and palmitic acid.

RESULTS—SOCS1 LysM-Cre mice had increased macrophage expression of CD11c, enhanced sensitivity to LPS, and palmitic acid and increased serum concentrations of tumor necrosis factor-α, interleukin-6, and monocyte chemoattractant protein. Increased inflammation was associated with impaired glucose tolerance and hyperinsulinemia as a result of reduced hepatic but not skeletal muscle insulin sensitivity.

CONCLUSIONS—The expression of SOCS1 in hematopoietic cells protects mice against systemic inflammation and hepatic insulin resistance potentially by inhibiting LPS and palmitate-induced TLR4 signaling in macrophages. Diabetes 60:2023–2031, 2011

The link between inflammation and diabetes was discovered more than a century ago when high doses of sodium salicylate were shown to ameliorate glycosuria (as reviewed in 1). Today, it is well established that obesity is associated with increased levels of proinflammatory cytokines that lead to insulin resistance (2) and defects in fatty acid metabolism (3). Accumulation of inflamed macrophages within adipose tissue is the major source of cytokines in obesity (4,5), and their activation has been linked to the Toll-like receptor (TLR) signaling family, which are known to activate proinflammatory signaling pathways. The best characterized member of this family, TLR4, binds to lipopolysaccharide (LPS) of Gram-negative bacterial cell walls and recruits the myeloid differentiation factor 88 to the Toll/interleukin (IL)-1 receptor domain of the receptor. This triggers the activation of the nuclear factor (NF)-κB pathway resulting in the expression of proinflammatory cytokines such as tumor necrosis factor (TNF)-α, IL-6, and IL-1β (6,7). In obesity, alterations in gut microbial flora that increase the endotoxin (LPS) load in the intestine have been postulated as a potential mechanism leading to obesity-related inflammation, insulin resistance, and nonalcoholic fatty liver disease (8,9). Alternatively, abrogation of LPS signaling in CD14 (a coreceptor of TLR4) mutant mice or reducing the content of gram-negative bacteria reduces inflammation and improves insulin resistance (10).

In addition to classical activation of the TLR signaling pathway via LPS several studies have demonstrated that saturated fatty acids such as palmitic acid also induce an inflammatory response in macrophages in part through activation of TLR signaling (11,12). Importantly, in mice deficient for both TLR2 and TLR4 obesity and free fatty acid–induced inflammation and insulin resistance is markedly blunted (11,13). These studies provide a compelling molecular connection for the strong correlation between inflammatory cytokines and circulating free fatty acids in obesity (14) and support findings demonstrating that the acute infusion of saturated fatty acids dramatically increases circulating TNF-α levels (15,16).

The suppressor of cytokine signaling (SOCS) family of proteins (SOCS1-SOCS7 and cytokine–inducible SH-2-containing protein) are induced by proinflammatory cytokines and negatively regulate cytokine signaling (17). SOCS1 inhibits signaling by interferons (18) and by cytokines that signal through the common-γ chain receptor, such as IL-2 (19) and IL-4 (20). SOCS1 has also been shown to negatively regulate TLR4 signaling by mediating the degradation of the adaptor protein Mal (21), which is involved in the transactivation of NF-κB after TLR4 ligation. In support of these findings genetic disruption of SOCS1 results in the dramatic dysregulation of immune and inflammatory responses (22,23).

Genetic polymorphisms in the promoter regions of the SOCS1 gene that influence its transcriptional activity have been described in humans (24,25) and the rs83977706 (−820 G>T) and rs243330 (−1456 G>A) polymorphisms
are associated with improved insulin sensitivity. It is noteworthy that the rs33977706 (−820 G>T) polymorphism in the SOC1 promoter is also associated with increased transcriptional activity. Increased SOC1 expression associated with improved insulin sensitivity would at first seem to be at odds with the reported role of SOC1 by us and others as a negative regulator of hepatic insulin sensitivity, effects that are mediated through downregulation and ubiquination of the insulin receptor substrate (IRS)-2 (26,27). However, we have shown that the deletion of SOC1 from myeloid and lymphoid cells in SOC1 LysM-Cre mice increases inflammation (23), and we hypothesize that this may lead to insulin resistance. In the current study, we used these mice and found they develop hyperinsulinemia and hepatic insulin resistance. Furthermore, deletion of SOC1 in macrophages increased their sensitivity to LPS and palmitic acid. Therefore, we speculate that the hypersensitivity of SOC1-deficient macrophages to LPS and palmitic acid may be a contributing factor to the increased inflammation and dysregulation in liver insulin sensitivity observed in SOC1 LysM-Cre mice.

**RESEARCH DESIGN AND METHODS**

**Animal experiments.** The animal ethics committee of St. Vincent’s Health approved all procedures. SOC1 LysM-Cre mice and their littermate controls (SOC1fl/fl) have been described previously (23). All studies were performed in male mice aged 12–15 weeks of age. SOC1fl/fl and SOC1Cre mice were generated on a C57BL/6 background, and LysM-Cre mice were on their 10th generation backcross to C57BL/6 before crossing to SOC1fl/fl mice. Mice were maintained with ad libitum access to food and water in microisolator cages, under pathogen-free conditions with a 12-h light/dark cycle. Blood glucose, insulin, and cytokines were measured after a 6-h fast or in randomly fed animals. Glucose tolerance tests (GTT) were performed in conscious mice after a 6-h fast. For GTTs, mice were injected with 1.0 g/kg of D-glucose (Sigma) for 4 h. The cells were then lysed for 5 min at 4°C. For cell sorting, the pellet was resuspended in 1 mL ice-cold PBS, and adherent cells were liberated with 0.05% trypsin–EDTA (Invitrogen, Carlsbad, CA) before stimulated with the following primary antibodies: F4/80 (anti-F4/80; eBioscience); CD11c (anti-CD11c; Biolegend); CD4, CD11c, or B220 (all from BD Pharmingen); CD8 or CD11b (both from Biolegend; Novo Nordisk, Bagsværd, Denmark), and radioactivity was measured by liquid scintillation counting (Tri-Carb 2000; Packard Instruments, Meriden, CT). Blood analysis. Plasma insulin was measured by ELISA (Linco Research). Adiponectin (leptin, TNF-α, resistin, t-Plasminogen activator inhibitor 1 [tPAI-1], MCP-1) were measured with a bio-plex assay using a mouse adipokine kit (Linco Research) and manufacturer’s recommendations. Liver enzymes were measured using an automated analyzer (Olympus AU 2700 chemistry immunoanalyzer). Immunohistochemistry. Liver tissue was collected in formalin and paraffin-embedded, or it was embedded in optimal cutting temperature compound (OCT Tissue-Tek; Sakura Finetek, Torrance, CA) and snap-frozen. For analysis of liver morphology, 5-μm sections of formalin-fixed paraffin-embedded tissues were stained using hematoxylin and eosin. For analysis of infiltrating cell types, sequential 5-μm cryosections were sectioned from the remaining OCT blocks.

**Statistical analyses.** Data are presented as mean ± SEM. Data were analyzed using a Student t test or where appropriate a two-way ANOVA with a Bonferroni post hoc test (GraphPad PRISM, version 4.0; GraphPad Software, Inc., La Jolla, CA); P < 0.05 was considered as significant.

**RESULTS**

Body weight, liver, and adipose tissue weight did not differ between SOC1 LysM-Cre mice and control littermates (Table 1). SOC1 LysM-Cre mice had systemic inflammation as indicated by elevated plasma TNF-α (+130%), IL-6 (+560%), tPAI-1 (46%), and MCP-1 (130%) (Fig. 1A–D).
Leptin levels were increased in SOCS1 LysM-Cre mice (Fig. 1E) in agreement with previous studies demonstrating stimulatory effects of TNF-α on leptin production (32). Serum resistin levels were not different between control and SOCS1 LysM-Cre mice (Fig. 1F).

To examine whether systemic inflammation in SOCS1 LysM-Cre mice was derived from macrophages, we isolated peritoneal cells and sorted them by flow cytometry based on the expression of the macrophage markers CD11b and F4/80 and found that there were no differences in macrophage numbers between genotypes (Fig. 2A). CD11c is considered to be a critical marker of macrophage activation, and we found that, consistent with the increase in serum proinflammatory cytokines, the percentage of CD11c+ macrophages was higher in SOCS1 LysM-Cre mice (Fig. 2B). Using intracellular cytokine staining, we found that 68% of SOCS1 LysM-Cre macrophages secreted IL-6 compared with 37% from littermate controls (Fig. 2C). Likewise, 57% SOCS1 LysM-Cre macrophages secreted TNF-α compared with 36% from littermate controls (Fig. 2D). We also quantitated the amount of each cytokine produced using a cytometric bead array (Fig. 2E) and found that macrophages from SOCS1 LysM-Cre mice secreted more IL-6, TNF-α, and MCP-1 compared to littermate controls. Increased inflammation was also observed in SOCS1 LysM-Cre macrophages isolated from the spleen (data not shown). The increased activation state of macrophages from SOCS1 LysM-Cre mice was also confirmed via RT-quantitative PCR analysis of bone marrow-derived macrophages (Supplementary Table 1). Collectively, these data demonstrate that macrophages from SOCS1 LysM-Cre mice are constitutively more activated compared with macrophages from control mice.

Given that adipose tissue macrophages are the primary source of circulating cytokines, we also examined markers of macrophage infiltration and inflammation from this tissue. Consistent with findings in the peritoneal cavity, the expression of the macrophage markers Emr1 (F4/80) and Cd68 was similar in the adipose tissue of wild-type and SOCS1 LysM-Cre mice (Fig. 2F). However, despite similar macrophage content, adipose tissue expression of Tnfa, Il6, and Il1b was increased in SOCS1 LysM-Cre mice (Fig. 2F). Taken together, these data indicate that increased systemic inflammation in SOCS1 LysM-Cre mice is associated with constitutively activated macrophages. We also have shown previously evidence for T-cell activation in these mice (23).

### Table 1

|                     | FL/FL | SOCS1 LysM-Cre |
|---------------------|-------|----------------|
| Body weight (g)     | 31.1 ± 1.2 | 27.4 ± 1.1 |
| Liver weight (g)    | 1.45 ± 0.1  | 1.28 ± 0.1  |
| Adipose tissue weight (g) | 0.6 ± 0.2 | 0.4 ± 0.1 |
| Fasting glucose (mmol/L) | 6.1 ± 0.3 | 6.9 ± 0.2 |

Data are means ± SEM; n = 12 mice per group. For fasting glucose, P = 0.06.

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Macrophages from SOCS1 LysM-Cre mice are hypersensitive to the inflammatory effects of LPS and saturated fatty acids. Inflammatory cytokine production after activation of TLR4 in macrophages by LPS and palmitic acid has been implicated as a potential mechanism linking inflammation to insulin resistance in obesity (33). Therefore, to test whether macrophages from SOCS1 LysM-Cre mice were hypersensitive to LPS and palmitate, we incubated bone marrow-derived macrophages from SOCS1 LysM-Cre mice and littermates with varying concentrations of these two TLR4 ligands. In the absence of the ligand, macrophage expression of Tnfa, Il6, and Il1b

### Figure 1

FIG. 1. Deletion of SOCS1 from macrophages results in systemic inflammation. Serum concentrations of TNF-α (A), IL-6 (B), MCP-1 (C), PAI-1 (D), leptin (E), and resistin (F) are shown. FL/FL control mice; SOCS1 LysM-Cre mice. Data are means ± SEM; n = 6.
FIG. 2. Macrophages from SOCS1 LysM-Cre mice are constitutively activated and inflamed. Peritoneal cells were isolated and stained with antibodies against F4/80, CD11b, CD11c, or isotype controls and analyzed by flow cytometry. A: Number of F4/80+CD11b+ cells in wild-type and SOCS1 LysM-Cre mice indicated as percentage of viable peritoneal cell population. B: Cells were gated for F4/80+CD11b+ cells and examined for expression of CD11c. Shown is the percentage of CD11c-positive or -negative cells within the total F4/80+CD11b+ population. C and D: Top panels are representative plots; bottom panels are means ± SEM, n = 8 per group. White bars, FL/FL control mice; black bars, SOCS1 LysM-Cre mice. Representative plots of the intracellular cytokine staining to detect secretion of IL-6 (C) and TNF-α (D) in peritoneal macrophages are shown. For each, cells were gated on the CD11b+ population, and data represented in the graph are combined from two experiments and expressed as mean ± SEM; n = 6 per group. E: Quantitation of cytokine secretion by CD11b+ peritoneal macrophages from littermate control and SOCS1 LysM-Cre mice. Secretion of IL-6, TNF, and MCP-1 by CD11b+ peritoneal macrophages was measured by cytokine bead array. F: Adipose tissue expression of Emr1, Cd68, Tnfa, Il6, and Il1b in SOCS1 LysM-Cre and control mice. Data are shown as mean ± SEM; n = 8 per group. White bars, FL/FL control mice; black bars, SOCS1 LysM-Cre mice. For all experiments, *P < 0.05, **P < 0.01, and ***P < 0.001 relative to control. (A high-quality color representation of this figure is available in the online issue.)
was low in control and SOCS1 LysM-Cre mice (Supplementary Table 1). Both LPS and palmitic acid dose-dependently increased Tnfa (Fig. 3A and D) and Il6 (Fig. 3B and E), an effect that was greater in macrophages from SOCS1 LysM-Cre mice. SOCS1 LysM-Cre macrophages also had increased Il1b mRNA in response to LPS (Fig. 3C) but not palmitate (Fig. 3F). TLR4 expression was not altered by genotype, LPS, or palmitate (data not shown).

Overall, these data suggest that increased in
tered by genotype, LPS, or palmitate (data not shown).

Hepatic insulin resistance in SOCS1

tions in glucose homeostasis of SOCS1 LysM-Cre mice, intraperitoneal glucose tolerance tests were performed, and SOCS1 LysM-Cre mice had higher glucose levels and greater area under the curve during the intraperitoneal glucose tolerance tests (Fig. 4B and C).

To assess the specific contribution of hepatic versus peripheral insulin resistance to the perturbed glucose homeostasis observed in SOCS1 LysM-Cre mice euglycemic-hyperinsulinemic-clamp studies were then performed. Basal glucose turnover was similar between the two groups of mice (Supplementary Table 2). The glucose infusion rate (the amount of 50% dextrose solution infused to maintain euglycemia) tended to be lower in SOCS1 LysM-Cre mice (Fig. 5A, P = 0.09). The glucose disposal rate (a measure of predominantly skeletal muscle insulin sensitivity) was not different between groups (Fig. 5B). However, hepatic glucose production (HGP) during the clamp was higher and was suppressed to a lesser degree in SOCS1 LysM-Cre mice (Fig. 5C and D). These results indicate that SOCS1 LysM-Cre mice have hepatic insulin resistance. Consistent with the similar rates of insulin-stimulated glucose disposal measured in vivo during the clamp, glucose uptake (Supplementary Fig. 1A) and Akt phosphorylation (Supplementary Fig. 1B) in isolated extensor digitorum longus muscles were not different between genotypes. This was despite greater muscle inflammation as indicated by elevated Tnfa, Il6, Il1b, and Emr1 (Supplementary Fig. 1C). To elucidate the mechanism underlying preserved muscle insulin sensitivity, despite the presence of greater muscle inflammation, we measured skeletal muscle AMPK phosphorylation (Supplementary Fig. 1D). We found skeletal muscle AMPK phosphorylation to be preserved in SOCS1 LysM-Cre mice, suggesting that IL-6 may have offset the negative effects of TNF-α on these signaling pathways in skeletal muscle (3,46).

Reduced hepatic insulin signaling and increased liver inflammation in SOCS1 LysM-Cre mice. To determine the mechanism of reduced HGP suppression observed during the clamp studies, we examined insulin signaling in the liver during the clamp. IRS-1, IRS-1-associated PKC-ε and Akt phosphorylation were all reduced in the liver of SOCS1 LysM-Cre mice after the clamp (Fig. 6A). Consistent with reduced insulin signaling and increased HGP during the clamp, the expression of Pck1 and G6pc were dramatically increased in SOCS1 LysM-Cre mice (Fig. 6B). Furthermore, the mRNA expression of Socs3, Tnfa, and Il6, as well as the macrophage markers Emr1 and Cd68, were increased in the liver of SOCS1 LysM-Cre mice (Fig. 6C). There was also a trend to increased Socs1 expression, although this did not reach statistical significance. The liver inflammation in SOCS1 LysM-Cre mice was accompanied by an increase in inflammatory cell infiltrate (Fig. 7) and liver enzymes (Supplementary Table 3).
However, liver synthetic function was unaffected as highlighted by similar albumin and bilirubin levels in both genotypes (Supplementary Table 3). This suggests that liver failure was not present in SOCS1 LysM-Cre mice at the time of analysis despite the presence of transaminitis. Taken together, these data indicate that the elevated cytokines associated with macrophage accumulation, liver inflammation, and upregulation of SOCS proteins may lead to hepatic insulin resistance in SOCS1 LysM-Cre mice.

DISCUSSION

Obesity-related insulin resistance is a multifaceted disease involving defects in multiple systems, and the subclinical release of inflammatory mediators by macrophages is one of many factors (3–5). However, the mechanisms underlying the overactivation of the innate immune system in obesity are not fully understood. In the current study, using mice that have constitutively activated macrophages (SOCS1 LysM-Cre mice), we demonstrate the importance of macrophage SOCS1 in maintaining hepatic insulin sensitivity. We show that SOCS1 LysM-Cre mice develop hepatic insulin resistance even in the absence of other factors contributing to obesity-induced insulin resistance. These findings suggest that therapies aimed at reducing SOCS1 in cells indiscriminately may increase systemic inflammation and be detrimental to insulin action.

The SOCS-1 LysM-Cre mouse is a model of inflammatory disease that occurs independent of changes in fat mass/obesity. In adipose tissue of obese humans and rodents, there is an increase in both the content as well as activation of adipose tissue macrophages (4,5,13,34). Although SOCS1 LysM-Cre mice have dramatic increases in macrophage activation, there was no increase in adipose tissue macrophage number. These data demonstrate that inflammation in itself is not sufficient to drive adipose tissue macrophage recruitment despite increases in circulating cytokines such as MCP-1, suggesting that additional factors...
related to the enlarged adipocyte, such as hypoxia (35) or free fatty acids (36), are important for adipose tissue macrophage recruitment in obesity.

Mice with hematopoietic deletion of TLR4 have reduced obesity-related inflammation and insulin resistance (37). The TLR4 ligands LPS and saturated fatty acids are both elevated in obesity, and this may explain the beneficial effects of TLR4 deletion on these parameters. Although it has been recognized for over a decade that SOCS1 is an important regulator of immune and inflammatory responses (22,23), more recent studies have demonstrated that the mechanisms by which SOCS1 inhibits inflammation involve downregulation of TLR4 signaling (21). In the current study, we demonstrate that SOCS1 LysM-Cre mice have increased CD11c+ macrophages and elevated circulating levels of inflammatory cytokines. In agreement with previous studies, we show that an important source of this increased inflammatory response is not only heightened sensitivity to LPS (current study and 23,38) but also to the saturated fatty acid palmitate. Future studies in SOCS1 LysM-Cre mice treated with antibiotics or nicotinic acid, to reduce circulating LPS and free fatty acids, respectively, are warranted to confirm the importance of the SOCS1/TLR4 pathway in vivo.

In the current study euglycemic-hyperinsulinemic clamps showed that the hyperinsulinemia and glucose intolerance of SOCS1 LysM-Cre mice was a result of insulin resistance in the liver. Consistent with this, we found that IRS-1 phosphorylation, IRS-1-associated p85 subunit of PI-3 kinase, and Akt phosphorylation were all reduced in the liver of SOCS1 LysM-Cre mice. Furthermore, this insulin resistance was associated with increased Socs3 expression consistent with previous reports showing an essential role for Socs3 in mediating cytokine-induced liver insulin resistance (28). The exact cause of hepatic insulin resistance in SOCS1 LysM-Cre mice is not known since we observed increases in both systemic and local (liver) inflammation. The observed increases in circulating cytokines such as...
TNF-α, IL-6, and IL-1β were higher than typically observed in obesity; however, our observed increases in liver macrophage content and activation are consistent with other rodent models of obesity (28,39,40). In support of the critical role of macrophages in mediating the liver insulin resistance of SOCS1 LysM-Cre mice, we have found that liver-specific deletion of SOCS1 does not affect serum glucose or insulin levels, glucose or insulin tolerance or hepatic insulin sensitivity as assessed by euglycemic-hyperinsulinemic clamp (N.S., S.L.F., G.R.S., and T.W.K., unpublished observations).

Our findings do pose the interesting question of why inflammation in SOCS1 LysM-Cre mice did not cause muscle insulin resistance. One possibility may be because of the elevated levels of IL-6 in SOCS1 LysM-Cre mice. Chronic elevations in IL-6 in muscle promote whole-body insulin sensitivity in lean (41) or obese mice (42). Consistent with this, IL-6 induces SOCS3 expression by twofold in muscle (45), which results in reduced fatty acid oxidation (43,44), effects that may be mediated by suppression of skeletal muscle AMPK signaling (3). However, in the current study, we found no difference in skeletal muscle Akt (Supplementary Fig. 1B) or AMPK (Supplementary Fig. 1D) phosphorylation, which may be because IL-6 had offset the negative effects of TNF-α on these signaling pathways. Although the reasons behind the tissue-specific effects of IL-6 on insulin action remain unknown, it has been speculated that low density of the signaling gpl30 receptor in skeletal muscle (45), which results in reduced SOCS3 expression, may be important (46). Consistent with this, IL-6 induces SOCS3 expression by twofold in muscle but 25-fold in liver (46). Therefore, although speculative, increased IL-6 levels may have negated the detrimental effects of TNF-α on skeletal muscle insulin action in SOCS1 LysM-Cre mice. Future studies following IL-6 neutralization in SOCS1 LysM-Cre mice may help determine whether this is an important factor.

Genetic polymorphisms in the promoter regions of the SOCS1 gene that increase its transcriptional activity have been shown to associate with insulin sensitivity despite the presence of obesity and higher BMI (24). Because SOCS1 directly inhibits insulin signaling through ubiquitination of IRS-2 (26,27), the finding that increased transcriptional activity of SOCS1 is associated with improved insulin sensitivity was difficult to comprehend. However, in light of our findings demonstrating the pronounced hyperinsulinemia, glucose intolerance, and hepatic insulin resistance in SOCS1 LysM-Cre mice, it is possible that attenuation of macrophage inflammation may be the primary mechanism by which this polymorphism, which increases SOCS1 expression, improves insulin sensitivity (24). Taken together, these data suggest that macrophage expression of SOCS1 is a critical regulator of inflammation and hepatic insulin sensitivity and that strategies aimed at increasing macrophage SOCS1 expression may be important for the treatment of insulin resistance.

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N.S. researched data, contributed to the discussion, and wrote the manuscript. K.L.G. and S.G. researched data, contributed to the discussion, and reviewed and edited the manuscript. J.E.H. researched data and contributed to the discussion. S.L.F. and K.A.H. assisted with experiments. G.R.S. and T.W.K. designed the study, contributed to the discussion, and edited the manuscript.

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