Amyloid-β Induces Hepatic Insulin Resistance by Activating JAK2/STAT3/SOCS-1 Signaling Pathway

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Insulin resistance is a fundamental aspect of the etiology of type 2 diabetes mellitus (T2DM), characterized by the function of impaired insulin on glucose disposal in skeletal muscle, adipocytes, and hepatic glucose production (1). Epidemiological studies indicate that patients with Alzheimer’s disease (AD) have impaired glucose regulation and an increased risk of developing T2DM (2,3). Similarly, experimental studies demonstrate that the cross-bred mice of APP23 transgenic AD model mice and ob/ob mice showed an accelerated diabetic phenotype compared with ob/ob mice, which suggests that AD exacerbates T2DM (2,3). However, the underlying mechanism is still largely unknown.

As a normal product during cell metabolism, Aβ has an early and vital role in the pathogenesis of AD according to the amyloid cascade hypothesis (5,6). In the central nervous system, Aβ has been reported to impair neuronal synaptic function in early AD by compromising insulin signaling (7–10). On the other hand, insulin can affect both the production and degradation of Aβ (11,12). It is believed that Aβ is expressed primarily in the central nervous system, and there is a normal dynamic equilibrium between cerebrospinal fluid and plasma Aβ (13,14). Meanwhile Aβ is also produced by peripheral cells (15,16), and peripheral tissues might contribute to both the circulating amyloid pool and AD pathology (15). But the role of Aβ in peripheral tissues is still unclear. Recent studies show that plasma Aβ levels have a positive correlation with body fat in healthy individuals and adipocyte amyloid precursor protein expression in obese individuals (17,18). These findings and the strong link between AD and T2DM (2–4) prompt us to examine whether the pathogenic factor Aβ of AD could influence insulin sensitivity in peripheral tissues.

In this study, we found that plasma Aβ40/42 levels were increased in patients with hyperglycemia. Remarkably, APPsw/PSEN1E9 transgenic AD model mice with increased plasma Aβ40/42 levels showed impaired glucose and insulin tolerance, hyperinsulinemia, and Aβ decreased insulin sensitivity in mouse liver and cultured hepatocytes. Furthermore, we showed that Aβ impaired hepatic insulin signaling mainly through the JAK2/STAT3/SOCS-1 pathway.

RESEARCH DESIGN AND METHODS

Reagents. Aβ25–35, AG490, DAPI, trypan blue solution, 3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyltetrazoliumbromide (MTT), and periodic acid Schiff (PAS) were from Sigma. Aβ42 was from Apeptide (Jiangsu, China). Aβ25–35 was dissolved in PBS at 1 mM and stored at −80°C and incubated at 37°C for 1 day before use as described previously (19). Aβ42 was dissolved in water at 2 mM and stored at −80°C and incubated at 37°C for 3 days before use as described (20). Antibodies against insulin receptor (InsR), Tyr1150/1151-phosphorylated InsR, Tyr1146-phosphorylated InsR, Thr308-phosphorylated Akt, Ser473-phosphorylated Akt, Akt, Ser9-phosphorylated glycogen synthase kinase (GSK)-3β, GSK-3β, SOCS-1, SOCS-3, Tyr705-phosphorylated STAT3, Tyr1007/1018-phosphorylated JAK2, Tyr505-phosphorylated STAT1, STAT3, or JAK2 were from Cell Signaling. Antibodies against α-tubulin or β-actin were from Sigma.

Animals. All animals were maintained and used in accordance with the guidelines of the Institutional Animal Care and Use Committee of the Institute for Nutritional Sciences, Shanghai Institutes for Biological Sciences, Chinese Academy of Sciences, Graduate School of the Chinese Academy of Sciences, Shanghai, China. Adult male C57BL/6 mice from Shanghai Slac (Shanghai, China). APPsw/PSEN1E9 (APP/PS1) mice and their wild-type littermates were from Jackson Laboratory (Stock number: 004402). Because the menstrual cycle could affect insulin sensitivity (21), only male mice were used in this study. The liver samples of APPsw/Ps1129+1307F mice (Jackson Laboratory; Stock number: 003378) and the wild-type controls were provided by Dr. Weidong Le (Baylor College of Medicine). Tissues of interest were snap-frozen in liquid nitrogen immediately after resection and stored at −80°C.

Cell culture and treatments. Primary mouse hepatocytes were isolated and cultured after perfusion and collagenase digestion of the liver (22). H4IIE and HepG2 hepatoma cells were cultured in minimum essential medium and Dulbecco’s modified Eagle’s medium, respectively, with 10% FBS. After overnight culture, cells were treated with Aβ in serum-free medium. AG490 was added after treatment with Aβ for 24 h.

Immunoblot and ELISA. Immunoblot was performed with antibodies against the indicated protein and quantified as described (23). Plasma Aβ40/42 levels were measured by ELISA kits from Covance.

Hepatocyte glucose production. Glucose production in H4IIE cells was measured as described previously (24). In brief, after the indicated treatments, cells in 12-well plate were incubated with 300 μM per well of glucose production buffer (glucose-free Dulbecco’s modified Eagle’s medium, pH 7.4, containing 20 mM sodium lactate and 2 mM sodium pyruvate without phenol red) for...
We then evaluated the potential roles of Aβ in whole-body insulin action and glucose metabolism using APPSwet/PSEN1dE9 (APP/PS1) mice. The APP/PS1 double transgenic mouse is a common AD mouse model, which overexpresses amyloid precursor protein and γ-secretase leading to overexpression of Aβ40/42 and development of amyloid deposits in the brain at ~6 months of age (28). As described previously (29), we also found that plasma Aβ40/42 levels were markedly elevated in 20-week-old APP/PS1 mice before the deposit appeared (Fig. 1B). Body weight and food intake were similar between APP/PS1 and wild-type littersmates (Supplementary Fig. 1A and B). Consistently, their fat content, lean content, plasma alanine transaminase and aspartate transaminase activity, and plasma triglyceride, total cholesterol, high-density lipoprotein cholesterol, and low-density lipoprotein cholesterol levels were indistinguishable with their wild-type littersmates (Supplementary Fig. 1C–F). Nevertheless, the glucose tolerance tests revealed that the glucose metabolism had a significant difference at 10 weeks of age and markedly deteriorated at 18 weeks of age in APP/PS1 mice (Fig. 1C–E). The insulin tolerance tests showed that insulin sensitivity moderately decreased at 13 weeks of age and severely decreased at 19 weeks of age in APP/PS1 mice (Fig. 1F–H). Moreover, the fasting and fed plasma insulin levels were significantly increased in 20-week-old APP/PS1 mice compared with wild-type littersmates (Fig. 1J), which suggests that insulin resistance induced compensatory insulin secretion in APP/PS1 mice. Taken together, these results demonstrate that APP/PS1 transgenic mice with increased Aβ levels develop systemic insulin resistance.

Aβ decreases insulin sensitivity in mouse liver and cultured hepatocytes. As circulating peripheral Aβ is uptaken and catabolized mainly by liver (30), we investigated the effect of Aβ on hepatic insulin sensitivity. Immunoblot showed that insulin-stimulated phosphorylation of InsR at Tyr1150/1151, as well as Akt at Thr308 and Ser473, was markedly decreased in the liver of APP/PS1 mice (Fig. 2A and B). To explore whether Aβ can impair insulin signaling directly, we treated mouse primary hepatocytes with Aβ25–35, the biologically active fragment of Aβ (31), at the similar direct concentration for neuronal cells (26). Immunoblot showed that insulin-stimulated phosphorylation of InsR at Tyr1150/1151 and Tyr1146, as well as Akt at Thr308 and Ser473, and GSK3β at Ser9 was impaired by Aβ25–35 in a dose- and time-dependent manner (Fig. 2C and D). Similarly, Aβ25–35 inhibited insulin-stimulated phosphorylation of InsR, Akt, and GSK3β in a dose- and time-dependent manner in HepG2 human hepatoma cells (Supplementary Fig. 2A and B). Full-length Aβ42 also showed similar effect on insulin signaling (Fig. 2E). We then investigated the effect of Aβ on insulin-induced suppression of glucose production in H4IEE rat hepatoma cells. Glucose release from the H4IEE cells was inhibited about 60% after insulin treatment, but the inhibitory effect of insulin on glucose output gradually declined with increasing dose of Aβ25–35 (Fig. 2F). In addition, no obvious effect of Aβ25–35 and Aβ42 on cell morphology or cell viability was observed in the above treatments, when monitored under a microscope or by MTT cell viability assay (Supplementary Fig. 3). These data demonstrate that Aβ can decrease insulin sensitivity in mouse liver and cultured hepatocytes.

Aβ induces insulin resistance in hepatocytes by upregulation of SOCS-1. It is well known that Aβ can trigger inflammatory reactions in microglia and neuron, and inflammatory signaling is involved in the development
of insulin resistance (32,33). To study whether inflammatory reactions are involved in Aβ-induced insulin resistance, we measured the inflammatory signaling in liver, muscle, and white adipose tissue (WAT) of APP/PS1 mice. We found that SOCS-1 and SOCS-3 mRNA levels were upregulated in liver (Fig. 3A), and the mRNA levels of GP130 in liver, IL-1α, and IL-8R in WAT were also increased (Supplementary Fig. 4B and D). However, the mRNA levels of other inflammatory factors and their downstream mediators were not altered in liver, muscle, and WAT (Supplementary Fig. 4A–D). These data suggest there was no obvious inflammatory reaction in liver, muscle, and WAT of APP/PS1 mice. It has been reported that upregulation of SOCS-1 and SOCS-3 not only inhibits cytokine signaling, but also induces insulin resistance (34,35). Immunoblot showed that the protein level of SOCS-1, but not SOCS-3, was markedly elevated in liver of another AD mouse model, APPswe/PS1(A246E) transgenic mice (36). APPswe/PS1(A246E) mice also overexpress Aβ, and their serum Aβ42 level is about five times higher than that of APP/PS1 mice at the age of 5 months (36). Immunofluorescence showed that SOCS-1 was also elevated in liver of APPswe/PS1(A246E) mice (Fig. 3D). Taken together, these results raise the possibility that SOCS-1 might be involved in the development of insulin resistance in APP/PS1 mice.

To investigate whether the upregulation of SOCS-1 is directly induced by Aβ, we treated mouse primary hepatocytes with Aβ25–35 and found that the mRNA level of SOCS-1, but not SOCS-3, was induced by Aβ25–35 in a time-dependent manner (Fig. 4A). Consistently, the SOCS-1 protein level was upregulated by Aβ25–35 in a time- and dose-dependent manner, whereas the SOCS-3 protein level remained unchanged (Fig. 4B and C). Similar results were observed when treated with Aβ42 (Fig. 4D). These results demonstrate that Aβ can upregulate the mRNA and protein level of SOCS-1.

To investigate whether SOCS-1 upregulation contributes to the insulin resistance induced by Aβ, we knocked down SOCS-1 by siRNA (Fig. 5A and B). As expected, knockdown of SOCS-1 by two different siRNAs all abolished the decreased phosphorylation of InsR and Akt induced by Aβ25–35 in mouse primary hepatocytes (Fig. 5C and D). Consistently, knockdown of SOCS-1 also attenuated the decreased phosphorylation of InsR and Akt induced by Aβ42 in mouse primary hepatocytes (Fig. 5E and F). These results together demonstrate that Aβ induces insulin resistance by upregulation of SOCS-1.

Aβ upregulates SOCS-1 and impairs insulin signaling in hepatocytes mainly through the JAK2/STAT3 pathway. We next explored the mechanism by which Aβ upregulates SOCS-1. The expression of SOCS-1 can be induced by activation of the JAK/STAT pathway (34), and Aβ can regulate STAT3 and JAK2 in neurons (26,37). So we first assessed whether STAT3 can be activated by Aβ25–35 in mouse primary hepatocytes. Immunoblot showed Aβ25–35 induced phosphorylation of STAT3 at Tyr705 in a dose-dependent manner (Fig. 5B). These results suggest that STAT3 can be activated by Aβ25–35 in mouse primary hepatocytes.

**FIG. 1.** Aβ affects the development of insulin resistance in vivo. A: Quantification of plasma Aβ40/42 levels in euglycemic and hyperglycemic subjects (n = 26–35 per group) by ELISA. B: Quantification of plasma Aβ40/42 levels in APP/PS1 mice and wild-type (WT) littermates (n = 4 per genotype) at 20 weeks of age by ELISA. ND, not detectable. C and D: Glucose tolerance tests (2 g/kg) in male APP/PS1 mice at the age of 10 weeks (10w; C) or 18 weeks (18w; D) (n = 14–16 per age) and male WT littermates (n = 17–19 per age). E: Area under the curve (AUC) of glucose tolerance tests in F and G: Plasma insulin levels in APP/PS1 mice (n = 6, 4) and WT littermates (n = 6, 6) at 20 weeks of age under fasting and fed states. Data are presented as mean and SEM. *P < 0.05, **P < 0.01, ***P < 0.001.
manner in hepatocytes, whereas phosphorylation of STAT1 at Tyr701 was not affected (Fig. 6A), suggesting that Aβ can specifically activate STAT3. Meanwhile phosphorylation of JAK2 at Tyr1007/1008 showed a similar pattern as STAT3 (Fig. 6A). Immunoblot also showed Aβ25–35 activated STAT3 and JAK2 in a time-dependent manner in hepatocytes (Fig. 6B), and Aβ42 had a similar effect (Fig. 6C). Furthermore, we found that the tyrosine phosphorylation levels of STAT3 and JAK2 were also significantly increased in the liver of APP/PS1 mice compared with wild-type

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**FIG. 2.** Aβ impairs insulin signaling in vivo and in vitro. A: Insulin-stimulated phosphorylation of insulin receptor (InsR) and Akt in liver of APP/PS1 and wild-type (WT) littermates at 20 weeks of age was measured by immunoblot. B: Quantification of phosphorylated InsR and Akt levels in A. The protein levels were normalized to tubulin. C–E: The effect of Aβ25–35 (C and D) and Aβ42 (E) on insulin signaling, including the phosphorylation of InsR, Akt, and GSK-3β in mouse primary hepatocytes was analyzed by immunoblot. Cells were incubated with the indicated concentrations of Aβ25–35 for 60 h (C), with 10 μmol/L Aβ25–35 for the indicated times (D) or with 10 μmol/L Aβ42 for 60 h (E) followed by treatment with or without 100 nmol/L insulin for 20 min. F: Aβ25–35 attenuated insulin-inhibited glucose production in H4IE rat hepatoma cells. Cells were incubated with the indicated concentrations of Aβ25–35 for 60 h and then treated with 50 nmol/L insulin for 3 h to measure the glucose production. Data are presented as mean and SEM. *P < 0.05, **P < 0.01, ***P < 0.001.
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littermates (Fig. 6D and E), suggesting JAK2/STAT3 is in a more active state in the liver of APP/PS1 mice. Immunoblot showed that the tyrosine phosphorylation levels of STAT3 and JAK2 were also elevated in the liver of APPSwe/PS1(A246E) mice (Fig. 6F and G). These results demonstrate hepatic JAK2/STAT3 is in a more active state in mice with overexpression of Aβ.

We then determined whether SOCS-1 upregulation induced by Aβ depended on STAT3 and JAK2. Immunoblot showed that the upregulation of SOCS-1 induced by Aβ25–35 was abolished when STAT3 was knocked down by siRNA in mouse primary hepatocytes (Fig. 7A). Consistently, immunoblot showed that the tyrosine phosphorylation of JAK2 and STAT3 and upregulation of SOCS-1 induced by Aβ25–35 were attenuated by AG490, an inhibitor of JAK2, in hepatocytes (Fig. 7B). To further confirm the role of JAK2 in SOCS-1 upregulation, JAK2 was knocked down by siRNA. Similarly, immunoblot showed that tyrosine phosphorylation of JAK2 and STAT3 and upregulation of SOCS-1 induced by Aβ25–35 were attenuated when JAK2 was knocked down (Fig. 7C and D).

Next, we investigated the effect of Aβ on insulin signaling when JAK2/STAT3 signaling was inhibited. As shown in Fig. 8A and B, the decreased phosphorylation of InsR and Akt caused by Aβ25–35 was restored by STAT3 siRNA. Consistently, the decreased phosphorylation of InsR and Akt caused by Aβ25–35 was also alleviated by JAK2 inhibitor AG490 (Fig. 8C and D). Moreover, the decreased phosphorylation of InsR and Akt caused by Aβ25–35 was also alleviated by JAK2 siRNA (Fig. 8E and F). Together, these results demonstrate that Aβ activates JAK2/STAT3, which leads to SOCS-1 upregulation and insulin resistance.

DISCUSSION

The results presented here indicate that Aβ induces insulin resistance in hepatocytes by activating JAK2/STAT3/SOCS-1 signaling pathway and suggest an important role of peripheral Aβ in modulating systemic insulin sensitivity and glucose metabolism.

Although epidemiological studies indicate patients with AD have impaired glucose regulation and an increased risk of developing T2DM (2,3), only a small portion of AD patients develop impaired fasting glucose and T2DM. Notably, plasma Aβ levels in AD patients have been reported to be increased or unchanged compared with controls (38,39), which limits the utility of plasma Aβ as a diagnostic marker of AD. The marginal change of plasma Aβ in AD may at least partially explain why only a small portion of AD patients develop impaired fasting glucose and T2DM. On the other hand, epidemiological studies indicate patients with T2DM have a significantly higher risk of developing AD (40), and experimental studies suggest that T2DM exacerbates AD (41). We observed that plasma Aβ levels are elevated in hyperglycemic subjects (Fig. 1A), but the causality and underlying mechanism between hyperglycemia and the increased plasma Aβ levels are still unclear. It has been reported that Aβ generation or aggregation is enhanced in brain of hyperglycemic or hyperinsulinemic mice (41,42). In this study, we used APP/PS1 transgenic mice with increased plasma Aβ levels to study the potential effect of Aβ on insulin sensitivity in vivo. However, this transgenic mouse model has its limitations, and further in vivo studies would be necessary to verify the effect of Aβ on insulin signaling in peripheral tissues. Nevertheless, previous epidemiological and experimental studies combined with our findings suggest that Aβ is an important pathogenic link between T2DM and AD.
Obesity is associated with an increased risk of developing insulin resistance and type 2 diabetes (43). In humans, plasma Aβ has a positive correlation with increased body fat (17). APP is overexpressed in subcutaneous abdominal adipocytes from obese humans (16). ApoE4 genotype, a high genetic risk factor for AD, has defects in Aβ clearance (5). Male obese ApoE4 carriers presented increased blood insulin and glucose levels (44). High-fat/cholesterol diet can promote Aβ generation in mice (42,45). These findings raised the possibility that Aβ may contribute to the complicated metabolic syndrome caused by obesity. In addition, APP23 transgenic AD model mice crossed with ob/ob or NSY diabetic model mice showed a deteriorated diabetic phenotype (4). Mice loss of β-site amyloid precursor protein-cleaving enzyme 1 exhibited reduced Aβ level and improved peripheral insulin sensitivity (46). These reports support the negative effect of Aβ on insulin sensitivity. We observed that Aβ-induced insulin resistance was not obvious in cultured hepatocytes until treatment for 48 h, and then the impaired insulin signaling lasted and deteriorated with time (Fig. 2D and Supplementary Fig. 2B). Similarly, the impaired glucose tolerance and insulin tolerance also worsened with time in APP/PS1 mice (Fig. 1C–H). These results are consistent with the chronic pathogenesis of T2DM and AD.

Previous studies showed that the physiological levels of plasma Aβ40/42 may range from tens to hundreds of picograms per milliliter (17,38), which are consistent with our observation (Fig. 1A and Supplementary Table 1). Aβ is prone to aggregate both in vitro and in vivo (47), and Aβ deposition is detectable in tissues other than brain in AD patients (48). However, whether Aβ deposition is detectable in the periphery of hyperglycemic subjects needs to be studied in the future. The Aβ used in this study was preincubated at 37°C. This method has been reported to promote the aggregation of Aβ (49). Immunoblot showed that the preincubation of Aβ resulted in various Aβ forms from monomers to oligomers and higher order forms (Supplementary Fig. 5). Which form of Aβ plays the major role in inducing insulin resistance and diabetes remains to be determined. Further studies are needed to investigate this issue.

**FIG. 4.** Aβ induces the upregulation of SOCS-1 in cultured hepatocytes. A: Quantitative RT-PCR analysis of SOCS-1 and SOCS-3 mRNA levels in mouse primary hepatocytes treated with 10 μmol/L Aβ25–35 for the indicated times. B: Immunoblot analysis of SOCS-1 and SOCS-3 protein levels in mouse primary hepatocytes treated with 10 μmol/L Aβ25–35 for the indicated times. C: Immunoblot analysis of SOCS-1 and SOCS-3 protein levels in mouse primary hepatocytes treated with the indicated concentrations of Aβ25–35 for 60 h. D: Immunoblot analysis of SOCS-1 and SOCS-3 protein levels in mouse primary hepatocytes treated with 10 μmol/L Aβ42 for 60 h. Data are presented as mean and SEM. *P < 0.05, **P < 0.01.

**FIG. 5.** Upregulation of SOCS-1 is required for the insulin resistance induced by Aβ. A: Knockdown of SOCS-1 in primary hepatocytes by two different siRNAs was confirmed by immunoblot. B: Quantification of SOCS-1 protein levels in A. C: Phosphorylation states of InsR and Akt in primary hepatocytes treated with or without Aβ25–35 for 60 h in the presence of the indicated siRNA with or without 100 nmol/L insulin for 20 min were analyzed by immunoblot. D: Quantification of phosphorylated InsR and Akt levels in C. E: Phosphorylation states of InsR and Akt in primary hepatocytes treated with or without Aβ42 for 60 h in the presence of the indicated siRNA with or without 100 nmol/L insulin for 20 min were analyzed by immunoblot. F: Quantification of phosphorylated InsR and Akt levels in E. All the protein levels were normalized to tubulin. Data are presented as mean and SEM. *P < 0.05, **P < 0.01. NS, no significant difference.
role in Aβ-induced impaired hepatic insulin signaling is yet to be investigated in the future.

It has been reported that cytokines induce insulin resistance by induction of several SOCS proteins (34). In this study, we showed that Aβ specifically upregulated SOCS-1 but didn’t affect SOCS-3 protein levels in hepatocytes (Fig. 4B–D) and mouse liver (Fig. 3B and C), which imply that the upregulation of SOCS-1 by Aβ does not result from the induction of inflammatory cytokines. Consistently, we didn’t observe obvious inflammatory reaction in liver,

FIG. 6. Aβ induces the activation of JAK2/STAT3. A: Immunoblot analysis of phosphorylation levels of STAT1, STAT3, and JAK2 in mouse primary hepatocytes treated with the indicated concentrations of Aβ25–35 for 36 h. B: Immunoblot analysis of phosphorylation levels of STAT3 and JAK2 in mouse primary hepatocytes treated with 10 μmol/L Aβ25–35 for the indicated times. C: Immunoblot analysis of phosphorylation levels of STAT3 and JAK2 in mouse primary hepatocytes treated with 10 μmol/L Aβ42 for 36 h. D: Immunoblot analysis of liver STAT3 and JAK2 phosphorylation states in APP/PS1 mice and wild-type (WT) littermates at 20 weeks of age (n = 3 per genotype). E: Quantification of phosphorylated STAT3 and JAK2 levels in D. F: Immunoblot analysis of liver STAT3 and JAK2 phosphorylation states in APPswe/PS1[A246E] mice and WT controls at 9 months of age. G: Quantification of phosphorylated STAT3 and JAK2 levels in F. All the protein levels were normalized to tubulin. Data are presented as mean and SEM. *P < 0.05, **P < 0.01.

FIG. 7. JAK2/STAT3 signaling is required for the SOCS-1 upregulation induced by Aβ. A: Knockdown of STAT3 by siRNA blocked the upregulation of SOCS-1 by Aβ. B: Inhibition of JAK2 by AG490 blocked the phosphorylation of JAK2 and STAT3 and the upregulation of SOCS-1 induced by Aβ. C: Knockdown of JAK2 by siRNA blocked the phosphorylation of JAK2 and STAT3 induced by Aβ. D: Knockdown of JAK2 by siRNA blocked the upregulation of SOCS-1 induced by Aβ.
A phosphorylation of InsR and Akt under insulin-resistant conditions induced by Aβ diabetes-infused conditions (23), and the development of insulin resistance in mice fed high-fat diet needs more than 2 months (23). Thus it is reasonable to observe the development of insulin resistance in hepatocytes after a chronic treatment. It has been reported that Aβ is an inducer of reactive oxygen species (ROS) (6). On the other hand, ROS have been shown to induce the activation of JAK2 (52). So ROS might be involved in the activation of JAK2/STAT3 signaling by Aβ. Future studies to figure out the upstream signaling of JAK2/STAT3 in Aβ-induced insulin resistance will be important to further elucidate the underlying molecular mechanisms.

Insulin signaling is involved in a variety of neuronal functions (12). Meanwhile, previous in vitro and in vivo studies showed insulin increases the extracellular level of Aβ by promoting its production/secretion and inhibiting its degradation via insulin-degrading enzyme (11,12). In addition, in the central nervous system, Aβ has been reported to compromise insulin signaling to impair neuronal function (7–10). Aβ competitively binds to InsR, interferes with its autophosphorylation, and prevents the activation of downstream kinases required for long-term potentiation in hippocampal neurons (7,10). Aβ oligomers caused down-regulation of plasma membrane InsR and synaptic spine deterioration in hippocampal neurons, which can be prevented by insulin in a rosiglitazone-enhanceable manner (8,9). These studies suggest that the early neuronal damage in AD might be triggered by Aβ-induced impairment of insulin signaling, and stimulation of insulin signaling is a potential strategy to treat AD (53). Whether binding to InsR and down-regulation of plasma membrane InsR are involved in Aβ-induced insulin resistance in peripheral tissues needs to be further studied. Our study focused on the role of Aβ in the periphery and demonstrates that Aβ induces insulin resistance in hepatocytes by activating the JAK2/STAT3/SOCS-1 signaling pathway. These findings suggest that strategies aimed at reducing peripheral Aβ signaling might be beneficial for insulin resistance and T2DM.

muscle, and WAT of APP/PS1 mice (Supplementary Fig. 4B–D). SOCS-1 is increased in the liver of insulin-resistant obese animals (35,50). Similarly, we observed that SOCS-1 is upregulated in the liver of APP/PS1 mice (Fig. 3A–C). SOCS-1 directly overexpressed in the liver can cause insulin resistance, and inhibition of SOCS-1 in obese diabetic mice improves insulin sensitivity (35). In addition, reduction of SOCS-1 in 3T3-L1 adipocytes alleviates the impaired insulin signaling caused by TNF-α (50). Consistently, we found APP/PS1 mice with upregulation of SOCS-1 in liver is insulin resistant (Fig. 1C–I), and knockdown of SOCS-1 in hepatocytes can attenuate the insulin resistance induced by Aβ (Fig. 5C–F). It has been reported that overexpression of SOCS-1 can target IRS1 and IRS2 for ubiquitin-mediated degradation in HEK293 cells (51). Another study reported SOCS-1 can target IRS1 and IRS2 for ubiquitin-mediated degradation in HEK293 cells (51). Another study reported SOCS-1 can target IRS1 and IRS2 for ubiquitin-mediated degradation in HEK293 cells (51). Another study reported SOCS-1 can target IRS1 and IRS2 for ubiquitin-mediated degradation in HEK293 cells (51). Another study reported SOCS-1 can target IRS1 and IRS2 for ubiquitin-mediated degradation in HEK293 cells (51). Another study reported SOCS-1 can target IRS1 and IRS2 for ubiquitin-mediated degradation in HEK293 cells (51). Another study reported SOCS-1 can target IRS1 and IRS2 for ubiquitin-mediated degradation in HEK293 cells (51). Another study reported SOCS-1 can target IRS1 and IRS2 for ubiquitin-mediated degradation in HEK293 cells (51). Another study reported SOCS-1 can target IRS1 and IRS2 for ubiquitin-mediated degradation in HEK293 cells (51)...
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Y.Z. and Q.Z. designed the study, analyzed the data, and wrote the manuscript. The experiments were performed by Y.Z., B.Z., F.Z., J.W., Y.H., and Y.L. Q.Z. supervised the project. Q.Z. is the guarantor of this work and, as such, had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

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