The Prostaglandin E2 Receptor EP4 Regulates Obesity-Related Inflammation and Insulin Sensitivity
（EP4 受容体は肥満に伴う炎症やインスリン抵抗性を調節する）

安井　美加

The Prostaglandin E2 Receptor EP4 Regulates Obesity-related Inflammation and Insulin Sensitivity

Mika Yasui[1], Yukinori Tamura[1,2], Manabu Minami[1]*, Sei Higuchi[1], Risako Fujikawa[1], Taichi Ikedo[1,3], Manabu Nagata[1,3], Hidenori Arai[4], Toshinori Murayama[1], and Masayuki Yokode[1]

[1] Department of Clinical Innovative Medicine, Kyoto University Graduate School of Medicine, Kyoto, Kyoto, Japan

[2] Department of Physiology and Regenerative Medicine, Kinki University Faculty of Medicine, Osakasayama, Osaka, Japan

[3] Department of Neurosurgery, Kyoto University Graduate School of Medicine, Kyoto, Kyoto, Japan

[4] National Center for Geriatrics and Gerontology, Obu, Aichi, Japan

* Corresponding author

E-mail: mminami@kuhp.kyoto-u.ac.jp (MM)

Abstract

With increasing body weight, macrophages accumulate in adipose tissue. There, activated macrophages secrete numerous proinflammatory cytokines and chemokines, giving rise to chronic inflammation and insulin resistance. Prostaglandin E_2 suppresses macrophage activation via EP4; however, the role of EP4 signaling in insulin resistance and type 2 diabetes mellitus remains unknown. In this study, we treated *db/db* mice with an EP4-selective agonist, ONO-AE1-329, for 4 weeks to explore the role of EP4 signaling in obesity-related inflammation *in vivo*. Administration of the EP4 agonist did not affect body weight gain or food intake; however, in the EP4 agonist–treated group, glucose tolerance and insulin resistance were significantly improved over that of the vehicle–treated group. Additionally, administration of the EP4 agonist inhibited the accumulation of F4/80-positive macrophages and the formation of crown-like structures in white adipose tissue, and the adipocytes were significantly smaller. The treatment of the EP4 agonist increased the number of anti-inflammatory M2 macrophages, and in the stromal vascular fraction of white adipose tissue, which includes macrophages, it markedly decreased the levels of proinflammatory cytokines and chemokines. Further, EP4 activation increased the expression of adiponectin and peroxisome proliferator–activated receptors in white adipose tissue. Next, we examined *in vitro* M1/M2 polarization assay to investigate the impact of EP4 signaling on determining the functional phenotypes of macrophages. Treatment with EP4 agonist enhanced M2 polarization in wild-type

peritoneal macrophages, whereas EP4-deficient macrophages were less susceptible to M2 polarization. Notably, antagonizing peroxisome proliferator–activated receptor δ activity suppressed EP4 signaling-mediated shift toward M2 macrophage polarization. Thus, our results demonstrate that EP4 signaling plays a critical role in obesity-related adipose tissue inflammation and insulin resistance by regulating macrophage recruitment and polarization. The activation of EP4 signaling holds promise for treating obesity and type 2 diabetes mellitus.

Introduction

Obesity predisposes to several metabolic diseases such as insulin resistance, type 2 diabetes mellitus (T2DM), and arteriosclerosis. Developing novel approaches for the prevention and treatment of T2DM is a matter of great importance.

Excess calorie intake contributes to increased body weight, which is associated with larger adipocytes, preadipocyte differentiation, and abnormal adipokine secretion [1]. Hypertrophic adipocytes secrete monocyte chemotactic protein-1 (MCP-1), which promotes macrophage infiltration into obese adipose tissue, thus inducing chronic, low-grade inflammation [2]. White adipose tissue (WAT) is an important site for obesity-related chronic inflammation where adipose tissue macrophages (ATMs) produce proinflammatory cytokines and chemokines, such as tumor necrosis factor alpha (TNFα) and MCP-1 [3]. The activation of inflammatory signaling can trigger whole-body

insulin resistance by directly influencing insulin signaling [4-6].

There are two major phenotypes for macrophages, M1 (classically activated) and M2 (alternatively activated) [7]. M1 macrophages produce proinflammatory cytokines and are induced by Th1 cell–derived interferon (IFN) γ and lipopolysaccharide (LPS). By contrast, M2 macrophages reduce inflammatory responses by producing anti-inflammatory factors, such as interleukin (IL)-10 and transforming growth factor (TGF)-β [7], and mainly reside in lean adipose tissue. When mice on a high-fat diet become obese, M1 macrophages accumulate in the adipose tissue, resulting in a shift toward M1 polarity, suggesting that the M1/M2 polarization of ATMs plays a key role in insulin resistance and T2DM [8].

Prostanoids, comprised of prostaglandin and thromboxane, are bioactive compounds synthesized in response to various stimuli and are crucial for maintaining tissue homeostasis and inflammation [9]. Prostaglandin E_2 (PGE_2) is one of the major prostanoids generated by the metabolism of arachidonic acid by cyclooxygenase (COX) and PGE synthases [10]. It has four G protein–coupled receptors: EP1 through EP4 [11]. PGE_2 suppresses the production of proinflammatory cytokines and chemokines via EP4 in LPS–treated human and murine macrophages [12,13]. In fact, EP4 activation suppresses chronic inflammation *in vivo* by mitigating macrophage activation during afflictions such as inflammatory bowel disease [14], ischemia-reperfusion injury [15], atherosclerosis [16], allograft rejection after cardiac transplantation [17], and abdominal aortic aneurysm [18]. In addition, EP4 signaling suppresses adipocyte differentiation [19] and protects against the diabetogenic toxicity of

streptozotocin in mice [20]. PGE_2 mediates, at least partially, the biological effects of adiponectin (a crucial anti-inflammatory and anti-atherosclerotic molecule including suppression of adipocyte differentiation [21] and inhibition of ischemia-reperfusion injury [22].

These findings imply important roles for EP4 signaling *in vivo* in obesity-related chronic inflammation and in the subsequent increase of insulin resistance. In this study, we pharmacologically activated the EP4 receptor in *db/db* mice to investigate the pathophysiological role of EP4 signaling in obesity and T2DM.

Results

Treatment with an EP4-selective agonist significantly improves glucose tolerance and insulin resistance in obese mice.

To determine the role of EP4 signaling in obesity-related inflammation *in vivo*, we administered the EP4-selective agonist ONO-AE1-329 or vehicle for 4 weeks to *db/db* mice. The dosage of the EP4 agonist was determined in accordance with previous reports using animal models of inflammation [23,24]. ONO-AE1-329 treatment did not affect body weight gain (Fig. 1A) or food intake (Fig. 1B). There was no significant difference in the plasma levels of total cholesterol, triglyceride, or hemoglobin A1C between the two groups (Table 1). Additionally, liver weight and epididymal WAT did not differ significantly (Table 1). Despite similar metabolic characteristics, treatment with the EP4

agonist markedly improved glucose tolerance (Fig. 1C). In addition, the insulin tolerance test indicated that the EP4 agonist increased insulin sensitivity (Fig. 1D). Thus, EP4 activation ameliorated obesity-induced abnormal glucose tolerance and insulin resistance.

Table 1. Effects of EP4 agonist on metabolic parameters

Measurement	Vehicle	ONO-AE1-329	p-value
T-Cho (mg/dl)	117.35 ± 21.71	115.51 ± 12.16	N.S.
TG (mg/dl)	141.27 ± 37.18	153.06 ± 33.89	N.S.
HbA1c (%)	6.28 ± 0.42	6.05 ± 0.22	N.S.
Liver (g)	2.49 ± 0.25	2.43 ± 0.17	N.S.
Epididymal WAT (g)	2.35 ± 0.09	2.30 ± 0.15	N.S.

Values are mean ± SEM (n = 3–8 each). T-Cho, total cholesterol; TG, triglyceride; HbA1c, Hemoglobin A1c; WAT, white adipose tissue.

EP4 signaling inhibits macrophage accumulation in crown-like structures and inflammatory activation in obese adipose tissues.

Accumulation of macrophages in adipose tissues elicits inflammation, which in turn, causes local and systemic insulin resistance and T2DM [2,25]. Because several lines of evidence indicate that EP4 signaling in macrophages has anti-inflammatory effects, we next investigated the impact of EP4 activation on inflammatory burden in obese adipose tissue. Immunohistochemistry revealed that the

accumulation of F4/80-positive macrophages in crown-like structures (CLSs) within epididymal WAT was markedly decreased in the EP4 agonist–treated group (Fig. 2A, B). Accordingly, the sizes of adipocytes in the EP4 agonist–treated group were significantly smaller compared to that of the vehicle–treated group (Fig. 2A, C). Though there was no significant difference in the mRNA expression of *Mcp-1* in WAT (S1A Fig.), there was a trend towards decreased secretion of MCP-1 protein in the EP4 agonist–treated mice ($p = 0.054$) (S1B Fig.).

To investigate the effect of EP4 activation on ATM activation, we isolated stromal vascular fraction (SVF) from epididymal WAT, which contains inflammatory cells including ATMs, and then measured the mRNA levels of proinflammatory cytokines and chemokines. The EP4 agonist–treated group had decreased expression of a number of genes encoding proinflammatory cytokines and chemokines such as *Tnfα*, *Il-6*, *Mcp-1*, and interferon gamma–induced protein 10 (*Ip-10*) (Fig. 3). These results indicate that activation of EP4 signaling has potent anti-inflammatory effects in ATMs.

EP4 signaling enhances the polarization of adipose tissue macrophages toward the M2 phenotype.

ATMs are comprised of two distinct subsets: the classically activated, proinflammatory M1 macrophages and the alternatively activated, anti-inflammatory M2 macrophages. The total number of infiltrated macrophages and the M1/M2 balance of those macrophages determine the features of chronic inflammatory diseases such as obesity and T2DM [8,26]. To evaluate the polarization of

ATMs, we performed quantitative PCR on total mRNA from epididymal WAT. The expression of genes encoding the M2 markers mannose receptor (*MR*) and *Cd163* was increased in the EP4 agonist–treated group, whereas the gene encoding the M1 marker *Cd11c* was not significantly different between the two groups (Fig. 4A). Peroxisome proliferator–activated receptor (PPAR) δ and PPARγ are key factors in polarizing macrophages to M2 status [26-29]. In our study, the expression of these genes in WAT was significantly increased by consecutive administration of EP4 agonist (S2 Fig.). Accordingly, immunofluorescence of epididymal WAT demonstrated that $F4/80^+$ $CD163^+$ M2 macrophages, not $F4/80^+$ $CD11c^+$ M1 macrophages, were more abundant in the EP4 agonist–treated group (Fig. 4B).

Impact of EP4 signaling on the balance of adipokine secretion.

Adipokines, including adiponectin, are produced and secreted from fat cells in adipose tissues and regulate systemic insulin sensitivity [30]. The nuclear receptors PPARα and PPARγ regulate the expression of adiponectin [31,32]. Adiponectin, in turn, suppresses macrophage infiltration into adipose tissue and promotes alternative M2 macrophage activation [33,34]. In the EP4 agonist–treated group, the expression levels of *PPARα* and *PPARγ* in WAT were significantly increased, along with production of adiponectin (S2 Fig. and Fig. 5A). Consequently, though not statistically significant ($p=0.079$), the plasma levels of adiponectin exhibited a possible trend toward significance in the EP4 agonist–treated group (Fig. 5B), suggesting that polarization of ATMs toward the anti-inflammatory

M2 phenotype balanced adipokine secretion and improved insulin sensitivity in obese mice.

EP4 signaling promotes M2 macrophage polarization in isolated murine macrophages.

To investigate whether EP4 signaling directly influences macrophage polarization, we freshly isolated peritoneal macrophages from WT mice and performed *in vitro* M1/M2 polarization assays as previously described [35]. The expression of marker genes for M1 and M2 macrophages was assayed by quantitative PCR. In WT macrophages, LPS stimulation induced the mRNA expression of M1 genes, such as *Tnfα* and *Il-6*, whereas adding the EP4 agonist to the LPS mixture decreased the mRNA expression of those genes (Fig. 6A). On the other hand, co-stimulation with IL-4 and IL-13 enabled peritoneal macrophages to polarize to M2 status (Fig. 6B). Notably, treatment with the EP4 agonist with IL-4 and IL-13 further increased the mRNA expression of M2 genes, including *MR* and *Cd163* (Fig. 6B).

To investigate the impact of EP4 deletion on macrophage polarization, we collected peritoneal macrophages from EP4 knockout mice and estimated M1/M2 polarization. EP4 deficiency resulted in increased susceptibility to M1 and less susceptibility to M2 macrophage polarization (Fig. 6C, D), suggesting that EP4 signaling may act directly on macrophage polarization. These results indicate that the activation of EP4 signaling mitigates chronic inflammation in adipose tissue by regulating ATM activation and polarization.

Next, we examined the downstream of EP4 signaling that enhanced M2 polarization. It is well known that the activation of PPARs is one of the keys in polarizing macrophages to M2 status [26-29]. When we added GSK3787, PPARδ selective antagonist, prior to IL-4/IL-13 in *in vitro* M1/M2 polarization assays, the EP4-dependent increase of *Cd163* or *MR* gene expression markedly inhibited (Fig. 6E). On the other hand, pretreatment of GW9662, PPARγ antagonist, suppressed the enhanced expression of *Cd163* but not *MR* by EP4 agonist (Fig. 6F). These results suggest that PPARs, especially PPARδ, might coordinate EP4 signaling in macrophage polarization toward an M2-like phenotype.

Discussion

Prostaglandin E_2 (PGE_2) has been shown to exert energy and metabolic homeostasis: for instance, PGE_2 regulates lipolysis and increases leptin release in primary culture of rodent and human adipose tissues [36-38], while EP3-deficient mice displayed increased feeding and body weight despite elevated plasma leptin levels [39]. In addition, a previous report demonstrated that intracerebroventricular administration of PGE_2 or EP4 agonist decreased food intake in fasted mice [40]. In this study, however, administration of EP4 selective agonist did not affect body weight gain, food intake or blood lipid profile. It may be partially because that in our study, we used leptin receptor-deficient *db/db* mice fed with normal chow *ad libitum*, and administered EP4 agonist

peripherally. Besides, in WAT, other EP receptors including EP3 express and activate intracellular signal transduction pathways differing from EP4.

EP4 activation is pivotally involved in ameliorating chronic inflammatory diseases [14-16,41]. Macrophages, known to have abundant EP4 expression [12], accumulate in hypertrophied adipose tissues and play crucial roles in the pathogenesis of insulin resistance and T2DM by promoting inflammation. Therefore, we examined the impact of EP4 signaling on obesity-related adipose tissue inflammation *in vivo* using an animal model of obesity and T2DM.

Obesity is generally caused by the combination of excess calorie intake, insufficient physical activity, and genetic predisposition. Obese adipose tissue is characterized by hypertrophied adipocytes, increased production of proinflammatory cytokines and chemokines, and infiltration by immune cells, including macrophages [42]. Though there was no significant difference in the weight of epididymal adipose tissue in our study, the adipocytes were less hypertrophied in the EP4 agonist–treated group. Hypertrophied adipocytes secrete MCP-1, leading to the recruitment of circulating monocytes and subsequent infiltration by macrophages into adipose tissues. Infiltrated ATMs, in turn, secrete MCP-1 and other proinflammatory cytokines and chemokines; consequently a number of ATMs accumulate in adipose tissues, causing chronic inflammation in WAT [2,8,25]. PGE_2-EP4 signaling suppresses MCP-1 expression in a variety of inflammatory settings [43,44]. Our data demonstrated that consecutive administration of EP4 receptor–agonist into obese mice significantly decreased MCP-1 production in SVF, a fraction containing macrophages but not adipocytes, suggesting that EP4

signaling mainly affects ATMs and inhibits the deleterious consequences of local chemokine production and macrophage infiltration.

Obesity causes a shift in macrophage polarity from the anti-inflammatory M2 to the pro-inflammatory M1 state, facilitating insulin resistance [8]. Using mice with mutations in key proteins of the inflammatory process, it has been demonstrated that an increase in M2 ATMs ameliorates obesity-related impaired glucose metabolism. In one example, mice lacking Tribbles homolog 1 (*Trib1*, which encodes an adaptor protein involved in proteasome-mediated protein degradation) in hematopoietic cells develop glucose intolerance and insulin resistance on a high-fat diet. They have a severely reduced number of M2 ATMs, but no change in M1 ATMs [45]. Hematopoietic deletion of COX-1, a major PGE_2-producing enzyme, was also associated with metabolic disorders and decreased counts of M2 ATMs in diet-induced obese mice, with M1 counts remaining the same [46]. How M2 ATMs contribute to the amelioration of glucose tolerance and insulin resistance is not fully understood; however, a number of previous reports indicated that M2 macrophages reside in adipose tissues have crucial roles in maintaining normal glucose homeostasis [3,47,48]. Polarized M2 ATMs secrete anti-inflammatory cytokines such as IL-10, improving insulin-stimulated glucose uptake in TNFα–treated 3T3-L1 adipocytes [8]. In addition to secreting cytokine or regulating adipokine production, some of M2 ATMs can store large amount of iron: loss of these alternatively activated macrophages may cause abnormal accumulation of iron in adipocytes and enhance iron-induced lipid peroxidation and oxidative stress, which consequently deteriorate

adipocyte insulin sensitivity [49]. Besides, M2 ATMs are capable of producing catecholamines such as norepinephrine, activating β3 adrenergic receptor on adipocytes: β3 adrenergic receptor signaling in WAT is pivotally involved in metabolic homeostasis through regulating lipolysis and mitochondrial functions [50,51].

Accordingly, we observed that the activation of EP4 signaling increased the number of M2 macrophages and led to a phonotypic switch toward M2 status in obese adipose tissue. Notably, in our study, EP4 signaling pivotally participated in M1/M2 differentiation *in vitro,* and in EP4 agonist–treated mice, the gene expression of *PPARδ* and *PPARγ* in WAT were significantly elevated. PPARδ is induced in response to adipocyte-derived Th2 cytokines, such as IL-4 and IL-13, and facilitates adipocyte differentiation, as well as the recruitment of M2 macrophages into adipose tissue and the liver [27,28]. PPARγ is necessary for the alternative activation of ATMs [26,29]. Thus, our data suggest that EP4 activation regulates macrophage accumulation in obese adipose tissue, as well as differentiation and polarization toward M2 phenotypes, resulting in the suppression of adipose tissue inflammation.

Adipose tissues secrete various adipokines, and the plasma adipokine levels can be an indicator of systemic inflammation and insulin resistance. Adiponectin is one of the major adipokines, exhibiting anti-diabetic, anti-atherosclerotic, and anti-inflammatory properties [52]. The activation of PGE_2-EP4 signaling is crucial for the protective function of adiponectin [22]. In addition, adiponectin promotes the alternative activation of macrophages and polarization toward the anti-inflammatory M2

phenotype [34,53]. Our study indicates that consecutive EP4 activation induces local adiponectin production in WAT, which in turn, might contribute to the phenotypic shift of ATMs into M2 status and suppression of adipose tissue inflammation. In contrast to enhanced adiponectin mRNA levels in WAT, we observed no statistically significant change in the plasma levels of total adiponectin in EP4 agonist–treated group; yet some previous works demonstrated that insulin sensitivity does not always correlate with the plasma total adiponectin levels, because adiponectin circulates in the blood in multimeric forms with different metabolic activities [54,55].

Defining the precise mechanisms by which EP4 activation enhances M2 polarization is beyond the scope of the current study; however, as discussed above, successive treatment of obese mice with EP4-selective agonist enhances *PPARγ*, *PPARδ*, and adiponectin expression, which may explain the polarity shift of accumulated macrophages, at least partially. EP4 is coupled to Gs, which stimulates adenylate cyclase, and thus, increases intracellular cAMP levels, consequently activating protein kinase A and cAMP response element binding protein (CREB) [56]. In differentiated 3T3-L1 adipocytes, adiponectin expression is mediated through cAMP–CREB–PPARγ pathways [57], but it remains controversial whether PGE_2 or EP4 signaling directly acts on the expression of these genes via a cAMP-dependent pathway. Unlike other EP receptors coupled with Gs, EP4 has a long cytoplasmic tail, where the receptor interacts with a novel protein designated EP4 receptor–associated protein (EPRAP) [12]. Because EPRAP exerts an anti-inflammatory effect in LPS-stimulated macrophages *in vitro* [12,13], EPRAP may also contribute to the suppression of obesity-related

inflammation.

In this study, we focused on the impact of EP4 signaling in adipose tissues on macrophage activation and polarization. PGE_2 regulates the profibrotic and proinflammatory activation of pancreatic stellate cells via EP4 and protects β-cells from apoptosis [58,59]. Other than adipose tissues, macrophages also infiltrate into the liver and the skeletal muscle in obese subjects, and the polarity appears to be shifted towards M1 status, which has a strong association with dysfunction of these organs and with insulin resistance [27,28,60]. Clarifying the roles of EP4 signaling in macrophage activation and phenotypic switching within these organs could be important for understanding the novel pathophysiological mechanisms of insulin resistance and T2DM.

In summary, administration of an EP4-selective agonist improved insulin sensitivity and glucose tolerance in obese mice. Treatment with EP4 agonist inhibited the accumulation of macrophages and decreased CLS formation, consequently attenuating the expression of proinflammatory cytokines and chemokines, and enhancing adiponectin production in white adipose tissue. EP4 activation promoted ATM polarization toward the M2 phenotype in obese mice; accordingly, our *in vitro* experiments verified that EP4 signaling played a crucial role in the differentiation and polarization of murine peritoneal macrophages. Further investigation to clarify the detailed molecular mechanisms underlying the effects of EP4 signaling on macrophage differentiation and polarization in other insulin-target organs will provide new insights into the pathogenesis, as well as novel therapeutic targets, of obesity-related insulin resistance and T2DM.

Materials and Methods

Ethics statement

All animal care and experiments were conducted following the guidelines for the Japan's Act on Welfare and Management of Animals (Act No. 105 of October 1, 1973). These studies were approved by the Institutional Animal Care and Use Committees (IACUC)/ethics committee of Kyoto University (Permit Number: MedKyo15183). All sections of this report are based on the ARRIVE Guidelines for reporting animal research [61]. A completed ARRIVAL guidelines checklist is included in S1 Checklist. All surgery was performed when mice were anesthetized by 40 mg/kg of pentobarbital sodium (Kyoritsu Seiyaku, Tokyo, Japan); blood and tissue collection were performed as terminal procedures under anesthesia as described above, and all efforts were made to minimize suffering.

Animals

Five-week-old male *db/db* mice were obtained from Oriental BioService (Kyoto, Japan). Homozygotic EP4-deficient mice and WT mice with the same genetic background were obtained by crossing mice heterozygous for the *PTGER4* mutation and were verified as previously described [62]. We used 26 *db/db* mice housed in groups of 2. Other varieties of mice had 6 mice per group and were housed in groups of 6. Mice were maintained in a specific pathogen-free facility (12 h light/dark cycles) and were fed normal chow *ad libitum* unless otherwise indicated.

Treatment of *db/db* mice with EP4 receptor–selective agonist

ONO-AE1-329 (Ono Pharmaceutical, Osaka, Japan), an EP4-selective agonist [14,63], was suspended in vehicle (0.3% ethanol and 0.1% Tween 80 in PBS), and 0.3 mg/kg of the reagent or vehicle was administrated subcutaneously to 7-week-old *db/db* mice twice a day for 4 weeks. We allocated animals into 2 groups as the vehicle–treated group and the ONO-AE1-329–treated group with 13 mice based on body weight (vehicle: 38.93 ± 0.62, ONO-AE1-329: 39.78 ± 0.52; mean ± SE, no significant difference) at the start of the experiment in order to minimize the effect of subjective bias.

Glucose and insulin tolerance test

After an overnight fast, we administered 1.5 g/kg of D(+)-glucose (Wako Pure Chemical Industries, Osaka, Japan) and 0.75 U/kg of Humulin R (Eli Lilly Japan, Kobe, Japan) intraperitoneally to perform the glucose tolerance test (ipGTT) and the insulin tolerance test (ITT), respectively.

Plasma variables

Plasma levels of blood glucose (BG), total cholesterol (T-Cho), triglyceride (TG), hemoglobin A1c (HbA1c), and adiponectin were measured using the Glucose CII Test Wako (Wako), the Total Cholesterol E-Test Wako (Wako), the Triglyceride E-Test Wako (Wako), the Glycohemoglobin A1c kit (Sanwa Kagaku Kenkyusho, Nagoya, Japan), and the Adiponectin ELISA kit (Otsuka

Pharmaceutical, Tokyo, Japan), respectively.

Histology

Epididymal adipose tissue was harvested and fixed overnight with 4% paraformaldehyde (Wako), embedded in paraffin, and sectioned. For H&E staining, we stained the rehydrated sections using Mayer's hematoxylin solution (Wako). For immunohistochemistry, the rehydrated sections were blocked with Protein Block Serum-Free (Dako, Glostrup, Denmark) and the macrophages were stained using rat monoclonal anti-F4/80 antibody (Abcam, Cambridge, MA, USA; clone CI:A3-1, 1:100; AB_1140040) and visualized by coloring with diaminobenzidine (DAB; Vector Laboratories, Burlingame, CA, USA). For immunofluorescence staining, blocked sections were incubated with a combination of rat anti-F4/80 antibody (Abcam; clone CI:A3-1, 1:100; AB_1140040) and either rabbit polyclonal anti-CD11c antibody (Santa Cruz Biotechnology, Dallas, TX, USA; clone M-50, 1:100; AB_2129774) or rabbit polyclonal anti-CD163 antibody (Santa Cruz Biotechnology; clone M-96, 1:100; AB_2074556). After washing, the sections were incubated with Alexa Fluor 488–conjugated donkey anti-rat antibody (Invitrogen, Carlsbad, CA, USA) or Alexa Fluor 594–conjugated donkey anti-rabbit antibody (Invitrogen). Non-immune rat IgG (Vector Laboratories) and rabbit IgG (Santa Cruz Biotechnology) served as negative controls for each experiment.

Quantitative PCR

Total RNA was extracted from adipose tissue, stromal vascular fraction (SVF), and peritoneal macrophages using the RNeasy Lipid Tissue Mini kit (Qiagen, Valencia, CA, USA), RNeasy Micro kit (Qiagen), and RNeasy Mini kit (Qiagen), respectively. RNA was reverse-transcribed by High-Capacity cDNA Reverse Transcription Kits (Applied Biosystems, Forster City, CA, USA). Samples were processed on the 7300 Real-Time PCR System (Applied Biosystems) using the Power SYBR Green PCR Master Mix (Applied Biosystems). All experiments were performed in duplicate, and results were normalized to *β-actin* expression level. The sequences of the sense and antisense primers used for amplification are as follows; *β-actin*: 5'-CCTGAGCGCAAGTACTCTGTGT-3', 5'-GCTGATCCACATCTGCTGGAA-3'; *Tnfα*: 5'-CATCTTCTCAAAATTCGAGTGACAA-3', 5'-TGGGAGTAGACAAGGTACAACCC-3'; *Il-6*: 5'-TAGTCCTTCCTACCCCAATTTCC-3', 5'-TTGGTCCTTAGCCACTCCTTC-3'; *Mcp-1*: 5'-GCTGGAGCATCCACGTGTT-3', 5'-ATCTTGCTGGTGAATGTGTAGCA-3'; *IP-10*: 5'-GCCGTCATTTTCTGCCTCAT-3', 5'-GCTTCCCTATGGCCCTCATT-3'; *Cd11c*: 5'-CTGGATAGCCTTTCTTCTGCTG-3', 5'-GCACACTGTGTCCGAACTC-3'; *MR*: 5'-GCTGAATCCCAGAAATTCCGC-3', 5'-ATCACAGGCATACAGGGTGAC-3'; *Cd163*: 5'-GGGTCATTCAGAGGCACACTG-3', 5'-CTGGCTGTCCTGTCAAGGCT-3'; *Adiponectin*: 5'- GATGGCAGAGATGGCACTCC-3', 5'-CTTGCCAGTGCTGCCGTCAT-3'; *PPARδ*: 5'-AGATGGTGGCAGAGCTATGACC-3', 5'-TCTCCTCCTGTGGCTGTTCC-3'; *PPARγ*: 5'-CTCCAAGAATACCAAAGTGCGA-3',

5'-GCCTGATGCTTTATCCCCACA-3'; *PPARα*: 5'- ATGCCAGTACTGCCGTTTTC-3', 5'-CCGAATCTTTCAGGTCGTGT-3'.

Isolation of stromal vascular fraction (SVF)

Epididymal adipose tissues were minced and digested in 0.2% collagenase (Wako) in PBS for 2 h at 37°C. The digested tissues were passed through a 100 μm nylon mesh filter (BD Biosciences, San Jose, CA, USA) to remove the floating adipocytes, and the filtrates were spun for 5 min at 1,200 rpm. The pellet was incubated with Lysing Buffer (BD Biosciences) for 2 min to remove the red blood cells.

In vitro M1/M2 polarization assay

Peritoneal macrophages were extracted from the peritoneal lavage of 12 to 15-week-old male EP4-deficient mice or WT mice with the same genetic background. The *in vitro* M1/M2 polarization assay was performed as previously described [35]. Briefly, together with 1 μM of ONO-AE1-329 or vehicle, peritoneal macrophages were treated with 1 μg/ml of LPS (*Escherichia coli* O55: B5, Calbiochem, La Jolla, CA, USA) or 20 ng/ml of IL-4 (R&D Systems, Minneapolis, MN, USA) and IL-13 (R&D Systems) for 8 h. Meanwhile, to explore the roles of PPARs in EP4-dependent M2 polarization, 0.1 μM of GSK3787 (Tocris Bioscience, Bristol, UK), selective antagonist for PPARδ, or 1 μM of GW9662 (Cayman Chemical, Ann Arbor, MI, USA), selective antagonist for PPARγ, was

added into the medium 2h before IL-4/IL-13 and the EP4 agonist treatment.

Cytometric bead assay

Epididymal WAT was homogenized in RIPA buffer (Wako) with Protease inhibitor cocktail (Roche Diagnostics, Indianapolis, IN, USA). MCP-1 concentration in the supernatants of epididymal WAT homogenates was measured using the BD CBA assay (BD Biosciences).

Statistical analysis

Results are presented as the mean ± SEM. All data were analyzed with Kaleida Graph software (version4.1J; Synergy Software, Reading, PA, USA). Differences between two value sets were determined using the unpaired, two-tailed Student's *t*-test. A one-way ANOVA followed by Turkey-Kramer analysis was used for testing the differences among three or more groups. Significance was defined as a p-value less than 0.05.

Acknowledgements

Tomoyuki Furuyashiki and Shu Narumiya (Kyoto University, Kyoto, JAPAN) kindly provided EP4-mutated mice. We thank Ono Pharmaceutical for supplying the EP4 agonist ONO-AE1-329. We also thank Erina Tajima and Yoshiko Fujiwara for skillful technical assistance.

References

1. Faust IM, Johnson PR, Stern JS, Hirsch J (1978) Diet-induced adipocyte number increase in adult rats: a new model of obesity. Am J Physiol 235: E279-286.

2. Xu H, Barnes GT, Yang Q, Tan G, Yang D, Chou CJ, et al. (2003) Chronic inflammation in fat plays a crucial role in the development of obesity-related insulin resistance. J Clin Invest 112: 1821-1830.

3. Olefsky JM, Glass CK (2010) Macrophages, inflammation, and insulin resistance. Annu Rev Physiol 72: 219-246.

4. Arkan MC, Hevener AL, Greten FR, Maeda S, Li ZW, Long JM, et al. (2005) IKK-beta links inflammation to obesity-induced insulin resistance. Nat Med 11: 191-198.

5. Ueki K, Kondo T, Kahn CR (2004) Suppressor of cytokine signaling 1 (SOCS-1) and SOCS-3 cause insulin resistance through inhibition of tyrosine phosphorylation of insulin receptor substrate proteins by discrete mechanisms. Mol Cell Biol 24: 5434-5446.

6. Osborn O, Olefsky JM (2012) The cellular and signaling networks linking the immune system and metabolism in disease. Nat Med 18: 363-374.

7. Mosser DM, Edwards JP (2008) Exploring the full spectrum of macrophage activation. Nat Rev Immunol 8: 958-969.

8. Lumeng CN, Bodzin JL, Saltiel AR (2007) Obesity induces a phenotypic switch in adipose tissue macrophage polarization. J Clin Invest 117: 175-184.

9. Ricciotti E, FitzGerald GA (2011) Prostaglandins and inflammation. Arterioscler Thromb Vasc Biol 31: 986-1000.

10. Needleman P, Turk J, Jakschik BA, Morrison AR, Lefkowith JB (1986) Arachidonic acid metabolism. Annu Rev Biochem 55: 69-102.

11. Coleman RA, Smith WL, Narumiya S (1994) International Union of Pharmacology classification of prostanoid receptors: properties, distribution, and structure of the receptors and their subtypes. Pharmacol Rev 46: 205-229.

12. Takayama K, Sukhova GK, Chin MT, Libby P (2006) A novel prostaglandin E receptor 4-associated protein participates in antiinflammatory signaling. Circ Res 98: 499-504.

13. Minami M, Shimizu K, Okamoto Y, Folco E, Ilasaca ML, Feinberg MW, et al. (2008) Prostaglandin E receptor type 4-associated protein interacts directly with NF-kappaB1 and attenuates macrophage activation. J Biol Chem 283: 9692-9703.

14. Kabashima K, Saji T, Murata T, Nagamachi M, Matsuoka T, Segi E, et al. (2002) The prostaglandin receptor EP4 suppresses colitis, mucosal damage and CD4 cell activation in the gut. J Clin Invest 109: 883-893.

15. Xiao CY, Yuhki K, Hara A, Fujino T, Kuriyama S, Yamada T, et al. (2004) Prostaglandin E2 protects the heart from ischemia-reperfusion injury via its receptor subtype EP4. Circulation 109: 2462-2468.

16. Tang EH, Shimizu K, Christen T, Rocha VZ, Shvartz E, Tesmenitsky Y, et al. (2011) Lack of EP4

receptors on bone marrow-derived cells enhances inflammation in atherosclerotic lesions. Cardiovasc Res 89: 234-243.

17. Ogawa M, Suzuki J, Kosuge H, Takayama K, Nagai R, Isobe M (2009) The mechanism of anti-inflammatory effects of prostaglandin E2 receptor 4 activation in murine cardiac transplantation. Transplantation 87: 1645-1653.

18. Tang EH, Shvartz E, Shimizu K, Rocha VZ, Zheng C, Fukuda D, et al. (2011) Deletion of EP4 on bone marrow-derived cells enhances inflammation and angiotensin II-induced abdominal aortic aneurysm formation. Arterioscler Thromb Vasc Biol 31: 261-269.

19. Sugimoto Y, Tsuboi H, Okuno Y, Tamba S, Tsuchiya S, Tsujimoto G, et al. (2004) Microarray evaluation of EP4 receptor-mediated prostaglandin E2 suppression of 3T3-L1 adipocyte differentiation. Biochem Biophys Res Commun 322: 911-917.

20. Vennemann A, Gerstner A, Kern N, Ferreiros Bouzas N, Narumiya S, Maruyama T, et al. (2012) PTGS-2-PTGER2/4 signaling pathway partially protects from diabetogenic toxicity of streptozotocin in mice. Diabetes 61: 1879-1887.

21. Yokota T, Meka CS, Medina KL, Igarashi H, Comp PC, Takahashi M, et al. (2002) Paracrine regulation of fat cell formation in bone marrow cultures via adiponectin and prostaglandins. J Clin Invest 109: 1303-1310.

22. Shibata R, Sato K, Pimentel DR, Takemura Y, Kihara S, Ohashi K, et al. (2005) Adiponectin protects against myocardial ischemia-reperfusion injury through AMPK- and COX-2-dependent

mechanisms. Nat Med 11: 1096-1103.

23. Shi J, Johansson J, Woodling NS, Wang Q, Montine TJ, Andreasson K (2010) The prostaglandin E2 E-prostanoid 4 receptor exerts anti-inflammatory effects in brain innate immunity. J Immunol 184: 7207-7218.

24. Liang X, Lin L, Woodling NS, Wang Q, Anacker C, Pan T, et al. (2011) Signaling via the prostaglandin E(2) receptor EP4 exerts neuronal and vascular protection in a mouse model of cerebral ischemia. J Clin Invest 121: 4362-4371.

25. Weisberg SP, McCann D, Desai M, Rosenbaum M, Leibel RL, Ferrante AW, Jr. (2003) Obesity is associated with macrophage accumulation in adipose tissue. J Clin Invest 112: 1796-1808.

26. Odegaard JI, Ricardo-Gonzalez RR, Goforth MH, Morel CR, Subramanian V, Mukundan L, et al. (2007) Macrophage-specific PPARgamma controls alternative activation and improves insulin resistance. Nature 447: 1116-1120.

27. Kang K, Reilly SM, Karabacak V, Gangl MR, Fitzgerald K, Hatano B, et al. (2008) Adipocyte-derived Th2 cytokines and myeloid PPARdelta regulate macrophage polarization and insulin sensitivity. Cell Metab 7: 485-495.

28. Odegaard JI, Ricardo-Gonzalez RR, Red Eagle A, Vats D, Morel CR, Goforth MH, et al. (2008) Alternative M2 activation of Kupffer cells by PPARdelta ameliorates obesity-induced insulin resistance. Cell Metab 7: 496-507.

29. Stienstra R, Duval C, Keshtkar S, van der Laak J, Kersten S, Müller M (2008) Peroxisome

proliferator-activated receptor gamma activation promotes infiltration of alternatively activated macrophages into adipose tissue. J Biol Chem 283: 22620-22627.

30. Piya MK, McTernan PG, Kumar S (2013) Adipokine inflammation and insulin resistance: the role of glucose, lipids and endotoxin. J Endocrinol 216: T1-T15.

31. Hiuge A, Tenenbaum A, Maeda N, Benderly M, Kumada M, Fisman EZ, et al. (2007) Effects of peroxisome proliferator-activated receptor ligands, bezafibrate and fenofibrate, on adiponectin level. Arterioscler Thromb Vasc Biol 27: 635-641.

32. Iwaki M, Matsuda M, Maeda N, Funahashi T, Matsuzawa Y, Makishima M, et al. (2003) Induction of adiponectin, a fat-derived antidiabetic and antiatherogenic factor, by nuclear receptors. Diabetes 52: 1655-1663.

33. Kim JY, van de Wall E, Laplante M, Azzara A, Trujillo ME, Hofmann SM, et al. (2007) Obesity-associated improvements in metabolic profile through expansion of adipose tissue. J Clin Invest 117: 2621-2637.

34. Lovren F, Pan Y, Quan A, Szmitko PE, Singh KK, Shukla PC, et al. (2010) Adiponectin primes human monocytes into alternative anti-inflammatory M2 macrophages. Am J Physiol Heart Circ Physiol 299: H656-663.

35. Nakanishi Y, Nakatsuji M, Seno H, Ishizu S, Akitake-Kawano R, Kanda K, et al. (2011) COX-2 inhibition alters the phenotype of tumor-associated macrophages from M2 to M1 in ApcMin/+ mouse polyps. Carcinogenesis 32: 1333-1339.

36. Fain JN, Leffler CW, Bahouth SW (2000) Eicosanoids as endogenous regulators of leptin release and lipolysis by mouse adipose tissue in primary culture. J Lipid Res 41: 1689-1694.

37. Fain JN, Leffler CW, Bahouth SW, Rice AM, Rivkees SA (2000) Regulation of leptin release and lipolysis by PGE2 in rat adipose tissue. Prostaglandins Other Lipid Mediat 62: 343-350.

38. Fain JN, Leffler CW, Cowan GS, Jr., Buffington C, Pouncey L, Bahouth SW (2001) Stimulation of leptin release by arachidonic acid and prostaglandin E(2) in adipose tissue from obese humans. Metabolism 50: 921-928.

39. Sanchez-Alavez M, Klein I, Brownell SE, Tabarean IV, Davis CN, Conti B, et al. (2007) Night eating and obesity in the EP3R-deficient mouse. Proc Natl Acad Sci U S A 104: 3009-3014.

40. Ohinata K, Suetsugu K, Fujiwara Y, Yoshikawa M (2006) Activation of prostaglandin E receptor EP4 subtype suppresses food intake in mice. Prostaglandins Other Lipid Mediat 81: 31-36.

41. Hishikari K, Suzuki J, Ogawa M, Isobe K, Takahashi T, Onishi M, et al. (2009) Pharmacological activation of the prostaglandin E2 receptor EP4 improves cardiac function after myocardial ischaemia/reperfusion injury. Cardiovasc Res 81: 123-132.

42. Chawla A, Nguyen KD, Goh YP (2011) Macrophage-mediated inflammation in metabolic disease. Nat Rev Immunol 11: 738-749.

43. Largo R, Diez-Ortego I, Sanchez-Pernaute O, Lopez-Armada MJ, Alvarez-Soria MA, Egido J, et al. (2004) EP2/EP4 signalling inhibits monocyte chemoattractant protein-1 production induced by interleukin 1beta in synovial fibroblasts. Ann Rheum Dis 63: 1197-1204.

44. Zahner G, Schaper M, Panzer U, Kluger M, Stahl RA, Thaiss F, et al. (2009) Prostaglandin EP2 and EP4 receptors modulate expression of the chemokine CCL2 (MCP-1) in response to LPS-induced renal glomerular inflammation. Biochem J 422: 563-570.

45. Satoh T, Kidoya H, Naito H, Yamamoto M, Takemura N, Nakagawa K, et al. (2013) Critical role of Trib1 in differentiation of tissue-resident M2-like macrophages. Nature 495: 524-528.

46. Saraswathi V, Ramnanan CJ, Wilks AW, Desouza CV, Eller AA, Murali G, et al. (2013) Impact of hematopoietic cyclooxygenase-1 deficiency on obesity-linked adipose tissue inflammation and metabolic disorders in mice. Metabolism 62: 1673-1685.

47. Brestoff JR, Artis D (2015) Immune regulation of metabolic homeostasis in health and disease. Cell 161: 146-160.

48. Hill AA, Reid Bolus W, Hasty AH (2014) A decade of progress in adipose tissue macrophage biology. Immunol Rev 262: 134-152.

49. Orr JS, Kennedy A, Anderson-Baucum EK, Webb CD, Fordahl SC, Erikson KM, et al. (2014) Obesity alters adipose tissue macrophage iron content and tissue iron distribution. Diabetes 63: 421-432.

50. Liu PS, Lin YW, Lee B, McCrady-Spitzer SK, Levine JA, Wei LN (2014) Reducing RIP140 expression in macrophage alters ATM infiltration, facilitates white adipose tissue browning, and prevents high-fat diet-induced insulin resistance. Diabetes 63: 4021-4031.

51. Nguyen KD, Qiu Y, Cui X, Goh YP, Mwangi J, David T, et al. (2011) Alternatively activated

macrophages produce catecholamines to sustain adaptive thermogenesis. Nature 480: 104-108.

52. Ouchi N, Parker JL, Lugus JJ, Walsh K (2011) Adipokines in inflammation and metabolic disease. Nat Rev Immunol 11: 85-97.

53. Fukushima J, Kamada Y, Matsumoto H, Yoshida Y, Ezaki H, Takemura T, et al. (2009) Adiponectin prevents progression of steatohepatitis in mice by regulating oxidative stress and Kupffer cell phenotype polarization. Hepatol Res 39: 724-738.

54. Pajvani UB, Hawkins M, Combs TP, Rajala MW, Doebber T, Berger JP, et al. (2004) Complex distribution, not absolute amount of adiponectin, correlates with thiazolidinedione-mediated improvement in insulin sensitivity. J Biol Chem 279: 12152-12162.

55. O'Leary VB, Jorett AE, Marchetti CM, Gonzalez F, Phillips SA, Ciaraldi TP, et al. (2007) Enhanced adiponectin multimer ratio and skeletal muscle adiponectin receptor expression following exercise training and diet in older insulin-resistant adults. Am J Physiol Endocrinol Metab 293: E421-427.

56. Regan JW (2003) EP2 and EP4 prostanoid receptor signaling. Life Sci 74: 143-153.

57. Otani T, Mizokami A, Hayashi Y, Gao J, Mori Y, Nakamura S, et al. (2015) Signaling pathway for adiponectin expression in adipocytes by osteocalcin. Cell Signal.

58. Charo C, Holla V, Arumugam T, Hwang R, Yang P, Dubois RN, et al. (2013) Prostaglandin E2 regulates pancreatic stellate cell activity via the EP4 receptor. Pancreas 42: 467-474.

59. Papadimitriou A, King AJ, Jones PM, Persaud SJ (2007) Anti-apoptotic effects of arachidonic acid

and prostaglandin E2 in pancreatic beta-cells. Cell Physiol Biochem 20: 607-616.

60. Varma V, Yao-Borengasser A, Rasouli N, Nolen GT, Phanavanh B, Starks T, et al. (2009) Muscle inflammatory response and insulin resistance: synergistic interaction between macrophages and fatty acids leads to impaired insulin action. Am J Physiol Endocrinol Metab 296: E1300-1310.

61. Kilkenny C, Browne WJ, Cuthill IC, Emerson M, Altman DG (2010) Improving bioscience research reporting: the ARRIVE guidelines for reporting animal research. PLoS Biol 8: e1000412.

62. Segi E, Sugimoto Y, Yamasaki A, Aze Y, Oida H, Nishimura T, et al. (1998) Patent ductus arteriosus and neonatal death in prostaglandin receptor EP4-deficient mice. Biochem Biophys Res Commun 246: 7-12.

63. Suzawa T, Miyaura C, Inada M, Maruyama T, Sugimoto Y, Ushikubi F, et al. (2000) The role of prostaglandin E receptor subtypes (EP1, EP2, EP3, and EP4) in bone resorption: an analysis using specific agonists for the respective EPs. Endocrinology 141: 1554-1559.

Figure Legends

Fig. 1. Effects of EP4 activation on glucose tolerance and insulin resistance

Seven-week-old male *db/db* mice subcutaneously received either the EP4-selective agonist ONO-AE1-329 (0.3 mg/kg) or vehicle twice a day for 4 weeks. (A) Change in body weight during the study period (n = 8 each). (B) Amount of food intake (n = 8 each). (C) Results of glucose tolerance test: left, time-course of blood glucose levels; right, area under curve (AUC) (n = 7–8 each). (D) Results of insulin tolerance test: left, time-course changes of blood glucose levels; right, the inverse AUC (n = 13 each). All values are mean ± SEM. * $p<0.05$; ♯ $p<0.01$ vs. vehicle.

Fig. 2. Adipose tissue morphology

(A) Representative images of epididymal adipose tissue stained with anti-F4/80 antibody (upper panel; the arrows indicate F4/80-positive cells) and H&E (lower panel) in *db/db* mice administered EP4 agonist (right column) or vehicle (left column). Scale bars: 100 μm. (B) Percent of $F4/80^+$ CLS areas in mouse epididymal adipose tissue (n = 7 each). (C) Quantification of adipocyte size (n = 7 each). All values are mean ± SEM. ♯ $p<0.01$ vs. vehicle. CLS, crown-like structures.

Fig. 3. Cytokine and chemokine gene expression in SVF

Relative expression of *Tnfα*, *Il-6*, *Mcp-1*, and *Ip-10* mRNA in SVF isolated from *db/db* mice administered EP4 agonist (black bar) or vehicle (white bar). All values are mean ± SEM (n = 3 each). * $p<0.05$; ♯ $p<0.01$ vs. vehicle. SVF, stromal vascular fraction; Tnfα, tumor necrosis factor α; Il-6,

interleukin-6; Mcp-1, monocyte chemotactic protein-1; Ip-10, interferon gamma–induced protein 10.

Fig. 4. Administration of EP4 agonist alters adipose tissue macrophage polarization

(A) Relative expression of marker genes for M1 (*Cd11c*) and M2 (*MR*, *Cd163*) macrophages in epididymal fat tissues from *db/db* mice administered EP4 agonist (black bar) or vehicle (white bar). All values are mean ± SEM (n = 4–5 each). ♯ $p<0.01$ vs. vehicle. (B) Epididymal adipose tissues of EP4 agonist– or vehicle–treated *db/db* mice were double stained with anti-F4/80 (green), and anti-CD11c (red, upper panel) or anti-CD163 (red, lower panel) antibodies. Arrows indicate double-positive cells. Scale bar: 100 μm. MR, Mannose Receptor.

Fig. 5. Impact of EP4 activation on adiponectin expression

Relative adiponectin mRNA levels in epididymal fat tissue (A) and plasma adiponectin concentrations (B) were measured in EP4 agonist– (black bar) or vehicle–treated (white bar) *db/db* mice. All values are mean ± SEM (n = 6 each). ♯ $p<0.01$ vs. vehicle.

Fig. 6. EP4 signaling is important in macrophage polarization

In vitro M1/M2 polarization assays were performed using peritoneal macrophages freshly isolated from 12 to 15-week-old male WT (white bar) or EP4-deficient mice (black bar). To determine M1 or M2 polarization, cells were incubated with 1 μg/ml of LPS (A, C), or with 20 ng/ml of IL-4 and IL-13 (B, D), as well as with 1 μM of EP4 agonist or vehicle. Eight hours later, marker gene expression for M1 (*Tnfα* and *Il-6*) (A, C) or M2 (*MR* and *Cd163*) (B, D) polarity was measured. To clarify the role of

PPARs in EP4-dependent M2 polarization, peritoneal macrophages were pretreated with GSK3787 (PPARδ antagonist) (E), GW9662 (PPARγ antagonist) (F) or vehicle prior to the administration of IL-4/IL-13 and the EP4 agonist. Results are expressed as the fold induction of M2 genes compared with unantagonized, vehicle-treated cells. All values are mean ± SEM (n = 6 each). * $p<0.05$; ♯ $p<0.01$. LPS, lipopolysaccharide.

Figure 1

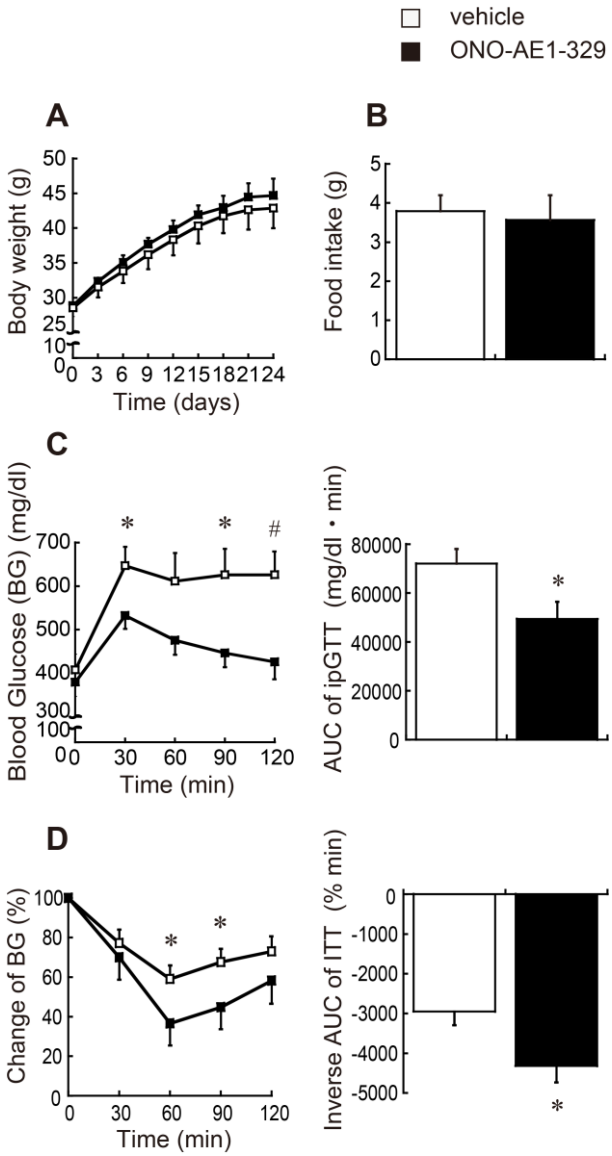

vehicle
ONO-AE1-329
A
Body weight (g)
Time (days)
B
Food intake (g)
C
Blood Glucose (BG) (mg/dl)
Time (min)
AUC of ipGTT (mg/dl • min)
D
Change of BG (%)
Time (min)
Inverse AUC of ITT (% min)

Figure 2

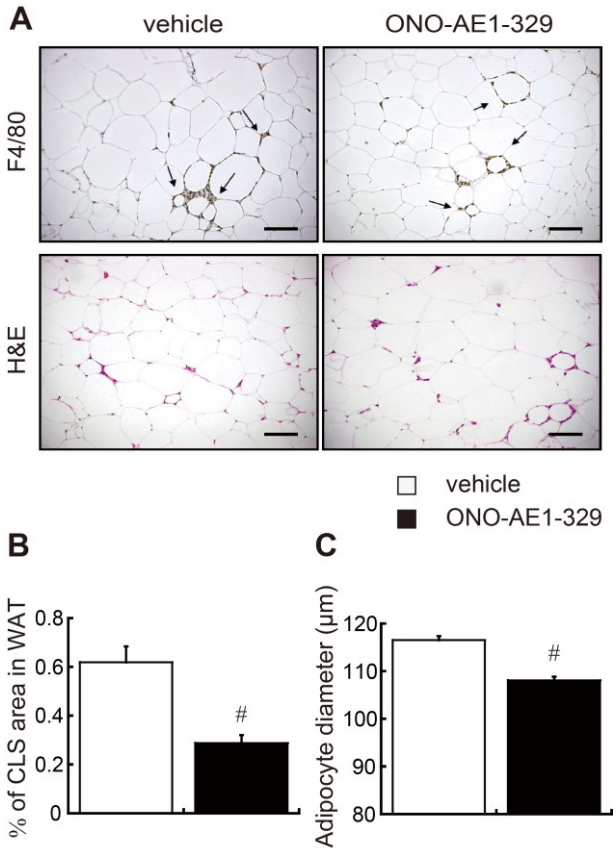

A
vehicle
ONO-AE1-329
F4/80
H&E
vehicle
ONO-AE1-329
B
% of CLS area in WAT
0.8
0.6
0.4
0.2
0
#
C
Adipocyte diameter (μm)
120
110
100
90
80
#

Figure 3

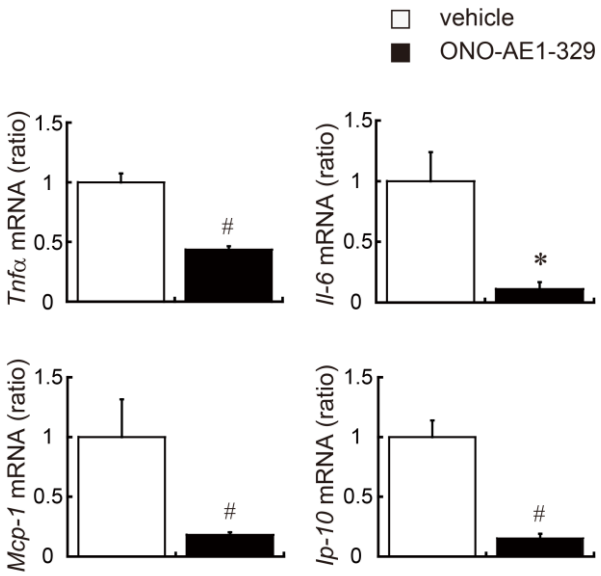

vehicle
ONO-AE1-329
Tnfα mRNA (ratio)
Il-6 mRNA (ratio)
Mcp-1 mRNA (ratio)
Ip-10 mRNA (ratio)
1.5
1
0.5
0
#
*
#
#

Figure 4

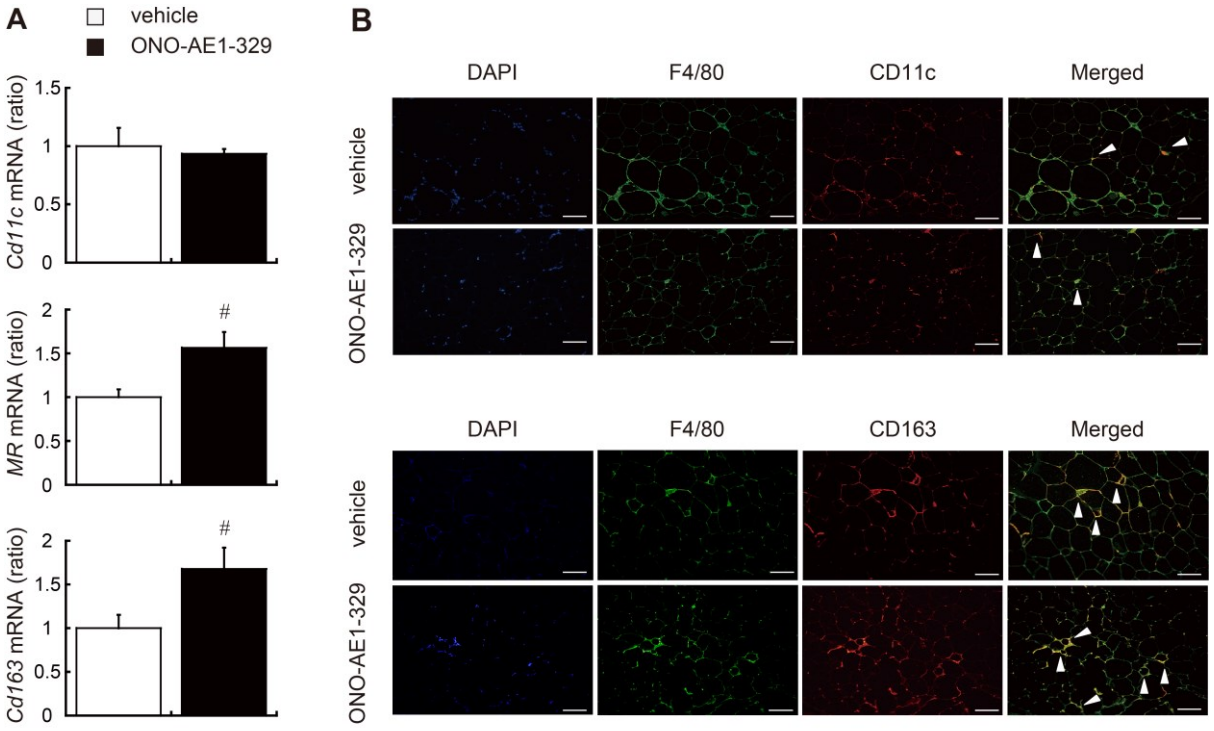

A
vehicle
ONO-AE1-329
Cd11c mRNA (ratio)
MR mRNA (ratio)
Cd163 mRNA (ratio)
#
B
DAPI
F4/80
CD11c
Merged
vehicle
ONO-AE1-329
DAPI
F4/80
CD163
Merged
vehicle
ONO-AE1-329

Figure 5

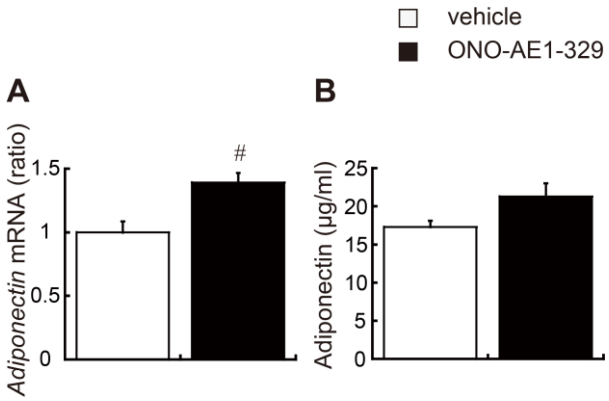
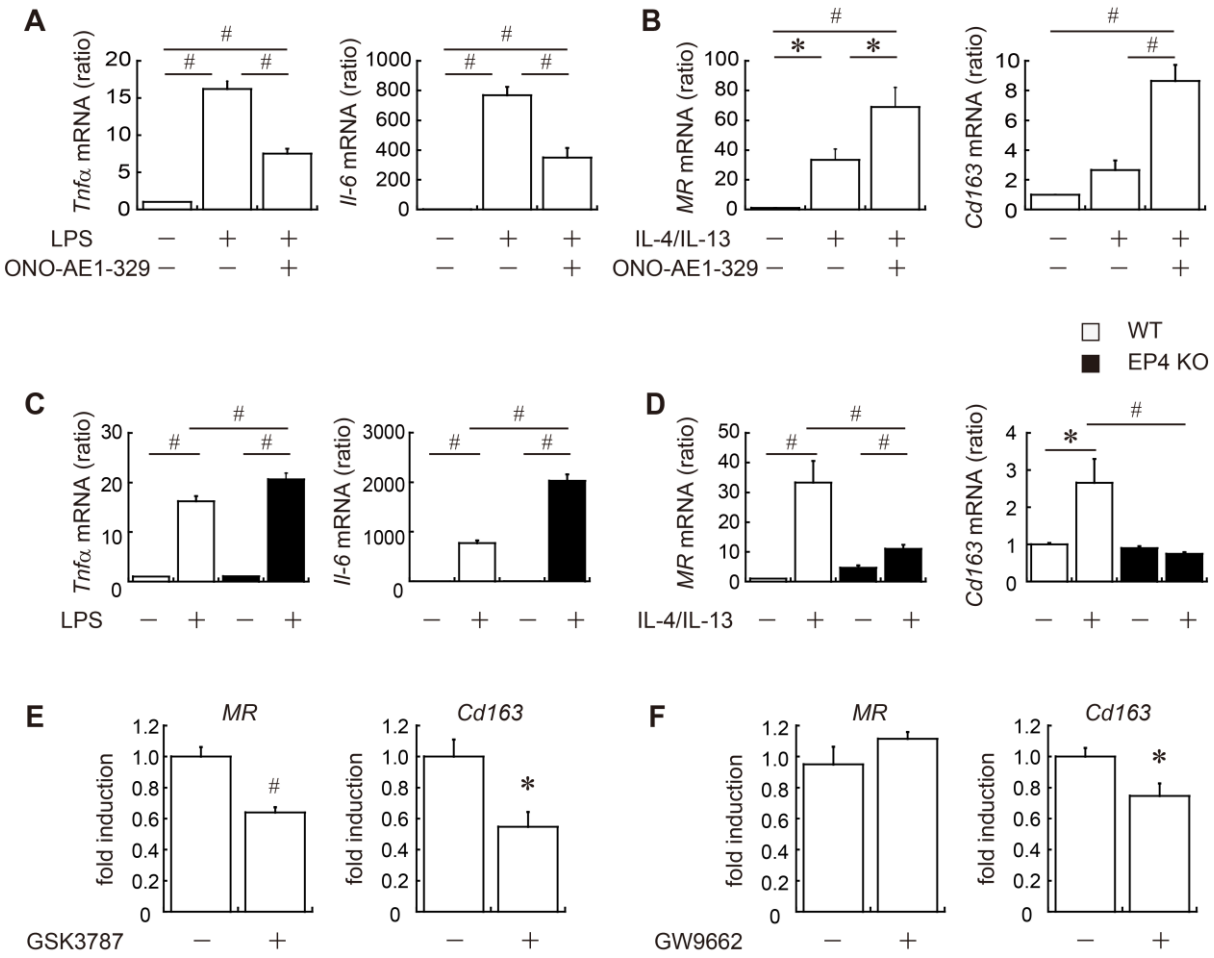

vehicle
ONO-AE1-329
A
B
Adiponectin mRNA (ratio)
1.5
1
0.5
0
#
Adiponectin (μg/ml)
25
20
15
10
5
0

Figure 6


A
Tnfα mRNA (ratio)
Il-6 mRNA (ratio)
LPS
ONO-AE1-329
B
MR mRNA (ratio)
Cd163 mRNA (ratio)
IL-4/IL-13
ONO-AE1-329
WT
EP4 KO
C
Tnfα mRNA (ratio)
Il-6 mRNA (ratio)
LPS
D
MR mRNA (ratio)
Cd163 mRNA (ratio)
IL-4/IL-13
E
MR
Cd163
fold induction
GSK3787
F
MR
Cd163
fold induction
GW9662

Supporting Information

S1 Checklist

Completed ARRIVE Guidelines Checklist for reporting animal data in this manuscript.

(PDF)

S1 Fig. Impact of EP4 activation on MCP-1 production in adipose tissue

The relative mRNA levels (A) and the protein concentrations (B) of MCP-1 in epididymal adipose tissue were measured in *db/db* mice administered EP4 agonist (black bar) or vehicle (white bar). All values are mean ± SEM (A: n = 6 each, B: n = 6–8 each).

S2 Fig. EP4 activation enhances the gene expression levels of PPARs in adipose tissue

Relative expression of *PPARδ*, *PPARγ*, and *PPARα* mRNA in epididymal adipose tissue from *db/db* mice administered EP4 agonist (black bar) or vehicle (white bar). All values are mean ± SEM (n = 4–5 each). ♯ $p<0.01$ vs. vehicle. PPAR, peroxisome proliferator–activated receptor.

S1 checklist

ARRIVE

The ARRIVE Guidelines Checklist

Animal Research: Reporting In Vivo Experiments

Carol Kilkenny[1], William J Browne[2], Innes C Cuthill[3], Michael Emerson[4] and Douglas G Altman[5]

[1]The National Centre for the Replacement, Refinement and Reduction of Animals in Research, London, UK, [2]School of Veterinary Science, University of Bristol, Bristol, UK, [3]School of Biological Sciences, University of Bristol, Bristol, UK, [4]National Heart and Lung Institute, Imperial College London, UK, [5]Centre for Statistics in Medicine, University of Oxford, Oxford, UK.

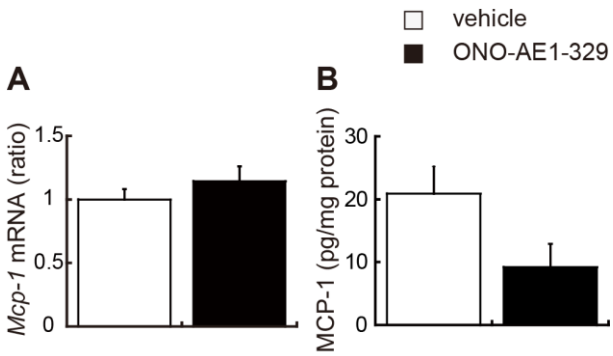
	ITEM	RECOMMENDATION	Section/ Paragraph
Title	1	Provide as accurate and concise a description of the content of the article as possible.	Title
Abstract	2	Provide an accurate summary of the background, research objectives, including details of the species or strain of animal used, key methods, principal findings and conclusions of the study.	Abstract
INTRODUCTION			
Background	3	a. Include sufficient scientific background (including relevant references to previous work) to understand the motivation and context for the study, and explain the experimental approach and rationale. b. Explain how and why the animal species and model being used can address the scientific objectives and, where appropriate, the study's relevance to human biology.	Throughout Paragraphs 4-5
Objectives	4	Clearly describe the primary and any secondary objectives of the study, or specific hypotheses being tested.	Paragraph 5
METHODS			
Ethical statement	5	Indicate the nature of the ethical review permissions, relevant licences (e.g. Animal [Scientific Procedures] Act 1986), and national or institutional guidelines for the care and use of animals, that cover the research.	Paragraph 1
Study design	6	For each experiment, give brief details of the study design including: a. The number of experimental and control groups. b. Any steps taken to minimise the effects of subjective bias when allocating animals to treatment (e.g. randomisation procedure) and when assessing results (e.g. if done, describe who was blinded and when). c. The experimental unit (e.g. a single animal, group or cage of animals). A time-line diagram or flow chart can be useful to illustrate how complex study designs were carried out.	Paragraph 2 Paragraph 3 Paragraph 2
Experimental procedures	7	For each experiment and each experimental group, including controls, provide precise details of all procedures carried out. For example: a. How (e.g. drug formulation and dose, site and route of administration, anaesthesia and analgesia used [including monitoring], surgical procedure, method of euthanasia). Provide details of any specialist equipment used, including supplier(s). b. When (e.g. time of day). c. Where (e.g. home cage, laboratory, water maze). d. Why (e.g. rationale for choice of specific anaesthetic, route of administration, drug dose used).	Paragraphs 1,3-10
Experimental animals	8	a. Provide details of the animals used, including species, strain, sex, developmental stage (e.g. mean or median age plus age range) and weight (e.g. mean or median weight plus weight range). b. Provide further relevant information such as the source of animals, international strain nomenclature, genetic modification status (e.g. knock-out or transgenic), genotype, health/immune status, drug or test naïve, previous procedures, etc.	Paragraph 2

The ARRIVE guidelines. Originally published in *PLoS Biology*, June 2010[1]

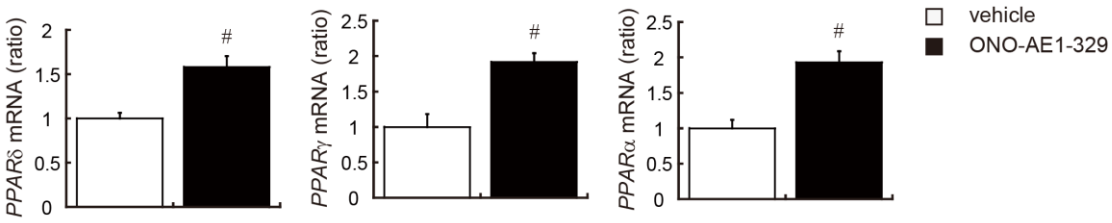
Housing and husbandry	9	Provide details of: a. Housing (type of facility e.g. specific pathogen free [SPF]; type of cage or housing; bedding material; number of cage companions; tank shape and material etc. for fish). b. Husbandry conditions (e.g. breeding programme, light/dark cycle, temperature, quality of water etc for fish, type of food, access to food and water, environmental enrichment). c. Welfare-related assessments and interventions that were carried out prior to, during, or after the experiment.	Paragraph 2
Sample size	10	a. Specify the total number of animals used in each experiment, and the number of animals in each experimental group. b. Explain how the number of animals was arrived at. Provide details of any sample size calculation used. c. Indicate the number of independent replications of each experiment, if relevant.	Paragraph 2-3
Allocating animals to experimental groups	11	a. Give full details of how animals were allocated to experimental groups, including randomisation or matching if done. b. Describe the order in which the animals in the different experimental groups were treated and assessed.	Paragraph 3
Experimental outcomes	12	Clearly define the primary and secondary experimental outcomes assessed (e.g. cell death, molecular markers, behavioural changes).	Paragraph 4
Statistical methods	13	a. Provide details of the statistical methods used for each analysis. b. Specify the unit of analysis for each dataset (e.g. single animal, group of animals, single neuron). c. Describe any methods used to assess whether the data met the assumptions of the statistical approach.	Paragraph 11
RESULTS			
Baseline data	14	For each experimental group, report relevant characteristics and health status of animals (e.g. weight, microbiological status, and drug or test naïve) prior to treatment or testing. (This information can often be tabulated).	paragraph 1 Methods Paragraph 3
Numbers analysed	15	a. Report the number of animals in each group included in each analysis. Report absolute numbers (e.g. 10/20, not 50%[2]). b. If any animals or data were not included in the analysis, explain why.	Methods Paragraph 2-3
Outcomes and estimation	16	Report the results for each analysis carried out, with a measure of precision (e.g. standard error or confidence interval).	Throughout
Adverse events	17	a. Give details of all important adverse events in each experimental group. b. Describe any modifications to the experimental protocols made to reduce adverse events.	Paragraph 1 Methods Paragraph 1
DISCUSSION			
Interpretation/ scientific implications	18	a. Interpret the results, taking into account the study objectives and hypotheses, current theory and other relevant studies in the literature. b. Comment on the study limitations including any potential sources of bias, any limitations of the animal model, and the imprecision associated with the results[2]. c. Describe any implications of your experimental methods or findings for the replacement, refinement or reduction (the 3Rs) of the use of animals in research.	Throughout Paragraph 7-8 Paragraph 2
Generalisability/ translation	19	Comment on whether, and how, the findings of this study are likely to translate to other species or systems, including any relevance to human biology.	Throughout
Funding	20	List all funding sources (including grant number) and the role of the funder(s) in the study.	Paragraph 9

References:
1. Kilkenny C, Browne WJ, Cuthill IC, Emerson M, Altman DG (2010) Improving Bioscience Research Reporting: The ARRIVE Guidelines for Reporting Animal Research. *PLoS Biol* 8(6): e1000412. doi:10.1371/journal.pbio.1000412
2. Schulz KF, Altman DG, Moher D, the CONSORT Group (2010) CONSORT 2010 Statement: updated guidelines for reporting parallel group randomised trials. *BMJ* 340:c332.

S1 Figure


vehicle
ONO-AE1-329
A
B
Mcp-1 mRNA (ratio)
1.5
1
0.5
0
MCP-1 (pg/mg protein)
30
20
10
0

S2 Figure


PPARδ mRNA (ratio)
2
1.5
1
0.5
0
#
PPARγ mRNA (ratio)
2.5
2
1.5
1
0.5
0
#
PPARα mRNA (ratio)
2.5
2
1.5
1
0.5
0
#
vehicle
ONO-AE1-329