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Adiponectin Regulates Cutaneous Wound Healing by Promoting Keratinocyte Proliferation and Migration via the ERK Signaling Pathway

Sayaka Shibata,* Yayoi Tada,* Yoshihide Asano,* Carren S. Hau,* Toyoaki Kato,* Hidehisa Saeki,* Toshimasa Yamauchi,† Naoto Kubota,† Takashi Kadowaki,† and Shinichi Sato*

Diabetic patients are at high risk of developing delayed cutaneous wound healing. Adiponectin plays a pivotal role in the pathogenesis of diabetes and is considered to be involved in various pathological conditions associated with diabetes; however, its role in wound repair is unknown. In this study, we elucidated the involvement of adiponectin in cutaneous wound healing in vitro and in vivo. Normal human keratinocytes expressed adiponectin receptors, and adiponectin enhanced proliferation and migration of keratinocytes in vitro. This proliferative and migratory effect of adiponectin was mediated via AdipoR1/AdipoR2 and the ERK signaling pathway. Consistent with in vitro results, wound closure was significantly delayed in adiponectin-deficient mice compared with wild-type mice, and more importantly, keratinocyte proliferation and migration during wound repair were also impaired in adiponectin-deficient mice. Furthermore, both systemic and topical administration of adiponectin ameliorated impaired wound healing in adiponectin-deficient and diabetic db/db mice, respectively. Collectively, these results indicate that adiponectin is a potent mediator in the regulation of cutaneous wound healing. We propose that upregulation of systemic and/or local adiponectin levels is a potential and very promising therapeutic approach for dealing with diabetic wounds. The Journal of Immunology, 2012, 189: 3231–3241.

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Abbreviations used in this article: AMPK, AMP-activated protein kinase; BHE, bovine hypothalamic extract; EGF, epidermal growth factor; HGF, hepatocyte growth factor; KO, knockout; qRT-PCR, quantitative real-time RT-PCR; siRNA, small interfering RNA.

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performed functional analyses regarding proliferative and migratory effects. We further examined how adiponectin would be involved in vivo during the wound repair process, using a mouse model of excisional skin wound healing in adiponectin-deficient and diabetic db/db mice. The results of this study indicate that adiponectin enhances proliferation and migration of keratinocytes through AdipoR1/AdipoR2 and the ERK signaling pathway in vitro and that adiponectin regulates the skin wound healing process in vivo by promoting keratinocyte proliferation and migration.

Materials and Methods

Reagents

Recombinant human adiponectin was isolated and purified as described previously (22). We verified that purified recombinant adiponectin was free of endotoxin using an endotoxin detection kit (GenScript, Piscataway, NJ). Abs against ERK, p-ERK, p38, p-p38, JNK, p-JNK, Akt, p-Akt, and β-actin were obtained from Cell Signaling Technology (Beverly, MA). Abs against adiponectin, AdipoR1, and AdipoR2 were from Abcam (Cambridge, U.K.). Abs against Ki67 and loricrin were obtained from Novo Castra Laboratories (Newcastle, U.K.) and Covance (Berkeley, CA), respectively. PD98059, U0126, wortmannin, LY294002, SB203580, and SP600125 were also purchased from Cell Signaling Technology.

Cell culture

Normal human epidermal keratinocytes were cultured with MCDB153 medium supplemented with insulin (5 μg/ml), hydrocortisone (1 μM), ethanolamine (0.1 mM), phosphoethanolamine (0.1 mM), bovine hypothalamic extract (BHE) (50 μg/ml), and Ca2+ (0.1 mM) as described previously (23, 24). Third or fourth passage cells were used in this study.

RNA interference for adiponectin receptors

All transfections were done using Lipofectamine 2000 following the manufacturer’s instructions (Invitrogen Life Technologies, Carlsbad, CA). Keratinocytes were plated in 6-well plates and cultured without antibiotics until reaching 30–50% subconfluency. AdipoR1/AdipoR2/calreticulin/T-cadherin and negative control small interfering RNA (siRNA) (Thermo Scientific Dharmacon, Lafayette, CO) were transfected into keratinocytes using Lipofectamine 2000. Medium was changed after 6 h after trans-
TGF-β well. After reaching subconfluency, the cells were fed MCDB153 medium according to the manufacturer’s instructions. Assessed using an MTT assay kit (Roche Diagnostics, Basel, Switzerland), containing designated amounts of adiponectin. After 3 d, cell viability was and the following day, they were fed once again with the same medium well. The next day, the cells were fed MCDB153 medium lacking BHE, and incubated for another 12 h. The cells were then incubated with 10% buffered formalin overnight and then stained with crystal violet. The membrane was then mounted between two glass slides with 90% glycerol, and the number of migrated cells was counted under a microscope.

In vitro wound closure assay Keratinocytes were seeded on 6-well plates at a density of 1 × 10^4 cells/well. After reaching subconfluence, wounds were created at the center of each well by scraping, and culture debris was removed by PBS washing. The remaining cells were cultured further with designated amounts of adiponectin and HGF. After 12 h, keratinocyte migration was observed under a phase contrast microscope. Wound closure was determined by identifying the front of cell migration and calculating a ratio of the migration area to the area of time 0.

**Mice** Adiponectin-deficient mice were generated as described previously (6). BKS.Cg + Lepr db/+ Lepr db (db/db) were purchased from CLEA Japan (Tokyo, Japan). Mice were 7- to 10-wk-old for all experiments, and age-matched wild-type C57BL/6j mice (CLEA Japan) were used as controls for adiponectin-deficient and db/db mice. All mice were maintained under a 12-h light/12-h dark cycle in a specific pathogen-free barrier facility. All studies and procedures were approved by the Committee on Animal Experimentation of Tokyo University.
Wounding and macroscopic examination
Mice were anesthetized with diethyl ether, and their backs were shaved and wiped with 70% alcohol. Four full-thickness excisional wounds per mouse were made using a disposable sterile 6-mm biopsy punch (Maruho, Osaka, Japan), and mice were caged individually. No signs suggestive of local infection were detected in the wounded skin. We excluded wounds with extreme distortion, which did not permit a precise determination of their size. Areas of open wounds were traced onto a transparency and analyzed using ImageJ (available online).

Histological assessment of wound healing
Skin sections of wounds including a 2-mm rim of unwounded skin tissue were taken from murine back skin. The samples were formalin fixed and embedded in paraffin. Five-micrometer sections were stained with H&E. The epithelial gap, which represents distance between the leading edge of migrating keratinocytes, was measured under a light microscope. For the analyses of staining for adiponectin, AdipoR1/AdipoR2, Ki67, and loricrin, immunohistochemistry was performed using a Vectastain avidin/biotin complex kit (Vector Laboratories, Burlingame, CA), according to the manufacturer’s instructions. The 5-μm sections were deparaffinized and rehydrated, endogenous peroxidase activity was eliminated by blocking with hydrogen peroxide, and the tissue sections were immersed in citrated buffer and boiled for 10 min for Ag retrieval. The sections were then incubated with indicated Abs overnight at 4°C, followed by the incubation with biotinylated secondary Ab. The concentration of each primary Ab was first tested to determine the optimal sensitivity range. The immunoreactivity was visualized with diaminobenzidine, and the sections were counterstained with Mayer’s hematoxylin.

Statistical analyses
Data obtained are presented as mean ± SE. Student t test was used for the statistical analysis of differences between two groups. One-way ANOVA with Dunnett’s multiple comparison test was used for statistical analysis of the differences among multiple groups. A p value < 0.05 was considered to represent a significant difference.

Results
Adiponectin receptors are expressed in human keratinocytes and AdipoR1 expression is upregulated by adiponectin stimulation
AdipoR1 is expressed widely in various tissues, with the highest expression level in skeletal muscle, whereas AdipoR2 is most abundantly expressed in the liver (30). Recently, new receptors for adiponectin, calreticulin, and T-cadherin also have been identified and reported to be involved in adiponectin cellular signaling (31–34). We first investigated the expressions of these adiponectin receptors in normal human keratinocytes. Human keratinocytes expressed both AdipoR1/AdipoR2 as well as calreticulin and T-cadherin at the mRNA level (Fig. 1A). Adiponectin upregulated gene expression levels of AdipoR1 in a dose-dependent manner but not those of AdipoR2, calreticulin, or T-cadherin in keratinocytes (Fig. 1B).

Adiponectin enhances keratinocyte proliferation
We next investigated the effect of adiponectin on keratinocyte proliferation using the MTT and BrdU assays. The MTT assay quantifies viable cells, whereas the BrdU assay determines BrdU incorporation into newly synthesized DNA of actively proliferating cells. Adiponectin increased the number of viable keratinocytes (Fig. 2A) and BrdU uptake (Fig. 2B) in a dose-dependent manner, reaching a plateau at a concentration of 25 μg/ml. Because plasma adiponectin concentrations in healthy humans are ~3–30 μg/ml (36), the stimulatory effects of adiponectin were significant within physiological concentrations. EGF, a positive control, significantly induced keratinocyte proliferation in the BrdU assay, whereas TGF-β, a negative control, had no effect (37).

Adiponectin induces keratinocyte migration
After establishing that adiponectin stimulates keratinocyte proliferation, we next investigated the effect of adiponectin on keratinocyte migration using two types of in vitro assay systems. In the Boyden chamber assay, we quantitatively investigated adiponectin-induced migration. Various amounts of adiponectin and cultured human keratinocytes were added to the lower and upper chambers, respectively. After incubation overnight, the number of migrated cells was counted. Adiponectin significantly stimulated keratinocyte migration at concentrations of 12.5–50 μg/ml (Fig. 3A). HGF was used as a positive control, which induced an ~7-fold increase relative to control (38).
Next, wounds were created in cultured keratinocytes by scraping (in vitro wounds). Keratinocytes were cultured with various concentrations of adiponectin or HGF. Acceleration of wound closure was observed in response to 25 μg/ml adiponectin 12 h after wounding (Fig. 3B, 3C).

**The ERK signaling pathway is activated by adiponectin via AdipoR1/AdipoR2 in keratinocytes**

MAPK is a well-known factor involved in cell proliferation (39–41). Akt and AMP-activated protein kinase (AMPK) are also known to enhance cell proliferation and suppress apoptosis (10). Therefore, we investigated whether adiponectin could induce phosphorylation of MAPKs, Akt and AMPK in normal human keratinocytes. As shown in Fig. 4A, adiponectin (25 μg/ml) induced phosphorylation of ERK in keratinocytes. The peak activation occurred at 5 min after stimulation, and thereafter, the phosphorylation level gradually decreased. Adiponectin had no effect on the phosphorylation of the p38 MAPK, JNK, Akt, and AMPK (Fig. 4B). To confirm the specificity of the identified pathway, keratinocytes were pretreated with 75 μM MEK1 in-

**FIGURE 4.** Involvement of AdipoR1/AdipoR2 and the ERK signaling pathway in adiponectin-stimulated keratinocytes. (A) Keratinocytes were incubated with adiponectin (25 μg/ml) for 0–60 min. The cell lysates were analyzed for phosphorylation of ERK1/2 by Western blotting. Results are representative of four independent experiments. (B) Keratinocytes were incubated with adiponectin (25 μg/ml) for 0–60 min. The cell lysates were analyzed for phosphorylation of p38 MAPK, JNK, Akt, and AMPK by Western blotting. Results are representative of four independent experiments. (C) Keratinocytes were pretreated with PD98059 (PD; 75 μM, MEK1 inhibitor) or U0126 (U; 10 μM, MEK1/2 inhibitor) for 30 min. After incubation with adiponectin (25 μg/ml) for 5 min, the cell lysates were analyzed for ERK1/2 phosphorylation by Western blotting. Results are representative of four independent experiments. (D) Keratinocytes were transfected with control siRNA or siRNA targeting AdipoR1/AdipoR2/calreticulin/T-cadherin. mRNA expression of these receptors in transfected cells was examined by qRT-PCR. Results are representative of three independent experiments. (E) Transfected cells were incubated with adiponectin (25 μg/ml) for 0–30 min. The cell lysates were analyzed for phosphorylation of ERK1/2 by Western blotting. Results are representative of three independent experiments. (F) Densitometry analysis of P5/P0 (P5, phospho-ERK protein expression levels/total ERK protein expression levels at 5 min after adiponectin stimulation; P0, phospho-ERK protein expression levels/total ERK protein expression levels before adiponectin stimulation), and data are expressed as mean ± SE (n = 3).
We performed immunohistochemistry for the proliferation marker of late-phase keratinocyte differentiation, by immunohistochemistry for wound contraction. To confirm the pattern of wound healing, which involves keratinocyte proliferation and migration, we performed experiments. Full-thickness round wounds of 6 mm in diameter were made, and the kinetics of wound closure were examined. Control experiments have revealed that AdipoR1 and AdipoR2 completely suppressed adiponectin-induced ERK phosphorylation in keratinocytes (Fig. 4E, 4F). However, downregulation of calreticulin or T-cadherin did not significantly suppress adiponectin-induced ERK phosphorylation. These results indicate that 1) adiponectin activates the ERK signaling pathway through AdipoR1 and AdipoR2 and that 2) calreticulin or T-cadherin appears not to be involved in the ERK signaling pathway mediated by adiponectin in keratinocytes.

**ERK signaling pathway mediates adiponectin-induced keratinocyte proliferation and migration**

To investigate the role of the ERK signaling pathway in keratinocyte proliferation induced by adiponectin, we incubated keratinocytes with PD98059 (75 μM) or U0126 (10 μM) for 30 min before stimulation with adiponectin (25 μg/ml), and then, BrdU uptake was analyzed. Both of these inhibitors attenuated BrdU uptake induced by adiponectin, indicating that adiponectin-induced keratinocyte proliferation is mediated by the ERK pathway (Fig. 5A). Other kinase inhibitors (wortmannin and LY294002 for inhibition of PI3K, SB203580 for inhibition of p38 MAPK, and SP600125 for inhibition of JNK) did not affect adiponectin-induced proliferation. We further investigated whether the ERK signaling pathway would be involved in the keratinocyte migration induced by adiponectin. After the addition of PD98059 (75 μM) or U0126 (10 μM) to the lower chamber with adiponectin, keratinocyte migration was analyzed using the Boyden chamber assay. Both of the inhibitors blocked adiponectin-induced keratinocyte migration (Fig. 5B). These results suggest that the ERK signaling pathway mediated adiponectin-induced keratinocyte migration as well as proliferation.

**Wound closure and keratinocyte re-epithelialization are significantly delayed in adiponectin-deficient mice**

To further strengthen our in vitro results and to determine the role of adiponectin during cutaneous wound healing in vivo, we first examined the excisional wound skin repair process in adiponectin-deficient and wild-type mice. Full-thickness round wounds of 6 mm in diameter were made, and the kinetics of wound closure were evaluated as percentage of original wound areas. Adiponectin-deficient mice exhibited significantly impaired wound repair compared with wild-type mice from day 3 (Fig. 6A, 6B). All the wounds of wild-type mice healed within 9 d after wounding, whereas the wounds of adiponectin-deficient mice took more than 13 d to heal. Next, we focused on the re-epithelialization phase of wound healing, which involves keratinocyte proliferation and migration for wound contraction. To confirm the pattern of keratinocyte differentiation to be normal in the adiponectin-deficient mice skin, we first examined the expression of loricrin, a marker of late-phase keratinocyte differentiation, by immunohistochemistry. Loricrin expression in the keratinocytes was comparable between wild-type and adiponectin-deficient mice (Fig. 6C). Next, we performed immunohistochemistry for the proliferation marker Ki67 on the skin samples of the wound margins (20, 42). Distribution of Ki67-positive proliferating keratinocytes was more extensive in the wound margins of control wild-type mice compared with adiponectin knockout (KO) mice (Fig. 6D, 6E). Furthermore, the epithelial gap, the distance between the migrating edges of keratinocytes, was significantly wider in adiponectin-deficient mice compared with wild-type mice (Fig. 6A, 6F), suggesting that keratinocyte migration was significantly inhibited in adiponectin-deficient mice. These results are in accordance with the in vitro results regarding the proliferative and migratory functions of adiponectin in keratinocytes.

**The gene expression of adiponectin and AdipoR1/AdipoR2 gradually increases during the wound healing process**

To determine whether the local adiponectin and AdipoR1/AdipoR2 expression levels change during the wound healing process, we determined the changes in expression of these genes over time. Skin samples, taken immediately before (at day 0) and 3 and 6 d (days 3 and 6) after wounding, were analyzed by the qrt-PCR. We demonstrated in this study that adiponectin expression at the wound site gradually increased during the course of wound repair in wild-type mice (Fig. 7A), suggesting that adiponectin production might be upregulated sensing tissue damage of wounding. Immunohistochemistry of adiponectin showed that the sources of adiponectin are adipocytes and fibroblasts but not keratinocytes (Fig. 7B). Regarding adiponectin receptors, AdipoR1 and AdipoR2 mRNA expression also increased gradually after wounding in both wild-
The expression levels of these receptors during wound repair were comparable between wild-type and adiponectin KO mice. We also analyzed AdipoR1 and AdipoR2 expression on cells in wound samples of wild-type and adiponectin KO mice by immunohistochemistry. Protein expression of AdipoR1 and AdipoR2 was detected in fibroblasts and adipocytes as well as keratinocytes, and their expression was upregulated after wounding (Fig. 7D). Taken together, adiponectin, locally produced by adipocytes after skin damage, might induce the upregulation of AdipoR1 and AdipoR2 expression on keratinocytes. This process would further enhance adiponectin-mediated signaling within keratinocytes, thus promoting keratinocyte proliferation and migration.

Systemically supplemented adiponectin ameliorates delayed wound healing in adiponectin-deficient mice but not in wild-type mice

To determine whether the impaired wound healing in adiponectin-deficient mice is particularly adiponectin dependent or not, wild-type and adiponectin-deficient mice were given daily i.p. injection of recombinant adiponectin (50 μg/day/mouse) from 1 d before wounding, and the wound repair process was examined. As shown in Fig. 8A, systemic injection of physiological dose of adiponectin significantly ameliorated impaired wound healing in adiponectin-deficient mice but not in wild-type mice at days 3 and 7. These results may indicate that adiponectin supplementation is effective only under the condition when adiponectin is insufficient.

Topically supplemented adiponectin accelerates delayed wound healing in db/db mice but not in wild-type mice

To evaluate a potential clinical application of adiponectin, we investigated whether adiponectin would also act directly at the wound site by administering adiponectin to wound beds directly in db/db mice, a rodent model for type 2 diabetes, and wild-type mice. We applied 2.5 μg adiponectin in 50 μl PBS on the left side of the murine back and the same dose of PBS on the right side under the occlusive dressing every day. db/db mice were previously shown to have decreased adiponectin levels and impaired wound healing (43). Topical adiponectin administration significantly reduced open wound area relative to PBS administration at days 13, 16, and 19 (Fig. 8B) in db/db mice. Re-epithelialization was also assessed at day 13 microscopically, and the epithelial gap was significantly shorter in adiponectin-treated mice relative to PBS-treated mice (Fig. 8C). In contrast, there was no significant difference between adiponectin- and PBS-applied wound areas in wild-type mice (Fig. 8D). These results, as in the case with systemic supplementation, suggest that wound treatment with topical adiponectin is effective in mice with low adiponectin levels (db/db mice) but not in mice with normal adiponectin levels (wild-type mice).
Adiponectin, a key mediator in the pathogenesis of diabetes, exerts multiple biological activities in various diseases; however, its role in cutaneous wound healing is unknown. To clarify this, we investigated pathophysiologic roles of adiponectin during cutaneous wound healing. We first demonstrated that keratinocytes express adiponectin receptors and that adiponectin induces proliferation and migration of keratinocytes in a dose-dependent manner through ERK activation in vitro. By using siRNAs of adiponectin receptors on keratinocytes, we also determined that AdipoR1 and AdipoR2 are mainly involved in the adiponectin-mediated ERK signaling pathway. These in vitro results suggest that adiponectin might contribute to the re-epithelialization phase of optimal wound healing. We have next undertaken a detailed functional analysis of adiponectin during wound repair in vivo. Wound closure was significantly delayed in adiponectin-deficient mice compared with wild-type mice. The number of Ki67-positive cells in the wound margin epithelial cells was decreased and re-epithelialization was delayed in adiponectin-deficient mice, which were supportive of in vitro results. The expression of AdipoR1/AdipoR2 as well as adiponectin gradually increased after wounding, which may consequently augment adiponectin signaling within keratinocytes and facilitate wound repair. Finally, we examined the curative effect of adiponectin on wounds. Both systemic and topical adiponectin supplementation normalized the impaired wound healing in adiponectin-deficient mice and db/db mice, respectively. Thus, adiponectin might contribute to optimal cutaneous wound healing in diabetic patients, whose adiponectin levels are persistently decreased.

With regard to cell proliferation and migration, the behavior of adiponectin seems to depend on cell types. For instance, adiponectin stimulates cell growth in colonic epithelial cells (39), osteoblasts (40), and cardiac fibroblasts (41), where adiponectin is involved in the gastrointestinal mucosal metabolism, bone me-
Metabolism, and myocardial hypertrophy, respectively. Migratory effects of adiponectin have been reported in endothelial progenitor cells (44). In contrast, adiponectin suppressed cell proliferation and migration in vascular smooth muscle cells (45) and hepatic stellate cells (46), acting as a modulator for vascular remodeling and liver fibrosis, respectively. Most importantly, a certain subset of cell types that are involved in the cutaneous wound healing process exhibit proliferative and migratory behaviors in response to adiponectin. Dermal fibroblasts are the dominant players in the process of granulation tissue formation during cutaneous wound healing. Recent reports have revealed that adiponectin induces proliferation of dermal fibroblasts and upregulation of collagen production (47, 48). Furthermore, adiponectin induces proliferation of HUVECs and stimulates angiogenesis (10), indicating the positive contribution of adiponectin to optimal wound repair. In addition, adiponectin induces neutrophil migration, which is an initial step of skin wound repair (14). In this study, adiponectin exhibited proliferative and migratory effects on primary human keratinocytes. Proliferation and migration of keratinocytes are crucial factors of re-epithelialization, which marks the final stage of wound healing (14). Given that inflammation, granulation tissue formation, re-epithelialization, and angiogenesis are sequential central events, adiponectin may play a vital role throughout the wound healing process. It should be mentioned that Kawai et al. (49) previously reported that adiponectin slightly suppressed the proliferation of the immortalized keratinocyte cell line HaCaT.

Therefore, we also investigated whether adiponectin would exert effects on HaCaT cells as well; however, in our hands, adiponectin had no effect on proliferation of these cells (Supplemental Fig. 1). Although the reason for the discrepancy of the results between primary normal human keratinocytes and HaCaT cells is not clear, HaCaT cells have been reported to behave differently from normal human keratinocytes regarding cell growth, differentiation, and cytokine production in several reports (50, 51).

Consistent with our in vitro results, a significant impairment of wound repair was also observed in adiponectin-deficient mice in the current study. Furthermore, both systemic and topical adiponectin accelerated wound repair in adiponectin-deficient and diabetic db/db mice, respectively. In contrast, the wound closure rate of wild-type mice did not change after systemic or local administration of adiponectin. Thus, adiponectin has beneficial and direct effects on cutaneous wound healing, especially in diabetic patients whose adiponectin levels are constitutively decreased. These findings would suggest that upregulating serum adiponectin levels through medical treatment as well as raising cutaneous local adiponectin levels by direct administration of adiponectin to the wound sites represents a novel effective therapeutic target for delayed diabetic wounds (52).

There has been no information available regarding the adiponectin-induced intracellular signaling in keratinocytes. The signaling pathways involved in cell proliferation and migration by adiponectin are tissue-/cell type-specific, including p38 MAPK,
JNK, ERK, PI3K, and Akt (10, 39–41). In the current study, we demonstrate that the proliferative and migratory activities of adiponectin are mediated through ERK signaling. It has been reported that the ERK signaling pathway is activated as a downstream signal molecule of adiponectin receptors in several cell types, including endothelial cells, macrophages, cardiac fibroblasts, and pancreatic cells (10, 41, 53, 54). Previous studies have shown that the ERK signaling pathway is activated upon injury or stretching of keratinocytes (55, 56). Interestingly, ERK pathways are required for wound healing in corneal epithelial cells under high glucose conditions (57). Considering that ERK activation is required for keratinocyte proliferation and migration (58), our present result showing that adiponectin activates the ERK signaling pathway in keratinocytes would suggest that adiponectin positively regulates the re-epithelialization process during cutaneous wound healing.

In summary, we propose a potential role for adiponectin, a key mediator of diabetes, in the regulation of keratinocyte proliferation and migration during cutaneous wound healing and provide a new mechanism underlying delayed wound repair in diabetic patients. On the basis of our data, we propose that systemic and/or local upregulation of adiponectin levels may represent a novel therapeutic strategy for diabetic wounds.

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References


