Regulation of Insulin/Insulin-like Growth Factor-1 Signaling by Proteasome-mediated Degradation of Insulin Receptor Substrate-2*

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Insulin and insulin-like growth factor-1 (IGF-1) regulate metabolism and body growth through homologous receptor tyrosine kinases that phosphorylate the insulin receptor substrate (IRS) proteins. IRS-2 is an important IRS protein, as it mediates peripheral insulin action and β-cell survival. In this study, we show that insulin, IGF-1, or osmotic stress promoted ubiquitin/proteasome-mediated degradation of IRS-2 in 3T3-L1 cells, Fao hepatoma, cells and mouse embryo fibroblasts; however, insulin/IGF-1 did not promote degradation of IRS-1 in 3T3-L1 preadipocytes or mouse embryo fibroblasts. MG132 or lactacystin, specific inhibitors of 26S proteasome, blocked insulin/IGF-1-induced degradation of IRS-2 and enhanced the detection of ubiquitinated IRS-2. Insulin/IGF1-induced ubiquitination and degradation of IRS-2 was blocked by inhibitors of phosphatidylinositol 3-kinase (wortmannin or LY294002) or mTOR (rapamycin). Chronic insulin or IGF-1 treatment of IRS-1-deficient mouse embryo fibroblasts inhibited IRS-2-mediated activation of Akt and ERK1/2, which was reversed by lactacystin pretreatment. By contrast, IRS-1 activation of Akt and ERK1/2 was not inhibited by chronic insulin/IGF-1 stimulation in IRS-2-deficient mouse embryo fibroblasts. Thus, we identified a novel negative feedback mechanism by which the ubiquitin/proteasome-mediated degradation of IRS-2 limits the magnitude and duration of the response to insulin or IGF-1.

Insulin and insulin-like growth factor 1 (IGF-1) regulate a variety of biological functions through homologous tyrosine kinases that phosphorylate the insulin receptor substrate (IRS) proteins. IRS proteins mediate signal specificity and diversity in various cellular backgrounds (1). Upon ligand binding, the activated insulin/IGF-1 receptors engage IRS proteins and promote the phosphorylation of multiple tyrosine residues, which activate various downstream signaling pathways, including the phosphatidylinositol (PI) 3-kinase and MAP kinase cascades (1, 2). These signaling pathways coordinate a network of protein kinases that regulate the activity of cytoplasmic enzymes and nuclear transcription factors (1–4). Four IRS proteins are known, including IRS-1 and IRS-2, which play a central role in many tissue and organ systems. Deletion of IRS-1 in mice impairs somatic growth and causes peripheral insulin resistance, but diabetes rarely develops owing to lifelong compensatory hyperinsulinemia (5, 6). By contrast, IRS-2 is essential for normal nutrient homeostasis because it mediates both peripheral insulin action and the effect of IGF-1 on β-cell growth; mice lacking IRS-2 fail to maintain sufficient compensatory insulin secretion and develop diabetes as young adults (7). Moreover, female mice lacking IRS-2 are hyperplastic and infertile, owing to a failure of the hypothalamic-pituitary-ovarian axis (8).

Many mechanisms are proposed to explain the inhibition of IRS protein signaling, including phosphotyrosine dephosphorylation, serine/threonine phosphorylation, and degradation (9–14). Recent studies suggest that proteasome-mediated degradation of IRS-1 might be involved in the down-regulation of signaling by insulin and IGF-1 and contribute to insulin resistance (12, 13, 15–17). However, there is no convincing evidence showing that the decrease of endogenous IRS-1 via the ubiquitin/proteasome system contributes to an inhibition of insulin signaling.

Proteasome-mediated degradation regulates many biological processes including gene transcription and cell cycle progression (18–20). Proteins targeted for destruction by 26S proteasome are usually ubiquitinated by a complex containing an ubiquitin-activating enzyme (E1), ubiquitin-conjugating enzyme (E2), and ubiquitin-protein ligase (E3) (20–22). In certain cases, phosphorylation promotes ubiquitination and degradation of signaling proteins, including IκBα and β-catenin (18, 23–25). Overexpressed recombinant IRS-1 is ubiquitinated in response to IGF-1, and PI 3-kinase inhibitors block IRS-1 degradation (12, 13, 15–17). However, it is unclear whether insulin promotes ubiquitination of endogenous IRS proteins or whether the ubiquitin/proteasome system inhibits IRS protein signaling. In this work, we show that insulin and IGF-1 stimulate ubiquitination and degradation of IRS-2 in multiple cell types via a PI 3-kinase/Akt/mTOR-dependent pathway, which correlates closely with the inhibition of insulin signaling. This negative feedback mechanism might limit the magnitude and duration of IRS-2-mediated signals, and contribute to insulin resistance associated with hyperglycemia and hyperinsulinemia.

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The abbreviations used are: IGF-1, insulin-like growth factor 1; IRS, insulin receptor substrate; PI, phosphatidylinositol; MEF, mouse embryo fibroblast; MAP, mitogen-activated protein; DEMEM, Dulbecco’s modified Eagle’s medium; E1, ubiquitin-activating enzyme; E2, ubiquitin carrier protein; E3, ubiquitin-protein isopeptide ligase; FBS, fetal bovine serum; PBS, phosphate-buffered saline; MEK, mitogen-activated protein kinase/extracellular signal-regulated kinase kinase; PAGE, polyacrylamide gel electrophoresis; EGF, epidermal growth factor; PDGF, platelet-derived growth factor; ERK, extracellular signal-regulated kinase.
EXPERIMENTAL PROCEDURES

Reagents—Human insulin and IGF-1 were a gift from Eli Li. Protein A-agarose was purchased from Repligen; 3-isobutylmethylxanthine, dexamethasone, aprotinin, and leupeptin were purchased from Sigma. Enhanced chemiluminescence (ECL) detection system was purchased from Amersham Pharmacia Biotech. Lactacystin, MG132, rapamycin, PD98059, LY294002, wortmannin, and Nonidet P-40 were purchased from Calbiochem. Polyonal anti-active ERK1/2 (opERK) was purchased from Promega. Polyclonal anti-phospho-Akt (on Ser-473) (opAkt) was purchased from New England Biolabs Inc. (Beverly, MA); monoclonal anti-ubiquitin was purchased from Santa Cruz Inc; polyonal anti-IRS-1 antibodies were raised against the full-length rat IRS-1 (JD#159, used at a dilution of 1:15,000 for immunoblotting). Polyclonal anti-IRS-2 antibodies were raised against the laboratory oligos raised against the amino acids 976–1094 (JD#110) or 618–747 (JD#101) of rat IRS-2. Polyclonal anti-p85 antibodies were raised against the N-terminal SH2 domain of p85 regulatory subunit of PI 3-kinase.

Cell Culture and Differentiation—Fao cells were grown at 37 °C in 5% CO2 in RPMI 1640 supplemented with 100 units/ml penicillin, 100 μg/ml streptomycin, and 10% fetal bovine serum (FBS). 3T3-L1 preadipocytes were grown at 37 °C in 10% CO2 in Dulbecco’s modified Eagle’s medium (DMEM) containing 25 mM glucose, 100 units/ml penicillin, 100 μg/ml streptomycin, and 10% calf serum (HyClone Laboratories, Inc). For adipocyte differentiation, confluent preadipocytes were cultured for 3 days in differentiation medium (DMEM supplemented with 25 mM glucose, 1 μM 3-isobutylmethylxanthine, 1 μM dexamethasone, and 10% FBS), and 3 days in DMEM supplemented with 1 μM insulin and 10% FBS. The cells were then grown for an additional 4–9 days in DMEM containing 25 mM glucose and 10% FBS without any other additives (>90% cells are adipocytes).

Preparation of Immortalized Mouse Embryo Fibroblasts (MEF)—The generation of IRS-1 and IRS-2 knockout mice has been described previously (5–7). IRS1−/− or IRS2−/− embryos were harvested on day 16 of gestation. After removal of the head and all internal organs, embryo carcases were washed with PBS, minced with scissors, and incubated with 0.25% trypsin on ice overnight. The embryos were incubated for an additional 20 min at 37 °C to activate trypsin. Growth medium (DMEM supplemented with 25 mM glucose, 10% heat-inactivated FBS, 100 units/ml penicillin, and 100 μg/ml streptomycin) was added to stop trypsin action, and the embryos were disrupted by vigorous pipetting. The resulting single cell suspension was centrifuged for 6 min at 1000 rpm. The cell pellet was resuspended in growth medium and cultured at 37 °C in 5% CO2. The MEF cells reached confluence in 2 days and were replated every 2 h at a density of 5 × 105 cells/cm2 until the establishment of permanent cell lines.

Immunoprecipitation and Immunoblotting—Confluent cells were deprived of serum overnight in DMEM (for 3T3-L1 and MEF cells) or RPMI 1640 (for Fao cells) containing 0.5% bovine serum albumin, and treated with different ligands at 37 °C. The cells were rinsed three times with ice-cold PBSV (10 mM sodium phosphate, pH 7.4, 150 mM NaCl, 1 mM Na3VO4), solubilized in lysis buffer (50 mM Tris, pH 7.5, 1% Nonidet P-40, 150 mM NaCl, 2 mM EGTA, 1 mM Na3VO4, 100 mM NaF, 10 mM NaN3, 1 mM phenylmethylsulfonyl fluoride, 10 μg/ml aprotinin, 10 μg/ml leupeptin), and centrifuged at 14,000 × g for 10 min at 4 °C. The supernatant (cell lysates) was boiled for 5 min in SDS-PAGE sample buffer (50 mM Tris-Cl, pH 6.8, 2% SDS, 10% glycerol, 2% β-mercaptoethanol, and 0.004% bromphenol blue) and separated by SDS-PAGE. In some experiments, the supernatant was incubated with the indicated antibody on ice for 2 h. The immune complexes were collected on protein A-agarose during a 1-h incubation at 4 °C. The beads were washed three times with washing buffer (50 mM Tris, pH 7.5, 1% Nonidet P-40, 150 mM NaCl, 2 mM EGTA) and boiled for 5 min in SDS-PAGE sample buffer. The solubilized proteins were separated by SDS-PAGE. Proteins on the gel were transferred to nitrocellulose membrane (Amersham Pharmacia Biotech) and detected by immunoblotting with the indicated antibody used in ECL. Some membranes were subsequently incubated at 55 °C for 30 min in stripping buffer (100 mM β-mercaptoethanol, 2% SDS, 62.5 mM Tris-HCl, pH 6.7) to prepare them for a second round of immunoblotting. To make clear cell lysates, cells were scraped in PBS, centrifuged at 14,000 × g for 1 min at 4 °C, and boiled for 5 min in SDS-PAGE sample buffer.

RESULTS

Insulin, IGF-1, and Osmotic Stress Reduce IRS-2 Protein Levels—To determine whether insulin and IGF-1 decrease IRS-2 protein levels, 3T3-L1 preadipocytes were treated for 6 h with either insulin (100 nm) or IGF-1 (100 ng/ml). Cell lysates prepared in 1% Nonidet P-40 were resolved by SDS-PAGE and analyzed by immunoblotting with polyonal antibodies against IRS-2 (αIRS2). IRS-2 was detected in control cell lysates, but not in insulin- or IGF-1-treated cells (Fig. 1A, top panel). To verify that this protein was IRS-2, 3T3-L1 preadipocytes were treated without or with insulin, and proteins in the cell lysates were immunoprecipitated and immunoblotted with αIRS2. C, cells were treated with insulin (100 nm) for 6 h and lysed in a buffer containing 2% SDS. Cell extracts were immunoblotted with αIRS2 or αop85. B, cells were treated with insulin and lysed as in A. Proteins in cell extracts were immunoprecipitated and immunoblotted with αIRS2. C, cells were treated with insulin (100 nm) for 6 h, and cell extracts were immunoblotted with αop85 or αIRS2 (#101), against the PH domain of rat IRS-2. D, cells were treated for 6 h (top two panels) or 10 min (bottom panel) with insulin (100 nm), EGF (100 ng/ml), or PDGF-BB (50 ng/ml). Cell extracts were immunoblotted with αIRS2, αop85, or antibodies against phosphorylated Akt (opAkt). The migration of molecular standards, IRS-1, IRS-2, and p85 is indicated.

To exclude the possibility that IRS-2 was redistributed into an inaccessible compartment, insulin-stimulated cells were lysed in buffer containing 2% SDS, and clear lysates were resolved by SDS-PAGE and immunoblotted with αIRS2. Consistent with the initial results, insulin reduced the level of IRS-2 but not p85 (Fig. 1C). Similar results were obtained with polyonal antibodies raised against other regions of IRS-2, excluding the possibility that phosphorylation of IRS-2 inhibited its immunoblotting by αIRS2 (Fig. 1D).

The degradation of IRS-2 was tested by other growth factors and in various cell backgrounds. 3T3-L1 preadipocytes were treated with epidermal growth factor (EGF) (100 ng/ml), platelet-derived growth factor-BB (PDGF) (50 ng/ml), or insulin. As expected, insulin stimulated reduction of IRS-2, but neither EGF nor PDGF altered the level of IRS-2; the level of p85 was not changed in response to insulin, EGF, or PDGF (Fig. 1E).
Both insulin and PDGF strongly stimulated phosphorylation and activation of Akt, whereas EGF stimulated Akt to a less extent (Fig. 1E).

Insulin-induced degradation of IRS-1 or IRS-2 was compared in several cell types, including 3T3-L1 adipocytes, Fao hepatoma cells, or MEF cells from wild-type, IRS1−/−, or IRS2−/− knockout mice. The cells were treated with insulin (100 nM) for 6 h, and proteins in cell lysates were immunoblotted with αIRS1, αIRS2, or αp85. IRS-2 levels decreased in all three of the cell types, whereas IRS-1 was not reduced in wild-type and IRS2−/− MEF cells; p85 did not change (Fig. 2).

Osmotic stress caused by hyperglycemia might exacerbate peripheral insulin resistance and β-cell dysfunction by impairing insulin/IGF-1 signaling (26). To examine whether osmotic stress induced reduction of IRS-2, Fao cells were treated for 60 min with various concentrations of D-sorbitol. Osmotic stress dramatically reduced the level of IRS-2 but not p85 in a dose-dependent fashion (Fig. 3). Consistent with this idea, lactacystin and MG132 did not alter the level of p85 (Fig. 4, B and E). Lactacystin and MG132 did not alter the level of IRS-2, owing largely to phosphorylation (Fig. 4A and lane 1). However, both lactacystin and MG132 inhibited insulin-induced reduction of IRS-2 protein levels (Fig. 4A, upper panel); lactacystin and MG132 also inhibited IGF-1-induced reduction of IRS-2 (data not shown). Similarly, insulin-induced reduction of IRS-2 was inhibited by lactacystin in Fao cells (Fig. 4B) and MEF (data not shown). Lactacystin and MG132 did not alter the level of p85 (Fig. 4, A and B, lower panel). Insulin ordinarily stimulates a shift in mobility of IRS-2, owing largely to phosphorylation (Fig. 4A). Lactacystin and MG132 did not significantly affect the insulin-induced mobility shift of IRS-2, suggesting that these inhibitors did not directly inhibit phosphorylation of IRS-2 (Fig. 4, A and B). Consistent with this idea, lactacystin and MG132 did not alter tyrosyl phosphorylation of IRS-1 and IRS-2 induced during 5 min of insulin stimulation (data not shown). Taken together, the data suggest that 26S proteasome mediates the degradation of IRS-2 during insulin/IGF-1 stimulation.

Ubiquitination targets proteins for degradation by 26S proteasome (27). To determine whether insulin promoted the ubiquitination of IRS-2, Fao cells were treated for 1 h with 100 nM insulin. IRS-2 was immunoprecipitated, resolved by SDS-PAGE and immunoblotted (IB) with αIRS2, αIRS1, or αp85 as indicated.
Ubiquitin/Proteasome-mediated Degradation of IRS-2

The PI 3-Kinase → Akt → mTOR Pathway Is Required for Insulin/IGF-1-induced Degradation of IRS-2—IRS proteins mediate the activation of the PI 3-kinase and the MAP kinase cascades during insulin/IGF-1 stimulation (1, 2). To determine whether these signaling pathways mediate degradation of IRS-2, 3T3-L1 preadipocytes or FAO cells were pretreated with wortmannin or LY294002 (inhibitors of type I PI 3-kinase), or PD98059 (an inhibitor of MEK1/2). As expected, both wortmannin and LY294002 blocked insulin-stimulated activation of the PI 3-kinase/Akt pathways without altering the activation of the MEKMAP kinase cascade, whereas PD98059 inhibited insulin-stimulated activation of ERK1/2 without effect on the PI 3-kinase/Akt pathways (data not shown). Moreover, wortmannin and LY294002, but not PD98059, inhibited insulin-induced degradation of IRS-2 (Fig. 5, A and B). Similarly, wortmannin and LY294002 but not PD98059 inhibited IGF-1-stimulated degradation of IRS-2 in 3T3-L1 preadipocytes (data not shown). These drugs did not change the level of p85 during these experiments (Fig. 5A). Consistent with these data, LY294002 inhibited insulin-induced ubiquitination of IRS-2 in the presence of lactacystin (Fig. 5C).

mTOR is a serine/threonine kinase downstream of the PI 3-kinase/Akt pathway that contributes to the activation of p70S6 kinase (28–32). To determine whether mTOR mediates the degradation of IRS-2, FAO cells were treated prior to insulin stimulation with rapamycin, an inhibitor of mTOR. Rapamycin inhibited insulin-stimulated degradation of IRS-2, as demonstrated by immunoblotting cell extracts with antibodies against phospho-Akt or phospho-ERK, respectively (Fig. 5B, lane 5). Similarly, rapamycin also blocked IGF-1-stimulated degradation of IRS-2 in 3T3-L1 preadipocytes (data not shown). As expected, rapamycin inhibited the activation of p70S6 kinase, as revealed by the inhibition of insulin-induced shift in mobility of p70S6 kinase that represents phosphorylation and activation of p70S6 kinase (Fig. 5B, lane 5). Rapamycin and insulin did not alter the level of p70S6 kinase (Fig. 5B, lower panel).

Proteasome-mediated Degradation of IRS-2 Down-regulates Signaling by Insulin and IGF-1—IRS-1 and IRS-2 mediate common and unique signals during insulin/IGF-1 action. Differential degradation of these IRS proteins may have important influence on metabolic regulation. However, this hypothesis is difficult to test in ordinary cell backgrounds that express both IRS-1 and IRS-2. To overcome these technical difficulties, MEF cells derived from IRS-1 and IRS-2 knockout mice were used.

The expression of IRS-1 or IRS-2 was undetectable in IRS1−/− and IRS2−/− MEF cells, respectively (data not shown). Deletion of either IRS-1 or IRS-2 did not alter the level of insulin/IGF-1 receptors (data not shown). Both insulin and IGF-1 promoted activation of Akt as well as ERK1/2 in IRS1−/− or IRS2−/− MEF, as demonstrated by immunoblotting cell extracts with antibodies against phospho-Akt or phospho-ERK, respectively (Fig. 6, lanes 1–3). These results suggest that IRS-1 and IRS-2 are redundant in mediating insulin-stimulated activation of the PI 3-kinase/Akt and the MEK → ERK pathways in this cell background. However, insulin stimulated degradation of IRS-2 in IRS1−/− MEF, but insulin did not promote IRS-1 degradation in IRS2−/− MEF cells (Fig. 2C).

To determine whether degradation of IRS-2 inhibits signaling by insulin and IGF-1, IRS1−/− MEF cells were pretreated for 4 h with 100 nM insulin or 100 ng/ml IGF-1. Cells were then washed, incubated in serum-free medium for additional 2 h, and stimulated for 5 min with 100 nM insulin or 100 ng/ml IGF-1. Activation of the PI 3-kinase → Akt and the MEK → ERK1/2 pathways was measured by immunoblotting cell extracts with antibodies against phospho-Akt or phospho-ERK1/2, respectively. Insulin or IGF-1 pretreatment did not alter the levels of Akt or ERK1/2 in these cells (Fig. 6, A and B). However, insulin pretreatment significantly reduced the activation of both Akt and ERK1/2 in response to a subsequent insulin or IGF-1 stimulation (Fig. 6, A and B). Similarly, IGF-1 pretreatment inhibited the activation of Akt and ERK1/2 induced by a subsequent insulin/IGF-1 stimulation to a greater extent (Fig. 6, A and B, lanes 7–9). IGF-1 pretreatment almost completely inhibited activation of Akt induced by subsequent insulin stimulation (Fig. 6A, lane 8). The difference in the magnitude of inhibition between insulin and IGF-1 might reflect a higher abundance of IGF-1 receptors in MEF cells (data not shown).
In the parallel experiments with IRS2−/− MEF cells, neither insulin nor IGF-1 pretreatment inhibited the activation of Akt and ERK1/2 induced by a subsequent acute stimulation with insulin or IGF-1 (Fig. 6, C and D). This resistance to the inhibition by insulin/IGF-1 pretreatment is consistent with the resistance of IRS-1 to degradation in IRS2−/− MEF cells. Moreover, these results revealed that insulin or IGF-1 pretreatment did not inhibit ligand-stimulated activation of the receptors for insulin or IGF-1, nor did it impair the PI 3-kinase/Akt and MEK/ERK1/2 pathways. Therefore, the inhibition of Akt and ERK1/2 by insulin or IGF-1 pretreatment in IRS1−/− MEF cells is most likely caused by insulin/IGF1-induced degradation of IRS-2.

To confirm the hypothesis that proteasome-mediated degradation of IRS-2 contributes to down-regulation of signaling by insulin and IGF-1, IRS1−/− MEF cells were incubated for 30 min with or without the proteasome inhibitor lactacystin prior to IGF-1 pretreatment. IGF-1 pretreatment inhibited activation of Akt and ERK1/2 in response to a subsequent IGF-1 stimulation as expected. However, lactacystin completely reversed the inhibition of Akt and ERK1/2 by IGF-1 pretreatment (Fig. 7).

DISCUSSION

The causes of prevalent forms of type 2 diabetes are poorly understood. Initially, patients develop mild insulin resistance and glucose intolerance. Hyperglycemia then prompts β-cells to secrete compensatory insulin to overcome insulin resistance, resulting in hyperinsulinemia. Although moderate hyperinsulinemia might be well tolerated in the short term, chronic hyperglycemia and hyperinsulinemia exacerbate insulin resistance; if uncontrolled, this process continues until β-cells fail to compensate, resulting in diabetes (3, 4, 26). IRS-2 is critical in both insulin action and β-cell function, as demonstrated by the finding that deletion of IRS-2 in mice causes severe insulin resistance and β-cell failure (7). In ob/ob mice, IRS-2 protein is undetectable in liver, which correlates with hyperglycemia and hyperinsulinemia, hallmarks of insulin resistance (33, 34). Exogenous leptin treatment not only reverses insulin resistance, but also increases concomitantly IRS-2 protein to a normal level (34). Thus, the decrease of hepatic IRS-2 might be a major determinant for overall insulin resistance (35).

In this study, we showed that insulin substantially reduces IRS-2 protein levels in multiple cell lines, which is blocked by specific inhibitors of the 26 S proteasome. These results suggest that proteasome-mediated degradation of IRS-2, rather than inhibition of transcription and/or translation of IRS-2, determines IRS-2 protein levels and activation of IRS-2-mediated signaling pathways. Consistent with this idea, insulin stimulates ubiquitination of IRS-2. During our experiments, the ubiquitinated IRS-2 is detected only in the presence of proteasome inhibitors, suggesting that ubiquitinated IRS-2 is degraded rapidly by the 26 S proteasome. Consistent with these findings, deletion of insulin receptor in liver increases specifically hepatic IRS-2 by more than 5-fold (35), suggesting that the ablation of the insulin signals might block IRS-2 degradation in a whole animal. Reduction of IRS-2 by ubiquitin/proteasome-mediated proteolysis in mouse embryo fibroblasts lacking IRS-1 dramatically inhibits the activation of Akt and ERK1/2 in response to insulin/IGF-1. Strikingly, proteasome inhibitors completely reverse this inhibition. Interestingly, inhibition of the PI 3-kinase → Akt → mTOR pathway, but not the MEK → ERK1/2 pathway, prevents insulin-induced degradation of IRS-2. These observations suggest that the ini-
Serine/threonine phosphorylation plays an important role in ubiquitin/proteasome-mediated degradation of signaling proteins. For instance, tumor necrosis factor α stimulates phosphorylation of IkBα at Ser-32 and Ser-36 by IKK complex, which enables β-TrCP, a F-box-containing subunit of the SCF complex, to recognize and bind to phosphorylated IkBα together with E2, resulting in the ubiquitination of IkBα. The ubiquitinated IkBα is subsequently degraded by the 26S proteasome (19, 23, 24). We propose a similar mechanism for IR2 degradation. Insulin or IGF-1 activates the PI 3-kinase → Akt → mTOR pathway. Kinase(s) within this pathway phosphorylate IRS-2, most likely on serines/threonines residues. This phosphorylated motif(s) in IRS-2 might serve as a signal tag for a specific E2-E3 complex with F-box-containing subunits. Consistent with this hypothesis, we and others observed that insulin, IGF-1, and osmotic stress promote serine/threonine phosphorylation of both IRS-1 and IRS-2 (14, 38). Phosphorylation of both IRS-1 and IRS-2 (14, 38) is consistent with this hypothesis, we and others observed that insulin, IGF-1, and osmotic stress promote serine/threonine phosphorylation of both IRS-1 and IRS-2 (14, 38–41). Serine/threonine phosphorylation of IRS-1 was reported recently to promote its degradation in some cell types (41), and we confirmed insulin-stimulated degradation of IRS-1 in 3T3-L1 adipocytes and Fao cells. However, insulin stimulates degradation of IRS-2 in 3T3-L1 adipocytes and MEF, but fails to promote IRS-1 degradation. Thus, degradation of IRS-1 and -2 may be mediated by different mechanisms. In addition, these observations raise an intriguing possibility that, in certain insulin/IGF-1 target cells, insulin/IGF-1-promoted degradation of IRS-2 might enhance IRS-1-mediated signaling by reducing the competition for IRS-2 of common signaling molecules including receptors for insulin/IGF-1 and downstream effector molecules; therefore, proteasome-mediated degradation of IRS-2 might positively propagate insulin/IGF-1 signals in some physiological contexts.

In summary, insulin and IGF-1 stimulate substantial degradation of IRS-2 mediated by the ubiquitin/proteasome system in multiple cell types, leading to an inhibition of insulin/IGF-1 signaling. The PI 3-kinase → Akt → mTOR pathway is required for insulin/IGF-1-induced degradation of IRS-2. We propose that the ubiquitin/proteasome-mediated degradation of IRS-2 is a component of negative feedback inhibition modulating the action of insulin and IGF-1. Inhibitors of 26S proteasome significantly improve insulin sensitivity, suggesting that these types of agents might have clinical value in the treatment of patients with type 2 diabetes.

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