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Rescue and Activation of a Binding-deficient Insulin Receptor

EVIDENCE FOR INTERMOLECULAR TRANSPHOSPHORYLATION*

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Binding of insulin to the α subunit of the insulin receptor (IR) leads to autophosphorylation of the β subunit. The reaction proceeds as intramolecular transphosphorylation between αβ half-receptors of the heterotetrameric receptor dimer (αβp). Since IRs are mobile in the plane of the plasma membrane, it is also possible that transphosphorylation may occur between adjacent homoreceptors (αβp) by an intermolecular reaction. To address this question, we cotransfected NIH-3T3 cells with two IR cDNA constructs: a truncated but functional normal IR lacking the C-terminal 43 amino acids (Δ43) and a full-length Leu233 mutant receptor that is expressed on the cell surface but does not bind insulin. A clonal cell line was selected from cells cotransfected with a 1/5 ratio of Δ43 cDNA/Leu233 cDNA. The two homodimers (Leu233 and Δ43) were expressed without detectable formation of hybrid receptors. By using specific antibodies, we demonstrate that in cells coexpressing both homodimers, the Leu233 mutant receptor was phosphorylated in vitro by the Δ43 IR in an insulin-dependent manner. However, when the Leu233 mutant receptor was expressed alone, no phosphorylation was detected. In addition, we demonstrate the association of the phosphorylated Leu233 mutant receptor with insulin receptor substrate-1 and with phosphatidylinositol 3-kinase. These findings indicate that insulin binding is not required for phosphorylation of the Leu233 mutant receptor, that the phosphorylation of the Leu233 mutant receptor occurs by an intermolecular transphosphorylation mechanism, and, finally, that the Leu233 mutant receptor, once phosphorylated, can associate with insulin receptor substrate-1 and phosphatidylinositol 3-kinase.

The insulin receptor (IR) is a transmembrane protein consisting of two identical disulfide-linked half-receptors. Each half (αβ) consists of an extracellular α subunit that binds insulin and a transmembrane β subunit that contains a tyrosine kinase domain (1, 2). Insulin binding to the α subunit results in autophosphorylation of the β subunit, activation of receptor tyrosine kinase activity, and tyrosine phosphorylation of intracellular targets of insulin action.

Several lines of evidence suggest that the binding of insulin to one half of the α subunit dimer within a tetrameric holoreceptor (αβαβ) can result in intramolecular transphosphorylation of the opposite β subunit (3–7). We have recently presented evidence that strongly supports this concept by expressing hybrid insulin receptors in which one αβ half contains a mutation from a patient with extreme insulin resistance that is expressed on the cell surface but does not bind insulin (Leu233 and is not phosphorylated (8, 9). The other αβ half-receptor (αβp) has a wild-type (WT) α subunit and a truncated β subunit lacking 43 amino acids in the C terminus; this truncation does not impair IR tyrosine kinase activity. The fact that this hybrid IR binds insulin with high affinity and phosphorylates the β subunit of the mutant half-receptor demonstrates this intramolecular transphosphorylation event.

The insulin receptor, like the epidermal growth factor receptor (10–12), is mobile in the plane of the plasma membrane. The epidermal growth factor receptor, a single chain monomer, appears to be phosphorylated and activated by an intramolecular reaction involving receptor aggregation (13). While phosphorylation of insulin receptors does not require interaction among individual receptor heterotetramers, IR interactions could augment the receptor signal.

In the present study, we have co-transfected NIH-3T3 cells with constructs encoding for the Leu233 mutant receptor and the truncated Δ43 IR. Using a clonal cell line that expresses homodimeric receptors (αβp) and (αβαβ), we demonstrate that the Δ43 insulin receptor phosphorylates the Leu233 mutant receptor in response to insulin. Additionally we demonstrate that, once the Leu233 mutant receptor is phosphorylated, it behaves similarly to a WT receptor in terms of association with IRS-1 and activation of PI 3-kinase.

EXPERIMENTAL PROCEDURES

Expression of Insulin Receptors in Transfected NIH-3T3 Cells—The human IR cDNA carrying the Leu233 mutation was constructed as described previously (8, 9).

Using site-directed mutagenesis, we introduced a premature chain termination codon at codon 1301 of the insulin receptor cDNA (14), leading to a C-terminal deletion of 43 amino acids of the β subunit of the insulin receptor (Δ43). WT and truncated cDNAs were ligated into pBluescript II (Stratagene, La Jolla, CA) and integrated into the genome of NIH-3T3 cells. Cells were transfected using Lipofectamine (Life Technologies, Inc.) and a mixture of insulin receptor expression vector (20 μg) and an expression vector containing the neomycin phosphotransferase gene (pRSV-Neo; 0.5 μg) (15, 16). Cells were transfected with an expression vector for a single type of insulin receptor or co-transfected with a mixture of expression vectors for two types of insulin receptor (8). Stable transfected cells were selected with 1 mg/ml of Geneticin.

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Stable transfected cells were selected with G418 (600 μg/ml; Life Technologies, Inc.). After selection, insulin receptor expression by stable transfected cells was assayed by measuring [125I]insulin binding and, in the case of cotransfected cells or cells expressing the Leu233 receptor alone, clones expressing both the full-length and Δ43 insulin receptors and cells expressing only the full-length insulin receptor, receptor expres-
sion was assayed by Western blot analysis.

**Biotinylation and Immunoprecipitation of Cell Surface Insulin Receptors**—Confluent monolayers of transfected NIH-3T3 cells in Petri dishes (10-cm diameter) were biotinylated as described elsewhere (8, 14). After cell solubilization, insulin receptors were immunoprecipitated using anti-receptor antibody B-10 directed against the α subunit (17, 18). A 1:100 dilution of 1:50 or with a rabbit antibody (rAb50) directed against a peptide corresponding to amino acids 1321–1336 of the β subunit of the human insulin receptor at a dilution of 1:500. Biotinylated insulin receptors were detected by ECL (Amersham Corp.).

**Insulin Binding to Intact Cells**—Insulin binding to intact cells was performed at 4 °C overnight in the presence of labeled insulin, and specific binding was determined in the presence of an excess of unlabeled insulin as described previously (20).

**Phosphorylation of Insulin Receptors and IRS-1 in Intact Cells**—Phosphorylation of insulin receptors in intact cells was conducted as described elsewhere (21). Insulin receptors were immunoprecipitated either with B10 or with rAb50. Endogenous IRS-1 was immunoprecipitated with 1:100 dilution of a rabbit antibody directed against the rat IRS-1 protein (rAb-IRS-1) (Upstate Biotechnology, Inc., Lake Placid, NY). Following SDS-PAGE and electrotransfer, proteins containing phosphotyrosine were detected by sequential incubation with a monoclonal anti-phosphotyrosine antibody (Upstate Biotechnology, Inc.) and horseradish peroxidase-linked anti-mouse γ-globulin (Amersham Corp.). Filters were washed and ECL was performed as described previously (8).

**Association of Insulin Receptor with PI 3-Kinase**—PI 3-kinase activity associated with the insulin receptor expressed in NIH-3T3 cells was determined in immunoprecipitated proteins as described previously (22, 23). Briefly, after cell solubilization and immunoprecipitation with anti-phosphotyrosine antibody, pellets were washed and resuspended in 40 ml of a buffer containing 10 mM Tris-HCl, 100 mM NaCl, 1 mM EDTA. To each tube was added 10 ml of MnCl₂ (100 mM) and 20 mg of phosphatidylinositol (Sigma). The phosphorylation reaction was started by addition of 10 ml of ATP (440 mM) containing 30 mCi of (γ-³²P)ATP. After 10 min, the reaction was stopped by the addition of 20 ml of HCl (8 N) and 160 ml of CHCl₃/methanol (1:1). The organic phase was extracted and applied to a silica gel thin layer chromatography plate (Merck). Chromatography plates were developed in CHCl₃/CH₃OH/H₂O/NH₄OH (60:47:11:3.2) and visualized by autoradiography for 2 h. The radioactivity was quantitated with a PhosphorImager (Molecular Dynamics, Sunnyvale, CA).

**RESULTS**

**Expression and Coexpression of Wild-type and Mutant Insulin Receptors**—Cells were either singly transfected with expression plasmids encoding the WT IR, the truncated Δ43 IR, which has a deletion of 43 amino acids at the C terminus of the β subunit (14, 24, 25), or the Leu³²³ mutant receptor or cotransfected with the truncated Δ43 IR and the Leu³²³ mutant IR. In order to identify each specific transfectant, cell-surface insulin receptors were biotinylated. Cells were then solubilized and immunoprecipitated with either B10 (Fig. 1) or rAb50 (Fig. 1). Cells transfected with the WT IR or the Leu³²³ mutant IR cDNAs express an α subunit of an apparent molecular mass of 135,000 Da and a β subunit of 95,000 Da, whereas cells transfected with the Δ43 IR construct express a β subunit of an apparent molecular mass of 90,000 Da, consistent with its truncation (Fig. 1). In co-transfected cells, immunoprecipitation with B10 showed, in addition to the α subunit, two bands corresponding to the truncated β subunit (Mᵦ = 90,000) and the full-length β subunit (Mᵦ = 95,000) (Fig. 1). However, when immunoprecipitation was carried out with rAb50, only the 95-kDa band was detected, demonstrating that the Δ43 IR and the Leu³²³ mutant IRs are expressed on the surface of this clonal cell line as homodimers, and the formation of hybrid receptors does not occur.

**Insulin Binding to the Wild-type and Mutant Insulin Receptors**—Following the isolation of these four clonal cell lines, insulin binding to intact cells was measured. Specific insulin binding was measured after an overnight incubation of cells with 125I-insulin at 4 °C. As expected, in cells expressing the Leu³²³ mutant receptor, no significant binding was detected. By contrast, in cells expressing the WT IR, the truncated Δ43 IR, and in cells co-expressing the Leu³²³ mutant and the Δ43 IR, similar levels of specific insulin binding were measured (Fig. 2).

**Intermolecular Transphosphorylation of Insulin Receptor**—Cells were incubated in the presence or absence of insulin for 1 min and lysed. Insulin receptors were immunoprecipitated with B10. Following SDS-PAGE and electrotransfer, phosphorylated receptors were detected by an anti-phosphotyrosine antibody. Insulin markedly increased the phosphorylation of the IR β subunit in all clonal cell lines, except those expressing only the Leu³²³ mutant receptor (Fig. 3A). In cells expressing the Δ43 IR, insulin stimulated the phosphorylation of a band of 90 kDa, corresponding to the truncated Δ43 β subunit and, as expected, in cells expressing the WT IR, a band of 96 kDa corresponding to the full-length β subunit was phosphorylated in response to insulin. In cells expressing both the Leu³²³ mutant and the Δ43 homodimeric receptors, two bands were phosphorylated in response to insulin: the full-length β subunit of the Leu³²³ mutant (Mᵦ = 95,000) and the truncated β subunit of the Δ43 IR (Mᵦ = 90,000) (Fig. 3).

In separate experiments, after stimulation with insulin and cell solubilization, receptors were immunoprecipitated either with B10 or rAb50. Following SDS-PAGE and electrotransfer, phosphorylated receptors were blotted with an anti-phosphotyrosine antibody. In cells expressing WT IRs, both antibodies immunoprecipitated a band of an apparent molecular mass of 95,000 Da, corresponding to the β subunit; this phosphorylation is insulin-dependent (Fig. 3B). In cells co-expressing the Leu³²³ mutant IR and the truncated Δ43 IR, B10 immunoprecipitated two bands with apparent molecular masses of 95,000 and 90,000 Da, corresponding to the β subunits of the Leu³²³ mutant receptor and to the Δ43 IR, respectively. When immunoprecipitation was carried out with rAb50, which does not interact with the Δ43 IR, only one band was immunoprecipitated, with an apparent molecular mass of 95,000 Da, corresponding to the β subunit of the Leu³²³ mutant receptor. When the Leu³²³ IR was expressed alone, no significant phosphory-
FIG. 2. Determination of specific insulin binding to intact cells. Confluent cells were incubated with 20,000 cpm of 125I-insulin in the presence or absence of an excess of unlabeled insulin (10^7 M). After incubation of cells at 4 °C overnight, specific insulin binding was determined in cells expressing neomycin resistance alone (Neo), wild-type insulin receptor (WT), truncated Δ43 insulin receptor (Δ43), Leu23 mutant receptor (Leu23), or in cell surface of cells coexpressing Leu23 and Δ43 insulin receptors (Leu23/Δ43). Binding is expressed as specific binding over total activity (B/T, %). The result is the mean of four separate experiments ± S.E.

FIG. 3. Insulin stimulates tyrosine phosphorylation of Leu23 and Δ43 homodimers in cotransfected cells. NIH-3T3 cells expressing either wild-type receptor (WT), truncated Δ43 receptor (Δ43), Leu23 mutant receptor (Leu23), or coexpressing Leu23 and Δ43 insulin receptors were incubated in the presence or absence of 10^8 M insulin at 37 °C for 1 min. Cells were solubilized, and insulin receptors were immunoprecipitated with either B10 (panels A and B) or rAb50 (panel B) for cells expressing WT insulin receptors or coexpressing Leu23 and Δ43 homodimers (Leu23/Δ43). Immunoprecipitates were analyzed on SDS-PAGE (6.5%), followed by electrophoretic transfer. The blot was probed with an anti-phosphotyrosine antibody, and bands were detected by ECL.

A

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<th>Cell Line</th>
<th>Leu23</th>
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<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>IP</td>
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B

<table>
<thead>
<tr>
<th>Cell Line</th>
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<td>Insulin (10^8M)</td>
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DISCUSSION

The insulin receptor gene encodes a single-chain polypeptide that is processed and inserted into the plasma membrane of the cell as an αβ heterodimer. The αβ dimer is required for high affinity binding, inasmuch as the α subunit monomer binds insulin with low affinity (27–30). We have recently demonstrated, however, that high affinity binding can be reconstituted in a hybrid between a wild-type receptor half (αβ) and a very low affinity mutated receptor half (αmutβmut). Furthermore, we have shown that, while the Leu23 holoreceptor neither binds insulin nor phosphorylates its β subunit, the αmutββ hybrid receptor binds and phosphorylates in an insulin-de-
Blot:

Insulin (10⁻⁸M)  

Cell Line  

WT  

Δ43  

Leu₁₁₅₃/Δ43  

Leu₁₃₂₃/Δ43  

WT  

Δ43  

Leu₁₃₂₃  

WT  

Δ43  

Leu₁₃₂₃/Δ43  

Leu₁₃₂₃

Fig. 4. Association of phosphorylated IRS-1 with Leu₁₁₅₃ mutant insulin receptors in cells coexpressing Leu₁₁₅₃ and Δ43 insulin receptors. NIH-3T3 cells expressing either the neomycin resistance gene alone (Neo), wild-type receptor (WT), Leu₁₁₅₃ mutant (Leu₁₁₅₃), truncated Δ43 receptor (Δ43), or coexpressing Leu₁₁₅₃ and Δ43 insulin receptors (Leu₁₁₅₃/Δ43) were incubated in the presence or absence of 10⁻⁸ M insulin for 1 min at 37 °C. IRS-1 was immunoprecipitated using rAb-IRS-1 as described under "Materials and Methods." The blot was probed with an anti-phosphotyrosine antibody, and bands were detected by ECL.

Shown in the upper panel is the autophosphorylation of the insulin receptor, where the phosphorylation was measured in cells expressing only the WT receptor (WT). This is in good agreement with previous in vitro findings and consistent with the fact that the Δ43 IR has lost a specific domain that reacts with the SH2 domain of PI 3-kinase (26). It is noteworthy that in cells expressing both the Leu₁₁₅₃ mutant and the Δ43 IRs, the PI 3-kinase activity is similar to that of cells expressing the WT and higher than that of cells expressing only the Δ43 IR. One possible explanation is that the Leu₁₁₅₃ IR, once phosphorylated by the Δ43 IRs, behaves like a WT IR and fully activates the PI-3 kinase either directly or via IRS-1 phosphorylation.

The present work has both similarities and differences from a previous demonstration of intermolecular phosphorylation (14). In the previous study the receptor phosphorylates a kinase mutant receptor (Ile₁₁₅₃). This phosphorylated receptor, however, was not active toward downstream effects. These experiments are similar in that the β subunits of both the Ile₁₁₅₃ and Leu₁₃₂₃ mutant receptors are phosphorylated. The Ile₁₁₅₃ mutant, however, cannot serve as a kinase because of the nature of its mutation, but the Leu₁₃₂₃ β subunit is normal as a kinase toward other substrates once it is activated. It is in this special context that genetic rescue is possible. It has also been
shown in vitro that the Val252 mutant IR can be phosphorylated by the WT IR; however, this mutant is expressed weakly on the cell surface (31).

In summary, we have demonstrated that a binding-deficient mutant insulin receptor can be transphosphorylated by a coexpressed insulin-binding IR. The transphosphorylated Leu252 IR can then associate with IRS-1 and with PI 3-kinase. Thus, contrary to mutations in the tyrosine kinase domain, the Leu252 mutation has no dominant-negative effect. Thus, its downstream effects may be rescued by coexpressing of a normal receptor. This represents a novel form of gene therapy, at least to cultured cells. Furthermore, it provides a molecular explanation for the observation that insulin resistance due to the receptor. This represents a novel form of gene therapy, at least to cultured cells. Furthermore, it provides a molecular explanation for the observation that insulin resistance due to the

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REFERENCES