Progestins Increase Insulin Receptor Content and Insulin Stimulation of Growth in Human Breast Carcinoma Cells

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ABSTRACT

The effects of progesterone on the growth of breast carcinoma cells are undefined. In the present study we investigated the effect of progesterone on insulin receptor gene expression and insulin action in human breast cancer cells. Treatment of T47D cells with the synthetic progestin R5020 induced a time- and dose-dependent increase in insulin receptor content as measured by both ligand-binding studies and radioimmunoassay. Binding was half-maximally stimulated at 300 nM R5020 and maximal levels were reached after 4 days of treatment. Progesterone was 10-fold less potent than R5020. Cortisol had no effect on insulin receptor levels, while 17β-estradiol and dihydrotestosterone had minimal effects. Progestin treatment both increased insulin receptor mRNA levels and altered the relative distribution of the multiple insulin receptor mRNA transcripts. In order to study the functional significance of the increased insulin receptor levels, we incubated T47D cells with progesterone and then treated them with insulin. Insulin alone had a small effect on cell growth; however, the effect of insulin was markedly potentiated by progesterone treatment. These studies in breast cancer cells demonstrate, therefore, that insulin receptor gene expression is under the regulation of progesterone and raise the possibility that progestin-insulin interactions may regulate breast cancer cell growth in vivo.

INTRODUCTION

The effects of progesterone on the growth of cancer cells are undefined. Both in vivo and in vitro studies have indicated that progesterone antagonizes estrogen-stimulated growth of endometrial cancer cells and normal uterine epithelial cells. This effect occurs by down-regulation of estrogen receptors (1–3). However, when similar studies were carried out with breast cancer cells, progesterone or synthetic progestins either inhibited (4, 5), stimulated (6), or had no effect (7) on cell growth. One explanation for these conflicting results in breast cancer cells is that there are interactions between progesterone and growth-promoting hormones which have not been elucidated.

Insulin is a known growth-promoting hormone for breast tissues. In cell culture insulin stimulates the growth of both human breast cancer cells (8) and normal human breast epithelial cells (9). However, whether insulin and progesterone interact to regulate breast cancer cell growth has not been explored. In the present study, we have investigated the effect of progesterone on insulin receptors in T47D human breast cancer cells. Herein, we demonstrate that progesterone treatment of these cells increases insulin receptor gene expression resulting in a two-fold increase in insulin receptor content. Moreover, we find that progesterin treatment of T47D cells enhances their growth response to insulin. These results suggest, therefore, that progesterone may stimulate the growth of breast cancer cells indirectly by increasing their sensitivity to insulin.

MATERIALS AND METHODS

Materials. The following chemicals were purchased: Hepes, bacitracin, phenylmethylsulfonyl fluoride, hydroxyethyl-methylglycine (tricine), and all steroids from Sigma Chemical Co. (St. Louis, MO); bovine serum albumin (fraction V) from Reheis (Chicago, IL); porcine insulin from Eli Lilly Products Co. (Indianapolis, IN); [125I]-labeled insulin (2200 Ci/mmol); [γ-32P]ATP (6000 Ci/mmole) and [α-32P]dCTP (3000 Ci/mmole) from New England Nuclear (Boston, MA); oligo(dT) (12–18) from Pharmacia Laboratory Division (Uppsala, Sweden). All other reagents were of analytical grade. MA-10, a mouse monoclonal antibody to the human insulin receptor, was prepared as previously described (10). IGF-1 was a gift from Ciba-Geigy (Summit, NJ). Insulin receptor cDNA probes were a gift of Dr. G. I. Bell (University of California, San Francisco); A-lamin cDNA probe was a gift of Dr. W. Miller (University of California, San Francisco).

Cell Culture. T47D cells (from Dr. C. Sonnenschein and Dr. A. Soto, Tufts University, Boston, MA) and MCF7 cells (from Drs. W. Nelson-Rees, Oakland Naval Biosciences Center, Oakland, CA) were routinely grown in DME containing 5% fetal calf serum, nonessential amino acids, glutamine, transferrin, penicillin, streptomycin, and sodium (Cell Culture Facility, University of California, San Francisco).

Growth Studies. For growth experiments 2 × 10⁵ cells/well were plated in 6-well plates in phenol red-free DME supplemented with 2% human serum stripped twice with 2.5% (w/v) dextran-coated charcoal at 37°C for 90 min. After 1 day of culture, cells were pretreated for 48 h with 30 nM progesterone. Fresh hormone was added every 24 h. Then, varying doses of insulin were added every 12 h for 6 days. In some experiments, progesterone treatment was continued with insulin treatment throughout the entire culture period. Cells were then harvested and plasma membranes lysed with 2 drops of Count-a-Part (Diagnostic Technology, Hauppauge, NY). Nuclei were fixed with Bouin's fixative and counted in a Coulter Counter (Coulter Electronics Inc., Hialeah, FL).

125I-Insulin Binding. For binding experiments in intact cells, mono- layers were harvested with 1 mM EDTA and the cells were then resuspended at 2–3 × 10⁶ cells/ml in binding buffer (DME containing 1% bovine serum albumin-25 mM tricine-25 mM Hepes, pH 7.8) (5). Binding studies were carried out in binding buffer containing 125I-insulin (12 pm) with or without unlabeled insulin (100 pm–1 µM). After incubation for 3 h at 16°C the cells were washed and dissolved in 0.3 mg/ml sodium dodecyl sulfate, and the radioactivity counted.

When binding studies were performed on solubilized receptors, the cells were solubilized with 1% Triton X-100 in the presence of protease inhibitors and 125I-insulin binding was then carried out as previously described (11).

Nonspecific binding (<1% of added ligand) was subtracted from total binding and binding data were normalized for DNA (12) content.

Insulin Receptor RIA. To measure the insulin receptor content by RIA, cells were solubilized in 50 mM Hepes, pH 7.4–1% Triton X-100-0.2 mM phenylmethylsulfonyl fluoride-1 mg/ml Bactracin for 60 min

7858
at 4°C. The lysate was then centrifuged for 10 min at 11,000 x g and the supernatant was used for RIA without further purification as previously described (13).

Preparation of RNA. Total cellular RNA was extracted from T47D cells according to the guanidinium isothiocyanate/cesium chloride gradient method (14). Poly(A)+ RNA was isolated by oligo(dT)-cellulose chromatography (15).

Slot Blots and Northern Transfers. For Northern transfers, poly(A)+ RNA was denatured in formaldehyde, subjected to electrophoresis in 1% agarose, and transferred to nitrocellulose paper (15). For slot blots poly(A)+ RNA was denatured as described by Thomas (16), and dilutions of RNA were immobilized to nitrocellulose with a Schleicher and Schuell slot blot apparatus. These studies used two human insulin receptor cDNA probes, 18.2 and 13.2 (1 and 4.2 kilobases, respectively), a kind gift from Dr. G. I. Bell (University of Chicago). They span the entire open reading frame of the receptor and extend into the 3'-untranslated region (17). These were labeled by nick-translation (15) to a specific activity of 10^6 cpm/μg. The nitrocellulose filters were prehydrated, hybridized, and washed as previously described (15). A probe for the nuclear envelope protein A-lamin (18) was labeled and hybridized as described for the insulin receptor. Poly(A)+ RNA content was normalized by using an oligo(dT) that was end labeled using the enzyme T4 polynucleotide kinase (19).

RESULTS

Studies in T47D Cells

Progestin Effects on 125I-Insulin Binding

Insulin-binding Specificity. We first characterized the insulin receptors in T47D cells by using 125I-insulin and unlabeled ligands in competition-inhibition studies (Fig. 1). T47D cells bound 125I-insulin and binding was competed for by unlabeled insulin at an EDso of 0.5 nM. The EDso for the related hormone IGF-1 was >10 nM. Monoclonal antibody MA-10, which inhibits insulin binding to the insulin receptor but not IGF-1 binding to the IGF-1 receptor (10), had an EDso of 2.0 nM. Normal mouse IgG had no effect. The maximal specific binding of 125I-insulin to the IGF-1 receptor (10), had an ED50 of 2.0 nM. Normal mouse IgG had no effect. The maximal specific binding of 125I-insulin to T47D cells was 1.12 ± 0.14%/mg protein or 2.51 ± 0.32%/100 μg DNA (mean ± SE, n = 10).

Time Course and Specificity of the Steroid Effect. Progesterone and its synthetic analog R5020 increased insulin binding to T47D cells in a time- and dose-dependent manner. 125I-insulin binding more than doubled after 24 h of incubation when R5020 was used at a concentration of 100 nM (Fig. 2A). After 4 days of incubation, when the effect of R5020 was maximal, binding was increased 3-fold. R5020 was the most potent steroid hormone studied with half-maximal stimulation occurring at 300 pM (Fig. 2B). Progesterone was 10-fold less potent than R5020. In contrast, cortisol had no effect on insulin binding, while 17β-estradiol and dihydrotestosterone had small effects (Fig. 2B).

Progestin Effects on Insulin Receptor Content

Studies were then carried out to understand the mechanism by which progestins increase insulin receptor binding. In order to determine whether treatment with progestins increased total cellular 125I-insulin binding, we directly measured total cellular insulin binding by solubilizing receptors from control and R5020-treated cells. 125I-insulin binding to solubilized control T47D cells was 1.57 ± 0.12%/100 μg DNA, whereas the binding to solubilized cells treated for 4 days with 100 nM R5020 was increased to 3.44 ± 0.75%/100 μg DNA (n = 3).

Next, we carried out Scatchard analysis (Fig. 3A) of insulin binding.
INSULIN RECEPTOR REGULATION BY PROGESTINS

Fig. 3. Effect of R5020 on insulin receptor content in T47D cells. Cells were grown for 2 days without R5020 and then incubated for 4 days in the absence or presence of 100 nM R5020. A, 125I-insulin binding. A representative of 3 experiments is shown. Inset, Scatchard plot of the data; insulin bound = femoles/100 µg DNA. B, radioimmunoassay of insulin receptors. Competition-inhibition curves for extracts of control (■) and R5020-treated (▲) T47D cells on the binding of 125I-insulin receptors to an antireceptor antiserum. A representative of 2 experiments is shown.

As an alternative method for measuring the insulin-binding capacity we used an insulin receptor radioimmunoassay as recently described (13). This assay is specific for the insulin receptor; insulin has no cross-reactivity. The related insulin-like growth factor I has <3% cross-reactivity (13). Assay of solubilized extracts from both control cells and cells treated for 4 days with 100 nM R5020 produced dilution slopes that were parallel to the purified human placenta standard (Fig. 3B). R5020-treated cells had a >2-fold higher concentration of insulin receptors measured by radioimmunoassay than control cells (8.77 ± 0.02 versus 4.12 ± 0.08 ng of insulin receptor/10⁶ cells, respectively; n = 3).

Progestin Effects on Insulin Receptor mRNA

Since progestins and other steroid hormones increase the rate of gene transcription (21, 22), we examined whether R5020 treatment was associated with an increase in insulin receptor mRNA levels. Poly(A)⁺ RNA from control and R5020-treated cells was slot blotted, and the filters were probed with labeled insulin receptor cDNA (Fig. 4A). After a 4-day incubation with 100 nM R5020 there was an approximately 2-fold increase in insulin receptor mRNA content. In contrast, treatment with R5020 had no effect on mRNA levels of the control A-lamin, a protein whose cellular content is not readily altered by changes in growth conditions (18).

Insulin receptor mRNA consists of several species of different molecular sizes (23). In order to determine whether R5020 treatment was associated with a qualitative difference in insulin receptor mRNA, poly(A)⁺ RNA was subjected to agarose gel electrophoresis, followed by transfer to nitrocellulose filters. These filters were then probed with labeled insulin receptor cDNA. In T47D cells, 3 major bands of insulin receptor mRNA were seen at 11.0, 8.5, and 7.5 kilobases (Fig. 4B). After 4 days of treatment with 100 nM R5020 the relative amount of these 3 insulin receptor mRNA species was significantly changed (Fig. 4B). Quantitative scanning of bands revealed that in control cells the most prominent mRNA species were the 8.5- and 7.5-kilobase species; in contrast, after R5020 treatment the most prominent species were the 11.0- and 8.5-kilobase species.

Effects of Progestins on Insulin Stimulation of Cell Growth

In order to determine whether the progestin-induced increase in insulin receptor content was associated with enhanced insulin action, we studied the growth of T47D cells (Fig. 5). Cells were continuously treated with 30 nM progesterone and then with or without insulin. In the absence of insulin, progesterone had a nonsignificant effect on growth. Insulin, in the absence of progesterone, increased growth by about 10%. In contrast, progesterone and insulin together had a synergistic effect, stimulating growth by 45%. In progesterone-treated cells, insulin had a detectable effect on growth at 100 pM and a maximal effect at 10 nM (Fig. 5).

Studies in MCF7 Cells

In order to establish that the progesterone effect on insulin action occurs in other breast cancer cell lines, we studied MCF7...
cells, a cell line known to be regulated by insulin (24). Treatment with progesterone for 3 days increased insulin receptor content by 40–50% (data not shown). As in T47D cells, progesterone potentiated insulin stimulation of cell growth (Fig. 6).

**DISCUSSION**

In the present study we find that treatment of human breast carcinoma cells with progestins increases insulin receptor gene expression and insulin receptor content. As a consequence, insulin stimulation of cell growth is enhanced. T47D cells were chosen for the majority of these studies for two reasons. First, it was previously reported that progestin treatment increases insulin receptor binding in this cell line (5). Second, these cells express high basal levels of progesterone receptors (25) and, therefore, estrogen treatment is not needed for progesterone receptor gene expression as is the case with other normal and cancer cell lines.

The insulin receptor is an αβ2-heterotetramer with two extracellular α subunits (Mr, 130,000) and two transmembrane β subunits (Mr, 90,000) that contain tyrosine kinase activity in their intracellular domains (23). One α and one β subunit are derived from a common precursor that is proteolyzed into separate subunits in the Golgi (23). This insulin receptor precursor is derived from a large single gene of 130 kilobases on chromosome 18 (23, 26). This gene has 22 exons.

Insulin receptor mRNA content in T47D cells was increased by progestin treatment. Moreover, the expression of insulin receptor mRNA was altered in a qualitative manner. In most cells that have been studied, several insulin receptor mRNA species are observed in agarose gels with molecular sizes ranging widely from 5.2 to 11 kilobases (23). Studies of these multiple transcripts suggest that they are due to variable splicing at the 3’ end of the insulin receptor RNA (23, 27). There are multiple 5’ start sites but they differ only by several hundred bases (28) and thus do not account for the size heterogeneity. While these multiple species are all involved in insulin receptor protein synthesis (since they are all found associated with ribosomes) (22), the biological role for these multiple mRNA species is unknown. In T47D cells we observed that progestin treatment increased the relative content of the higher molecular weight mRNA forms. While progestins and other steroid hormones act primarily to increase gene transcription (21, 22), in some instances they have been reported to alter RNA processing and turnover (21, 29, 30). The present study of the insulin receptor in T47D cells provides a new example, therefore, of steroid hormone regulation of mRNA metabolism.

In the present study we observed that the increment in insulin receptor mRNA content was paralleled by an increase in insulin receptor protein content as measured by both Scatchard analysis and radioimmunoassay. In addition to changing binding capacity, progestin treatment also altered the affinity of the high affinity insulin-binding sites. The reason for this effect is unknown but may reflect an effect of progestins on other elements of the plasma membrane such as lipids which are known to influence receptor affinity (23).

Progestins also increase insulin binding to its receptor in ZR-75 human breast cancer cells (31) and in a variant subline of T47D (5), but the mechanism of this up-regulation was not reported. Also, we have now observed that progesterone pre-treatment of both T47D cells and MCF7 cells enhances insulin stimulation of cell growth. This observation indicates that up-regulation of insulin receptors by progestin in human breast cancer cells is directly related to enhanced insulin action.

The present observations demonstrating an interaction between insulin receptor and steroid receptors in cultured human breast carcinoma cells may have clinical implications. We have recently observed that insulin receptors are elevated 7-fold in breast carcinomas when compared with normal breast tissues (32). It is possible, therefore, that the interaction between progesterone and insulin receptors in breast cancer cells may also occur in vivo and this interaction may have a role in regulating the growth of breast tumors (33). These findings may also be relevant to the proliferation rate of normal breast epithelial cells. In rodents progesterone, in the presence of insulin, stimulates the growth of cultured mammary epithelial cells (34). Also, several studies have shown that the mitotic activity of normal breast epithelial cells is highest during the luteal phase of the menstrual cycle when progesterone levels are highest (35).

**REFERENCES**

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