A Negative Feedback Loop Attenuates EGF-induced Morphological Changes

John B. Welsh,*$ Gordon N. Gill,* Michael G. Rosenfeld,* and Alan Wells‡

*Department of Medicine, Division of Endocrinology and Metabolism and ‡Department of Pathology, University of California, San Diego, La Jolla, California 92093

Abstract. Activation of the EGF receptor tyrosine kinase by ligand indirectly activates a series of other cellular enzymes, including protein kinase C. To test the hypothesis that phosphorylation of the EGF receptor by protein kinase C provides an intracellular negative feedback loop to attenuate EGF receptor signaling, we used scanning EM to follow the characteristic EGF-induced retraction of lamellipodia and concomitant cell shape changes. Wild type and mutant EGF receptors were expressed in receptor-deficient NR6 cells. The mutant receptors were prepared by truncation at C' terminal residue 973 (c'973) to provide resistance to ligand-induced down regulation that strongly attenuates receptor signaling and by replacement of threonine 654 (T654) with alanine (A654) to remove the site of phosphorylation by protein kinase C. Cells expressing WT and c'973 EGF receptors demonstrated characteristic lamellipodial retraction after exposure to EGF, with the non-down regulating c'973 EGF receptors responding more rapidly. Exposure of cells to TPA blocked this response. Replacement of T654 by alanine resulted in EGF receptors that were resistant to TPA. Cells expressing the A654 mutation underwent more rapid and more extensive morphologic changes than cells with the corresponding T654 EGF receptor. In cells expressing T654 EGF receptors, down regulation of protein kinase C resulted in more rapid and extensive EGF-induced changes similar to those seen in cells expressing A654 EGF receptors. These data indicate that activation of protein kinase C and subsequent phosphorylation of the EGF receptor at T654 lead to rapid physiological attenuation of EGF receptor signaling.

A complex network of growth stimulatory and growth inhibitory factors provides environmental information that regulates cell proliferation. Sufficient signal strength is required to elicit cell proliferation while mechanisms for attenuating signaling are necessary to limit inappropriate cell division. Posttranscriptional mechanisms that attenuate signaling by ligand-activated EGF receptors include down regulation and transmodulation. On ligand binding, EGF receptors, which are diffusely distributed on the cell surface, cluster in coated pits (Haigler et al., 1978), undergoing internalization via a high affinity saturable endocytic process (Lund et al., 1990), and are ultimately degraded (Stoscheck and Carpenter, 1984). Mutant EGF receptors that fail to down regulate in response to ligand activation display increased mitogenesis and transformation at low concentrations of EGF (Chen et al., 1989; Wells et al., 1990), emphasizing the consequences of loss of this attenuation mechanism.

Other signaling pathways can decrease the ability of EGF to act. The most extensively characterized mechanism for transmodulation of the EGF receptor involves protein kinase C. Activated protein kinase C catalyzes phosphorylation of the EGF receptor at threonine 654 (T654)1 (Hunter et al., 1984), resulting in decreased affinity of the receptor for EGF (Shoyab et al., 1979; Lin et al., 1986), decreased EGF-stimulated protein tyrosine kinase activity (Cochet et al., 1984; Friedman et al., 1984; Downward et al., 1985), and inhibition of ligand-induced receptor internalization and down regulation (Lund et al., 1990). Ligand activation of EGF receptors also results in phosphorylation at T654 (Whiteley and Glaser, 1986; Decker et al., 1990). This presumably results from EGF receptors activating phospholipase C (Hepler et al., 1987) and phospholipase D (Bes-}

© The Rockefeller University Press, 0021-9525/91/08/533/11 $2.00
The Journal of Cell Biology, Volume 114, Number 3, August 1991 533–543

1. Abbreviations used in this paper: A654, alanine 654; DAG, diacylglycerol; SEM, scanning EM; T654, threonine 654; PDGF, platelet-derived growth factor; TPA, 12-0-tetradecanoylphorbol-13-acetate.
late (A. Wand J. M. Bishop, unpublished data). Sequences covering the ligand-induced internalization and downregulation. The A651 variant of the receptors defective in ligand-induced internalization and down regulation, it has become possible to assess the existence of a protein kinase C-mediated negative feedback loop initiated by ligand-activated EGF receptors. With scanning EM (SEM), we have assessed cell morphology which is a sensitive assay of integrated biological responses elicited by EGF (Chinkers et al., 1981; Miyata et al., 1989). In response to EGF, membrane ruffling, lamellipodial retraction, and "rounding up" occur; these cytoskeletal changes are rapidly induced and involve disengagement of lamellipodia from the underlying substrate. Actin and α-actinin are redistributed in cells exposed to EGF (Schlessinger and Geiger, 1981); myosin, spectrin, ezrin, and fimbrin also show a reorganization coincident with these shape changes (Bretscher, 1989). Filopodia become more apparent during lamellipodial retraction as attachment to the substrate is lost. Eventually, the filopodia are subsumed as the cell becomes increasingly rounded with blebs and ridges becoming the most apparent features (Jackowski et al., 1990). We used morphological changes in NR6 cell lines expressing wild type and mutant EGF receptors that contain alanine at residue 654 (A654) to remove the site of protein kinase C phosphorylation (Lin et al., 1986; Davis, 1988) and mutant EGF receptors defective in ligand-induced internalization and down regulation (c973) (Chen et al., 1989; Wells et al., 1990) to critically examine the operation of this proposed negative feedback pathway of signal attenuation in vivo.

Materials and Methods

EGF Receptor Constructions

Three independently derived cDNA clones of the human EGF receptor were analyzed in parallel. Two clones, Gen (Ulrich et al., 1984) and UCSD (Lin et al., 1984), were isolated from A431 cells that have a 25-fold amplified EGF receptor gene. These were compared to a human placental isoform (Lin et al., 1986), protein kinase C is down regulated (Collins and Rozengurt, 1984; Ballester and Rosen, 1985) and phosphatases are activated (Cohen, 1989). By using mutant EGF receptors that are defective in ligand-induced internalization and down regulation, it has become possible to assess the existence of a protein kinase C-mediated negative feedback loop initiated by ligand-activated EGF receptors. With scanning EM (SEM), we have assessed cell morphology which is a sensitive assay of integrated biological responses elicited by EGF (Chinkers et al., 1981; Miyata et al., 1989). In response to EGF, membrane ruffling, lamellipodial retraction, and "rounding up" occur; these cytoskeletal changes are rapidly induced and involve disengagement of lamellipodia from the underlying substrate. Actin and α-actinin are redistributed in cells exposed to EGF (Schlessinger and Geiger, 1981); myosin, spectrin, ezrin, and fimbrin also show a reorganization coincident with these shape changes (Bretscher, 1989). Filopodia become more apparent during lamellipodial retraction as attachment to the substrate is lost. Eventually, the filopodia are subsumed as the cell becomes increasingly rounded with blebs and ridges becoming the most apparent features (Jackowski et al., 1990). We used morphological changes in NR6 cell lines expressing wild type and mutant EGF receptors that contain alanine at residue 654 (A654) to remove the site of protein kinase C phosphorylation (Lin et al., 1986; Davis, 1988) and mutant EGF receptors defective in ligand-induced internalization and down regulation (c973) (Chen et al., 1989; Wells et al., 1990) to critically examine the operation of this proposed negative feedback pathway of signal attenuation in vivo.

Analysis of EGF Receptor Distribution by Fluorescence-activated Cell Scanning and Immunocytochemistry

For fluorescence-activated cell scanning analysis, cells were dissociated from their substrate with EDTA, fixed with 3.7% paraformaldehyde, and incubated with a monoclonal mouse antibody directed against the external domain of the EGF receptor (528 IgG) at 37°C for 30 min. After washing, cells were incubated with goat anti-mouse immunoglobulin linked to phycoerythrin for a further 30 min at 37°C. Analysis was carried out on groups of 10,000 cells in a FACScanner (Becton Dickinson & Co., Mountain View, CA); data were analyzed with the accompanying LYSYS II software package. Histograms were taken through one round of smoothing. For indirect immunofluorescence, cells were fixed without dissociation and stained as described above; photographs were taken with an Optiphot microscope (Nikon Inc., Garden City, NY) at a magnification of 400×. Parental NR6 cells lacking EGF receptors were analyzed in parallel to provide a control for background fluorescence.

SEM

For SEM analyses, cells were plated on half-inch glass coverslips and allowed to adhere. Where indicated, TPA (10 nM; Sigma Chemical Co., St. Louis, MO) was added either 24 h or 10 min before the experiment. The coverslips were transferred to a tank of 37°C media containing 10% dialyzed FBS and EGF (50 nM). Cells were maintained at 37°C until being fixed in 2.5% buffered glutaraldehyde (EMS, Fort Washington, PA) at room temperature for 1 h, postfixed in 2% OsO4 for 1 h, and dehydrated in absolute ethanol. Peldri II (Ted Pella Inc., Irvine, CA), a sublimation dehydrant was used in place of critical point drying (Kennedy et al., 1989). After 1 h in a 1:1 mix of ethanol and Peldri II, the samples were transferred to liquid Peldri II, cooled to room temperature, and dried under vacuum for 12 h.

Table I. Comparison of the Sequence of Three Cloned Human EGF Receptor cDNAs

| Base | Placental | Gen | UCSD | Effect |
|------|-----------|-----|------|--------|
| 738  | C         | C   | T    | L160 ← L |
| 1806 | C         | C   | C    | No HindIII site |
| 2547 | G         | A   | A    | Q763 ← Q |

The entire coding sequence from nucleotide 167 to 3880 was obtained using dideoxynucleotide chain terminating reactions. Reactions were run on parallel lanes of sequencing gels and the points of difference verified. Differences at bases 738 and 2547 do not change the predicted amino acids. None of the clones contain a HindIII restriction site at 1806 as indicated in the GenBank EGF receptor sequence.
Figure 1. Scanning electron microscopic comparison of the rate and extent of EGF-induced morphological changes in NR6 cells expressing wild type and C' terminal truncated EGF receptors. Cells expressing either the wild type (WT) or the c'973 T654 receptor (c'973) were exposed to 50 nM EGF for the indicated lengths of time. The cells were subsequently fixed, prepared, and visualized by SEM. Bar, 10 μm.

The coverslips were mounted on slotted specimen holders and coated with ~500 Å Au. A scanning electron microscope (model 360; Cambridge Instruments, Cambridge, U.K.) was used to image the cells. Representative individual cells were photographed at 2,500× magnification.

Quantitation of the Relative Cross-Sectional Area of Individual Cells
To quantitate the extent of morphological change of the cells under investi-
Figure 2. Expression of c'973 T654 and c'973 A654 EGF receptors in NR6 cells. Cells expressing either c'973 T654 or c'973 A654 EGF receptors were analyzed by indirect immunofluorescence and by fluorescence flow cytometry to ascertain expression of receptors. Cells were stained using the mouse mAb 528 IgG directed against the EGF receptor and visualized using phycoerythrin-conjugated goat anti-mouse Ig antibody.

**Results**

C Terminal Truncated EGF Receptors Elicit a More Rapid Change in Cell Morphology

EGF-induced morphological changes were compared be-
Figure 3. Effects of the phorbol ester TPA on EGF-induced morphologic changes in cells expressing T<sup>654</sup> compared to A<sup>654</sup> EGF receptors. NR6 cells expressed EGF receptors truncated after amino acid 973 and having either a threonine residue (c'<sup>973</sup> T<sup>654</sup>) or an alanine residue (c'<sup>973</sup> A<sup>654</sup>) at position 654. These cells were either mock treated (no tx), exposed to 50 nM EGF for 10 min (EGF), or to 10 nM TPA for 10 min followed by 50 nM EGF for 10 min (TPA-EGF). Bar, 10 μm.

Welsh et al. Feedback Inhibition of EGF Receptor Signaling

TPA Inhibits EGF-induced Morphological Changes in Cells Expressing T<sup>654</sup> but Not A<sup>654</sup> EGF Receptors

The threonine at amino acid 654 (T<sup>654</sup>) was changed to alanine (A<sup>654</sup>) to create a model system for studying signal attenuation by mechanisms distinct from down-regulation. The c'<sup>973</sup> EGF receptor does not undergo signal attenuation by ligand-induced down-regulation (Chen et al., 1989; Wells et al., 1990), making it more feasible to isolate other modes of signal attenuation. The more rapid and extensive morphological response of cells expressing c'973 EGF receptors presumably results from enhanced EGF-stimulated protein tyrosine kinase activity (Walton et al., 1990).
the single protein kinase C phosphorylation site at T654 with

Protein Kinase C Phosphorylation Site at Residue 654 Respond More Rapidly and Extensively to EGF

Cells Expressing EGF Receptors Lacking a Protein Kinase C Phosphorylation Site at Residue 654 Respond More Rapidly and Extensively to EGF

If endogenously activated protein kinase C attenuates EGF receptor signaling, receptors that lack a feedback phosphorylation site would be expected to respond more rapidly and more extensively to EGF. The more extensive morphological change with EGF in cells expressing A654 compared to T654 receptors at 10 min (Fig. 3) suggested this was occurring. To examine this more closely, we compared the time-dependent extent of morphological changes in cells expressing T654 and A654 EGF receptors. Fig. 5 shows that, on exposure to EGF, the cytoskeletons of both cells rearrange as demonstrated by lamellipodial retraction and increases in apparent height at various points along the cell margin. The change in morphology was more extensive in cells expressing A654 compared to T654 EGF receptors at each of the time points examined (3, 6, and 9 min after addition of 50 nM EGF). These results, which show that the rate and extent of EGF-induced morphological change is greater in cells expressing A654 receptors than in those expressing T654 receptors, suggest this mutation removes an inhibitory constraint.

To quantitate the morphological changes observed with SEM, individual cells were followed throughout the time course of EGF treatment by viewing and photographing randomly selected fields at low power (200x). When a cell retracts, the cross-sectional area parallel to the surface of attachment decreases. The cross-sectional area of individual cells was therefore measured at 3-min intervals after EGF addition. Fig. 6 shows that the rate and extent of decrease in cross-sectional area was significantly greater for cells expressing c973 A654 than c973 T654 EGF receptors. The changes observed with SEM are thus quantitative and representative of the entire population. The greater decrease in cross-sectional area in response to EGF in c973 A654 EGF...
Figure 5. Time course of lamellipodial retraction in cells expressing T\textsuperscript{654} or A\textsuperscript{654} EGF receptors. Cells expressed EGF receptors truncated after amino acid 973 and had either a threonine residue (c'973 T\textsuperscript{654}) or an alanine residue (c'973 A\textsuperscript{654}) at position 654. They were exposed to 50 nM EGF for the indicated lengths of time and processed for SEM. Bar, 10 µm.
Uegf-induced Morphological Changes

Down Regulation of Protein Kinase C Increases EGF-induced Morphological Changes

Figure 6. Cell retraction in response to EGF. NR6 cells, expressing the c973 EGF receptor with either T or A at residue 654, were plated on coverslips. These were treated with 50 nM EGF. Random cells were followed individually at 3-min intervals by light microscopy at 200x magnification. The cross-sectional area of each cell was measured and scored as a percent of the area in the untreated state. (a) NR6 cells expressing the T654 EGF receptor; (b) the same cells after 24-h exposure to 10 nM TPA; (c) NR6 cells expressing the A654 EGF receptor; (d) the same cells after 24-h exposure to 10 nM TPA. Results are mean ± standard error of means of 10 to 30 cells. **, P < 0.001 with respect to cells expressing c973 A654 EGF receptors and to TPA-treated cell expressing either receptor.

Discussion

Activation of protein kinase C by the pharmacologic action of phorbol esters or by DAG produced in response to other hormones leads to decreased EGF receptor kinase activity (Cochet et al., 1984; Friedman et al., 1984; Downward et al., 1985; Lund et al., 1990). Transmodulation between signaling pathways also occurs through less well-defined mechanisms. Platelet-derived growth factor, which increases phosphorylation of the EGF receptor at $T^{654}$, also causes a decrease in high affinity EGF binding by a protein kinase C–independent mechanism (Olashaw et al., 1986; Davis and Czech, 1987). Interleukin 1 and tumor necrosis factor also act independently of protein kinase C to transmodulate the EGF receptor (Bird and Saklatvala, 1990). Palytoxin, a non-TPA type tumor promoter, may act through mediation of sodium fluxes to decrease both high and low affinity components of EGF binding (Wattenberg et al., 1989). A variety of mechanisms thus exists to coordinate responses among different signaling systems.

Similar mechanisms have been proposed to function as a negative feedback loop to attenuate EGF receptor signaling. King and Cooper (1986) demonstrated that some EGF receptor molecules were both self phosphorylated on tyrosine residues and at $T^{654}$. Because prior phosphorylation at $T^{654}$ inhibits EGF receptor self phosphorylation (Cochet et al., 1984; Whiteley and Glaser, 1986; Decker et al., 1990; Lund et al., 1990), these findings were interpreted as evidence for a feedback loop that could attenuate further signaling by ligand-activated receptors. It has been difficult to critically test whether this proposed mechanism functions in vivo to attenuate EGF-induced responses because of the rapid and dominant effects of EGF-induced receptor internalization and down regulation. In the present studies we have used EGF receptor mutants defective in ligand-induced internalization and down regulation, and have examined the early morphologic alterations of lamellipodial retraction and membrane ruffling that reflect cytoskeletal responses to EGF. Several cytoskeletal proteins such as ezrin, spectrin (Bretscher, 1989), and calpactin II (Campos-Gonzales et al., 1990) are tyrosine phosphorylated in response to EGF and are thought to be involved in the morphologic changes induced by the growth factor.

Using c973 T654 EGF receptors, TPA was shown to block EGF-induced morphologic changes and to inhibit EGF-stimulated protein tyrosine kinase activity in vivo. Replacement of the single major protein kinase C phosphorylation site with a non-phosphorylatable alanine residue rendered the mutant EGF receptor completely refractory to the inhibitory effects of TPA. This strongly supports previous findings that phosphorylation at $T^{654}$ is the principal mechanism through which protein kinase C inhibits EGF receptors (Lin et al., 1986; Davis, 1988; Lund et al., 1990).

Although NR6 cells expressing c973 T654 and c973 A654 EGF receptors exhibit similar time response curves for the late response of EGF-stimulated cell growth (data not shown), the morphologic response to EGF was both more rapid and more extensive in cells expressing the A654 receptor. The enhanced EGF stimulated lamellipodial retraction and membrane ruffling in cells expressing c973 A654 EGF receptors suggested that a negative feedback restraint, operative at $T^{654}$, was removed. This was further tested by down regulating protein kinase C in cells expressing c973 T654 receptors. When protein kinase C was down regulated, the c973 T654 receptor-expressing cells responded more rapidly...
Figure 7. Effect of down regulation of protein kinase C on the response to EGF by the c'973 T654 EGF receptor-containing cells. NR6 cells expressing c'973 T654 EGF receptors were grown in the absence (no TPA tx) or presence (TPA tx) of 10 nM TPA for 24 h. Cells were subsequently exposed to 50 nM EGF for the indicated times. Bar, 10 µm.
and extensively, similar to those expressing c973 A64 receptors. Thus, either elimination of the protein kinase C phosphorylation site (T64) or down regulation of the enzyme led to a more rapid and extensive response to EGF. Together these results indicate that a feedback loop involving protein kinase C acts to attenuate EGF-stimulated responses. The experimental system may underestimate the strength of the negative feedback loop regulating EGF receptor signaling. C terminal truncation not only removes sequences required for ligand-induced down regulation but also removes sequences required for EGF-stimulated increases in cytosolic [Ca\(^{2+}\)] (Chen et al., 1989). The ability of ligand-activated EGF receptors to increase inositol phosphate production is also decreased by removal of C terminal sequences (Q. C. Vega and G. N. Gill, unpublished observations). This suggests that EGF may activate protein kinase C by increasing DAG via mechanisms in addition to phospholipase C-\(\gamma\) activation. Wright et al. (1990) found that the rise in DAG in response to EGF stimulation is in large part because of hydrolysis of phosphatidylcholine, a process that can occur rapidly (Besterman et al., 1986). They implicate phospholipase D, which hydrolyzes phosphatidylcholine to choline and phosphatic acid, the latter being converted to DAG. This receptor-mediated hydrolysis of phosphatidylcholine can lead to DAG production for the rapid activation of protein kinase C (Slivka et al., 1988). As reported for PDGF (Olashaw et al., 1986; Davis and Czech, 1987), other kinase pathways may also lead to phosphorylation at T64. Use of c973 A64 EGF receptors cannot distinguish such mechanisms, but the effects of down regulation of protein kinase C suggest that protein kinase C is strongly involved in EGF-induced receptor attenuation. If other kinases are involved, their principal target appears to be T64 (Countaway et al., 1990; Heiserman et al., 1990). These morphological data thus strongly support the hypothesis that protein kinase C is involved in physiologic regulation of EGF receptor signaling.

The Gen EGF receptor cDNA was provided by Axel Ulrich. We thank Thomas Lane and Geraldine Lamkin for protein kinase C activity measurements and Cheri S. Lazar for measurements of EGF binding.

These studies were supported by research grants from the American Cancer Society (G. N. Gill, CD-456N) and National Institutes of Health (M. G. Rosenfeld, DK07541; G. N. Gill, DK13149). J. B. Welsh was supported by Medical Scientist Training Program grant GM07198. M. G. Rosenfeld is a Howard Hughes Medical Institute Investigator.

Received for publication 28 December 1990 and in revised form 25 April 1991.

References

Akinslasia, P., J. Teixido, M. Laito, J. H. Pearce, J. S. Greenberger, and J. Massague. 1990. Cell-cell adhesion mediated by binding of membrane-anchored transforming growth factor alpha to epidermal growth factor receptors promotes cell proliferation. Proc. Natl. Acad. Sci. USA. 87:3289-3293.

Ballerina, R., and T. M. Rosen. 1985. Fate of immunoprecipitable protein kinase C in GH3 cells treated with phorbol 12-myristate 13-acetate. J. Biol. Chem. 260:15194-15199.

Besterman, J. M., V. Duronio, and P. Cuatrecasas. 1986. Rapid formation of diacylglycerol from phosphatidylcholine: a pathway for generation of a second messenger. Proc. Natl. Acad. Sci. USA. 83:6785-6789.

Bird, T. A., and J. Saklatvala. 1990. Down-modulation of epidermal growth factor receptor affinity in fibroblasts treated with interleukin 1 or tumor necrosis factor is associated with phosphorylation at a site other than threonine 654. J. Biol. Chem. 265:235-240.

Bishop, W. R., and R. M. Bell. 1986. Attenuation of an-1,2-diacylglycerol sec-
Lin, C. R., W. S. Chen, C. S. Lazar, C. D. Carpenter, G. N. Gill, R. M. Evans, and M. G. Rosenfeld. 1986. Protein kinase C phosphorylation at Thr 654 of the unoccupied EGF receptor and EGF binding regulate functional receptor loss by independent mechanisms. Cell. 44:839-848.

Lund, K. A., C. S. Lazar, W. S. Chen, B. J. Walsh, J. B. Welsh, J. J. Herbst, G. M. Walton, M. G. Rosenfeld, G. N. Gill, and H. S. Wiley. 1990. Phosphorylation of the epidermal growth factor receptor at threonine 654 inhibits ligand-induced internalization and down-regulation. J. Biol. Chem. 265: 20517-20523.

Lund, K. A., L. K. Opresko, C. Starbuck, B. J. Walsh, and H. S. Wiley. 1990. Quantitative analysis of the endocytic system involved in hormone-induced receptor internalization. J. Biol. Chem. 265:15713-15723.

Miyata, Y., E. Nishida, S. Koyasu, I. Yahara, and H. Sakai. 1989. Protein kinase C-dependent and -independent pathways in the growth factor-induced cytoskeletal reorganization. J. Biol. Chem. 264:15565-15568.

Nishizuka, Y. 1984. The role of protein kinase C in cell surface signal transduction and tumour promotion. Nature (Lond.). 308:693-698.

Olashaw, N. E., E. J. O'Keefe, and W. J. Pledger. 1986. Platelet-derived growth factor modulates epidermal growth factor receptors by a mechanism distinct from that of phorbol esters. Proc. Natl. Acad. Sci. USA. 83:3834-3838.

Pruss, R. M., and H. R. Herschman. 1977. Variants of 3T3 cells lacking mitogenic response to epidermal growth factor. Proc. Natl. Acad. Sci. USA. 74:3918-3921.

Sanger, F., S. Nicklen, and A. R. Coulson. 1977. DNA sequencing with chain-terminating inhibitors. Proc. Natl. Acad. Sci. USA. 74:5463-5467.

Schlessinger, J., and B. Geiger. 1981. Epidermal growth factor induces redistribution of actin and &alpha;-actinin in human epidermal carcinoma cells. Exp. Cell Res. 134:273-279.

Scott, J., M. Urdea, M. Quiroga, R. Sanchez-Pescador, N. Feng, M. Selby, W. I. Rutter, and G. I. Bell. 1983. Structure of a mouse submaxillary messenger RNA encoding epidermal growth factor and seven related proteins. Science (Wash. DC). 221:236-240.

Shoyab, M., J. E. DeLarco, and G. J. Todaro. 1979. Biologically active phorbol esters specifically alter affinity of epidermal growth factor receptor membrane receptors. Nature (Lond.). 279:387-391.

Slivka, S. R., K. E. Meier, and P. A. Insel. 1988. Alpha 1-adrenergic receptors promote phosphatidylinositol hydrolysis in MDCK-D1 cells. A mechanism for rapid activation of protein kinase C. J. Biol. Chem. 263:12242-12246.

Stoscheck, C. M., and G. Carpenter. 1984. "Downregulation" of EGF receptors: direct demonstration of receptor degradation in human fibroblasts. J. Cell Biol. 98:1048-1053.

Ullrich, A., L. Coussens, J. S. Hayflick, T. J. Dull, A. Gray, A. W. Tam, J. Lee, Y. Yarden, T. A. Libermann, J. Schlessinger, J. Downward, E. L. V. Mayes, N. Whittle, M. D. Waterfield, and P. H. Seeburg. 1984. Human epidermal growth factor receptor cDNA sequence and aberrant expression of the amplified gene in A431 epidermoid carcinoma cells. Nature (Lond.). 309:418-425.

Welsh et al. Feedback Inhibition of EGF Receptor Signaling