

Ectodomain shedding of the EGF-receptor ligand epigen is mediated by ADAM17

Umut Sahin^a, Carl P. Blobel^{a,b,*}

^a Arthritis and Tissue Degeneration Program, Caspary Research Building, Room 426, Hospital for Special Surgery, 535 East 70th Street, New York, NY 10021, USA

^b Departments of Medicine and of Physiology and Biophysics, Weill Medical College of Cornell University, New York, NY 10021, USA

Received 26 October 2006; accepted 26 November 2006

Available online 6 December 2006

Edited by Richard Marais

Abstract All ligands of the epidermal growth factor receptor (EGFR), which has important roles in development and disease, are made as transmembrane precursors. Proteolytic processing by ADAMs (a disintegrin and metalloprotease) regulates the bioavailability of several EGFR-ligands, yet little is known about the enzyme responsible for processing the recently identified EGFR ligand, epigen. Here we show that ectodomain shedding of epigen requires ADAM17, which can be stimulated by phorbol esters, phosphatase inhibitors and calcium influx. These results suggest that ADAM17 might be a good target to block the release of bioactive epigen, a highly mitogenic ligand of the EGFR which has been implicated in wound healing and cancer.

© 2006 Federation of European Biochemical Societies. Published by Elsevier B.V. All rights reserved.

Keywords: EGF-receptor; EGF-receptor ligands; Epigen; ADAMs; Ectodomain shedding

1. Introduction

Epigen is a recently identified ligand of the epidermal growth receptor (EGFR, ErbB1), and belongs to a group of functionally and structurally similar growth factors that mediate cellular responses ranging from cell survival to proliferation and migration [6,29]. Epigen was first isolated from a mouse keratinocyte cDNA library due to its homology to the EGFR-ligand epiregulin [25]. It shows 24–37% identity to other EGFR ligands (EGF, TGF α , HB-EGF, amphiregulin, betacellulin, epiregulin), and contains six spatially conserved cysteine residues that are characteristic of members of this protein family [6]. The biological activity of recombinant epigen is similar to that of other EGFR ligands. In epithelial cells, it stimulates phosphorylation of the EGFR and downstream signaling molecules such as the mitogen activated protein kinase (MAPK), and it promotes cell proliferation in a dose-dependent manner [25].

Despite its relatively low affinity for the EGFR, epigen has an increased mitogenic potential compared to other EGFR ligands. When EGFR expressing cells were treated with equal

concentrations of EGF, TGF α or epigen, epigen was found to be the most potent mitogen [12]. Epigen effectively activates signaling via an EGFR-homodimer or through a heterodimer between EGFR and ErbB2 [12]. Epigen is widely expressed in a variety of mouse tissues, especially in multiple developing structures in the embryo, such as developing tongue papillae, the dorsal root ganglion and the inner and outer root sheath of hair follicles, all of which are regions of active proliferation [12]. Moreover, epigen expression is also observed in invasive adenocarcinomas of the breast and prostate in humans [12].

All seven EGFR ligands described to date (TGF α , HB-EGF, amphiregulin, epiregulin, EGF, betacellulin and epigen) are synthesized as membrane-anchored precursors that are subsequently released from the cell surface by proteolysis [6]. This proteolytic processing is considered to be a key regulatory step controlling the bioavailability of soluble EGFR-ligands, and thus signaling via the EGFR [18] (for a recent review, see [2]). Membrane-anchored metalloprotease-disintegrin proteins (ADAMs, a disintegrin and metalloprotease) have been implicated in the ectodomain shedding of six out of the seven currently known EGFR ligands [3,18,21,26]. Specifically, ADAM17 has been shown to have a major role in processing of TGF α , HB-EGF, amphiregulin and epiregulin, and ADAM10 is a major sheddase of EGF and betacellulin [16,18,21,22,26]. However, little is known about the enzyme(s) responsible for the proteolytic release of epigen. In this study, we show that the ectodomain of epigen is released from the cell membrane constitutively at low levels, and that its shedding can be highly upregulated by phorbol esters, calcium ionophores and tyrosine phosphatase inhibitors. Moreover, we provide evidence for a major role of ADAM17 in stimulated shedding of epigen. These results uncover a fifth EGFR-ligand as a substrate for ADAM17, an enzyme with an essential role in activating the EGFR during mouse development [18].

2. Materials and methods

An expression vector encoding the alkaline phosphatase (AP)-tagged epigen was constructed by inserting a partial cDNA for mouse epigen, which encoded for the EGF repeat, the juxtamembrane domain containing the putative cleavage site, transmembrane domain and cytoplasmic domain, into the 3' end of human placental alkaline phosphatase in the CMV-based vector APTag-5 (Genhunter Corp.). The junction between AP and epigen was placed in frame at Leu 53 at the N-terminus of the EGF repeat of mouse epigen, which has 152 amino acid residues. The epigen-AP fusion construct also contains a C-terminal Myc and His tag attached to the cytoplasmic domain of epigen.

*Corresponding author. Address: Arthritis and Tissue Degeneration Program, Caspary Research Building, Room 426, Hospital for Special Surgery, 535 East 70th Street, New York, NY 10021, USA. Fax: +1 212 774 2560.

E-mail address: blobelc@hss.edu (C.P. Blobel).

Wild type mouse embryonic fibroblasts (mEFs), generated from wild type E13.5 mouse embryos and cultured as described previously [28], and *Adam17*^{-/-} mEFs, which have also been described previously [19] were transfected with a cDNA vector encoding the AP-epigen fusion protein with LipofectAMINE (Invitrogen). Fresh Opti-MEM (Invitrogen) medium was added the next day, conditioned for 1 h, and then replaced with fresh medium containing one of the following: 20 ng/ml PMA (Sigma), 2 μ M ionomycin, 100 μ M pervanadate, 1 μ M batimastat (BB94, provided by D. Becherer, GlaxoSmithKline, Research Triangle Park, NC), 1–10 μ M GI254023X or GW280164X [13]. The conditioned medium containing inhibitors or activators of ectodomain shedding was collected after 1 h. Evaluation of AP activity by SDS-PAGE or spectrophotometry was performed as described previously [20].

3. Results

In order to study the ectodomain shedding of epigen from cells, an alkaline phosphatase (AP) moiety was attached to the amino terminus of the EGF repeat of epigen (Fig. 1a). A similar approach has previously been used to study ectodomain shedding of other EGFR ligands [21,28]. The main advantage of adding an AP tag is that it facilitates the detection and quantitation of shed forms of epigen. Moreover, previous studies have shown that the AP tag did not affect which enzyme was responsible for shedding other EGFR-ligands, since both the AP-tagged forms of TGF α or HB-EGF and untagged wild type forms of these EGFR-ligands were shed by ADAM17 [11,18,21,26]. When COS-7 cells were transfected with AP-tagged epigen, low levels of constitutive shedding into the culture supernatant were observed (Fig. 1b, lanes 1 and 3). Constitutive release of epigen was strongly induced after addition of the phorbol ester PMA (Fig. 1b, lane 2 and Fig. 1c). Both the constitutive and the PMA-regulated components of epigen-AP shedding could be effectively inhibited by the hydroxamate-type metalloprotease inhibitor BB94 (batimastat, Fig. 1b, lane 4 and Fig. 1c) suggesting that a metalloprotease, most likely an ADAM, is involved in this process. Specifically, the strong stimulation of epigen shedding by PMA is reminiscent of ADAM17 mediated ectodomain shedding of four other EGFR ligands, TGF α , HB-EGF, amphiregulin and epiregulin, as well as of other ADAM17-substrates such as TNF α [21,30]. Essentially identical results were obtained when these experiments were repeated in CHO cells (data not shown).

To further characterize the epigen sheddase in COS-7 cells, we tested how two distinct hydroxamate-type metalloprotease inhibitors with some selectivity against ADAM10 or ADAM17 affected epigen shedding in these cells. The hydroxamate GI254023X (GI) had previously been shown to block ADAM10-mediated constitutive release of IL6R, CX3CL1 and CXCL16 at concentrations between 1 and 10 μ M, while compound GW280264X (GW) blocked PMA induced cleavage mediated by ADAM17 at these concentrations [13]. Constitutive shedding of epigen from COS7 cells was not affected by 1 μ M GI, whereas it was effectively blocked by GW at concentrations as low as 1 μ M (Fig. 2). GI had a partial inhibitory effect on epigen shedding at 5 μ M, and increasing inhibition was observed at higher concentrations of GI (7.5 μ M and 10 μ M). However, at all concentrations tested here (1–10 μ M), GW inhibited epigen shedding more efficiently than GI. This inhibition profile suggested that ADAM17, but not ADAM10, was responsible for epigen shedding. The increased shedding of epigen following stimulation by PMA was also

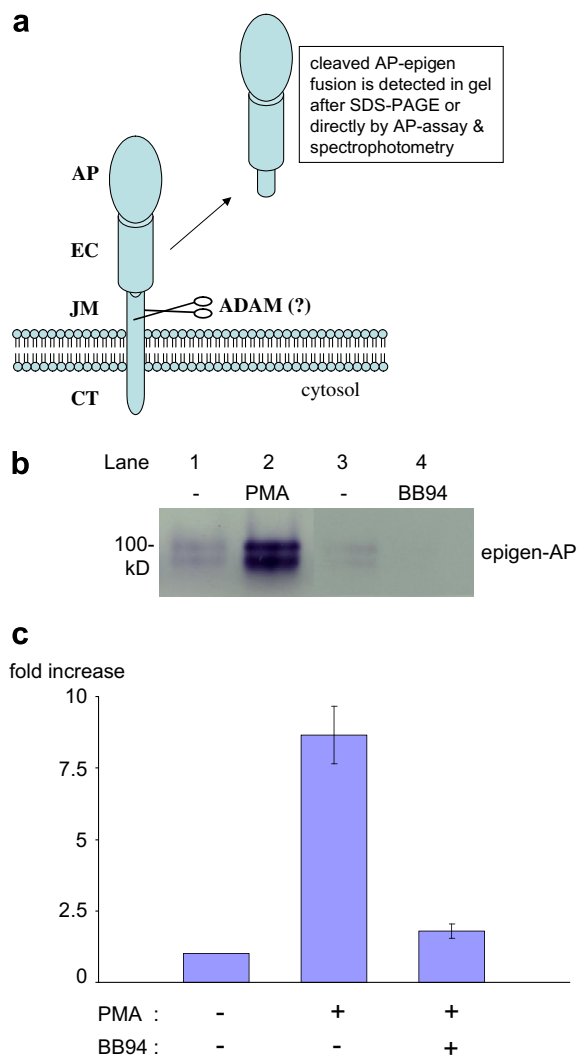


Fig. 1. Constitutive and stimulated shedding of epigen from COS-7 cells. (a) Diagram of the alkaline phosphatase (AP) reporter detection system used to monitor epigen shedding from COS-7 cells. An AP moiety was fused in frame N-terminal to the EGF-repeat (EC, extracellular domain) of mouse epigen. Proteolytic cleavage in the juxtamembrane (JM) region releases the epigen-AP fusion protein into the culture supernatant. The released epigen-AP can be detected by SDS-PAGE (b) or through spectrophotometry (c for details, see materials and methods, and reference [20]). (b) Epigen-AP is constitutively released at low levels from transiently transfected COS-7 cells (lanes 1,3). Release of epigen-AP from COS-7 cells was upregulated by 20 ng/ml PMA (lane 2) and blocked by the metalloprotease inhibitor BB94 at a concentration of 1 μ M (lane 4) (c) Upregulation of epigen-AP release from COS-7 cells upon PMA treatment is detected by a spectrophotometric assay for AP activity [20]. PMA stimulated shedding of epigen can be abolished by BB94 which also inhibits its constitutive processing. $n = 6$, error bars: standard deviation.

consistent with a role for ADAM17 in this process, since ADAM17 is considered to be one of the principal enzymes that responds to short-term stimulation with PMA (<1 h) [7,21].

In order to directly test whether ADAM17 is required for epigen shedding, we compared epigen processing in response to various stimuli in wild type mouse embryonic fibroblasts (mEF) versus mouse embryonic fibroblasts derived from *adam17*^{-/-} knockout mice (E2 cells) [18,19]. Similar to COS-7 cells, the epigen ectodomain was constitutively released from wild type mEFs at low levels, and this constitutive release

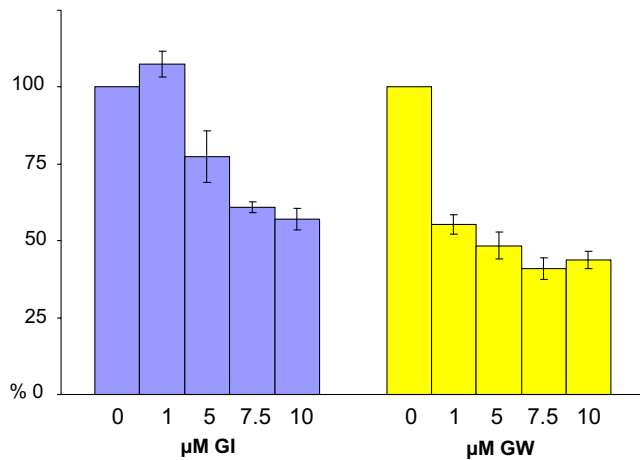


Fig. 2. Inhibition of constitutive release of epigen from COS-7 cells by the ADAM10-selective inhibitor GI254023X (GI), or the inhibitor GW280264X (GW), which has a similar IC₅₀ towards ADAM10 and ADAM17 in cell based assays [8,13]. Constitutive shedding of epigen is set to 100%. At 1 µM, GW effectively inhibits epigen shedding, whereas GI does not, suggesting that this process is mediated by ADAM17. $n = 3$, error bars: standard deviation.

was strongly stimulated by addition of PMA (Fig. 3). In addition, the phosphatase inhibitor pervanadate (PV) stimulated epigen shedding more than 12-fold compared to constitutive release in wild type cells, and the calcium ionophore ionomycin (IO) stimulated epigen shedding nearly 4-fold (Fig. 3). The increase in epigen shedding following stimulation with PMA, PV and IO was almost completely abolished in *adam17*^{-/-} E2 cells (Fig. 3). Shedding could be partially rescued by reintroduction of wild type ADAM17, but not of a catalytically inactive mutant form of ADAM17 (data not shown). These results

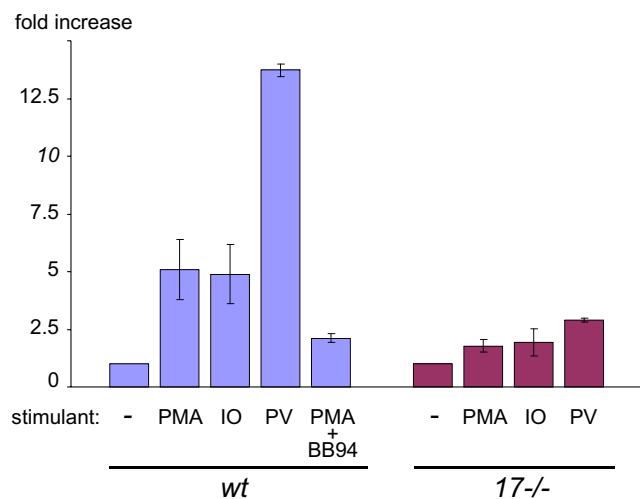


Fig. 3. Epigen shedding from mouse embryonic fibroblasts following stimulation with PMA, pervanadate (PV) or ionomycin (IO) requires ADAM17. Transiently transfected wild type and *adam17*^{-/-} mEFs were stimulated with PMA, PV or IO for 1 h and levels of epigen-AP released into culture media were compared. Similar to COS-7 cells shown in Fig. 1, mEFs release high amounts of soluble epigen-AP following PMA stimulation, and this release can be blocked by 1 µM BB94. The increased shedding of epigen following addition of PMA, IO or PV is almost completely abolished in *adam17*^{-/-} cells. $n \geq 4$, error bars: standard deviation.

demonstrate that ADAM17 is the major sheddase for epigen in mEF cells, corroborating the results obtained with the hydroxamates GI and GW in COS7 cells. In addition, no defect in the stimulation of epigen shedding by PMA, ionomycin and pervanadate was observed in *adam10*^{-/-} mEFs compared to their *adam10*^{+/-} counterparts, suggesting that ADAM10 is not required for epigen shedding (data not shown).

4. Discussion

Signaling via the EGFR (ErbB1) has essential roles in developing embryos and in adults [6,29]. In addition, dysregulation of the EGFR signaling network has been tied to tumor formation and invasion [5]. Release of soluble EGFR ligands from their membrane anchored precursors is considered to be a key step in initiating the EGFR-signaling; therefore enzymes mediating this release are potential drug targets for treatment of EGFR-dependent tumors [1,2,9,23,31].

Here we show that shedding of epigen, an EGFR-ligand with high mitogenic potential, can be stimulated by the phorbol ester PMA, the phosphatase inhibitor pervanadate and the calcium ionophore ionomycin. Moreover, we demonstrate that shedding of epigen induced by these three stimuli requires ADAM17. These results extend our previous analysis of the role of ADAMs in shedding EGFR-ligands, and show that all seven EGFR ligands identified to date are substrates of either ADAM10 or ADAM17. ADAM17 is thought to be essential for activating the EGFR via shedding of several of its ligands, since mice lacking ADAM17 [18] resemble mice lacking TGF α [15], HB-EGF [10,11] or amphiregulin [14], or the EGFR [17,24,27]. It will now be interesting to evaluate the phenotype of animals lacking epigen in relation to *egfr*^{-/-} or *adam17*^{-/-} animals as epigen is widely expressed in the embryo in a variety of developing structures [12,25]. Moreover, whereas previous studies have demonstrated that ADAM17 is stimulated by phorbol esters such as PMA, and by the phosphatase inhibitor pervanadate [4,21,30], this study is the first, to our knowledge, to demonstrate that ADAM17 also responds to calcium influx, since ionomycin induced shedding of epigen is abolished in the absence of ADAM17.

In summary, this study shows that ectodomain shedding of the recently identified EGFR ligand, epigen, is mediated by ADAM17. Identification of the epigen sheddase may have important implications for cancer treatment since soluble epigen, like other EGFR ligands, induces cell proliferation and migration, two major processes that are dysregulated in tumor cells. Since ectodomain shedding of EGFR-ligands is critical for their functional activation, the identification of ADAM17 as major sheddase of epigen further expands the potential of ADAM17 as a novel anti-cancer drug target.

Acknowledgements: We thank Drs. Roy Black and Jacques Peschon for providing *Adam17*^{-/-} E2 cells and Drs. David Becherer and Andreas Ludwig for providing the hydroxamate inhibitors GI254023X (GI), GW280264X (GW), and batimastat (BB94). This study was supported by NIH R01 grant GM64750 to Carl P. Blobel.

References

- [1] Arribas, J., Bech-Serra, J.J. and Santiago-Josefat, B. (2006) ADAMs, cell migration and cancer. *Cancer Metastasis Rev.* 25 (1), 57–68.

- [2] Blobel, C.P. (2005) ADAMs: key players in EGFR-signaling, development and disease. *Nat. Rev. Mol. Cell Biol.* 6, 32–43.
- [3] Borrell-Pages, M., Rojo, F., Albanell, J., Baselga, J. and Arribas, J. (2003) TACE is required for the activation of the EGFR by TGF- α in tumors. *EMBO J.* 22 (5), 1114–1124.
- [4] Doedens, J.R. and Black, R.A. (2000) Stimulation-induced down-regulation of tumor necrosis factor- α converting enzyme. *J. Biol. Chem.* 275 (19), 14598–14607.
- [5] Gschwind, A., Fischer, O.M. and Ullrich, A. (2004) The discovery of receptor tyrosine kinases: targets for cancer therapy. *Nat. Rev. Cancer* 4 (5), 361–370.
- [6] Harris, R.C., Chung, E. and Coffey, R.J. (2003) EGF receptor ligands. *Exp. Cell Res.* 284 (1), 2–13.
- [7] Horiuchi, K., Le Gall, S., Schulze, M., Yamaguchi, T., Reiss, K., Murphy, G., Toyama, Y., Hartmann, D., Saftig, P., and Blobel, C. (2006). Substrate selectivity and regulation of EGF-receptor ligand sheddases by phorbol esters and calcium influx. *Mol. Biol. Cell.*, in press.
- [8] Hundhausen, C., Misztela, D., Berkhout, T.A., Broadway, N., Saftig, P., Reiss, K., Hartmann, D., Fahrenholz, F., Postina, R., Matthews, V., Kallen, K.J., Rose-John, S. and Ludwig, A. (2003) The disintegrin-like metalloproteinase ADAM10 is involved in constitutive cleavage of CX3CL1 (fractalkine) and regulates CX3CL1-mediated cell-cell adhesion. *Blood* 102 (4), 1186–1195.
- [9] Hynes, N.E. and Schlange, T. (2006) Targeting ADAMs and ERBBs in lung cancer. *Cancer Cell* 10 (1), 7–11.
- [10] Iwamoto, R., Yamazaki, S., Asakura, M., Takashima, S., Hasuwa, H., Miyado, K., Adachi, S., Kitakaze, M., Hashimoto, K., Raab, G., Nanba, D., Higashiyama, S., Hori, M., Klagsbrun, M. and Mekada, E. (2003) Heparin-binding EGF-like growth factor and ErbB signaling is essential for heart function. *Proc. Natl. Acad. Sci. USA* 100 (6), 3221–3226.
- [11] Jackson, L.F., Qiu, T.H., Sunnarborg, S.W., Chang, A., Zhang, C., Patterson, C. and Lee, D.C. (2003) Defective valvulogenesis in HB-EGF and TACE-null mice is associated with aberrant BMP signaling. *EMBO J.* 22 (11), 2704–2716.
- [12] Kochupurakkal, B.S., Harari, D., Di-Segni, A., Maik-Rachline, G., Lyass, L., Gur, G., Kerber, G., Citri, A., Lavi, S., Eilam, R., Chalifa-Caspi, V., Eshhar, Z., Pikarsky, E., Pinkas-Kramarski, R., Bacus, S.S. and Yarden, Y. (2005) Epigen, the last ligand of ErbB receptors, reveals intricate relationships between affinity and mitogenicity. *J. Biol. Chem.* 280 (9), 8503–8512.
- [13] Ludwig, A., Hundhausen, C., Lambert, M.H., Broadway, N., Andrews, R.C., Bickett, D.M., Leesnitzer, M.A. and Becherer, J.D. (2005) Metalloproteinase inhibitors for the disintegrin-like metalloproteinases ADAM10 and ADAM17 that differentially block constitutive and phorbol ester-inducible shedding of cell surface molecules. *Comb. Chem. High Throughput Screen* 8 (2), 161–171.
- [14] Luetke, N.C., Qiu, T.H., Fenton, S.E., Troyer, K.L., Riedel, R.F., Chang, A. and Lee, D.C. (1999) Targeted inactivation of the EGF and amphiregulin genes reveals distinct roles for EGF receptor ligands in mouse mammary gland development. *Development* 126 (12), 2739–2750.
- [15] Mann, G.B., Fowler, K.J., Gabriel, A., Nice, E.C., Williams, R.L. and Dunn, A.R. (1993) Mice with a null mutation of the TGF α gene have abnormal skin architecture, wavy hair, and curly whiskers and often develop corneal inflammation. *Cell* 73 (2), 249–261.
- [16] Merlos-Suarez, A., Ruiz-Paz, S., Baselga, J. and Arribas, J. (2001) Metalloprotease-dependent protransforming growth factor- α ectodomain shedding in the absence of tumor necrosis factor- α -converting enzyme. *J. Biol. Chem.* 276 (51), 48510–48517.
- [17] Miettinen, P.J., Berger, J.E., Meneses, J., Phung, Y., Pedersen, R.A., Werb, Z. and Derynck, R. (1995) Epithelial immaturity and multiorgan failure in mice lacking epidermal growth factor receptor. *Nature* 376 (6538), 337–341.
- [18] Peschon, J.J., Slack, J.L., Reddy, P., Stocking, K.L., Sunnarborg, S.W., Lee, D.C., Russel, W.E., Castner, B.J., Johnson, R.S., Fitzner, J.N., Boyce, R.W., Nelson, N., Kozlosky, C.J., Wolfson, M.F., Rauch, C.T., Cerretti, D.P., Paxton, R.J., March, C.J. and Black, R.A. (1998) An essential role for ectodomain shedding in mammalian development. *Science* 282, 1281–1284.
- [19] Reddy, P., Slack, J.L., Davis, R., Cerretti, D.P., Kozlosky, C.J., Blanton, R.A., Shows, D., Peschon, J.J. and Black, R.A. (2000) Functional analysis of the domain structure of tumor necrosis factor- α converting enzyme. *J. Biol. Chem.* 275 (19), 14608–14614.
- [20] Sahin, U., Weskamp, G., Zheng, Y., Chesneau, V., Horiuchi, K. and Blobel, C.P. (2006) A sensitive method to monitor ectodomain shedding of ligands of the epidermal growth factor receptor (Patel, T.B., Ed.), *Epidermal Growth Factor: Methods and Protocols*, Vol. 327, pp. 99–113, Humana Press Inc., Totowa, NJ.
- [21] Sahin, U., Weskamp, G., Zhou, H.M., Higashiyama, S., Peschon, J.J., Hartmann, D., Saftig, P. and Blobel, C.P. (2004) Distinct roles for ADAM10 and ADAM17 in ectodomain shedding of six EGFR-ligands. *J. Cell Biol.* 164, 769–779.
- [22] Sanderson, M.P., Erickson, S.N., Gough, P.J., Garton, K.J., Wille, P.T., Raines, E.W., Dunbar, A.J. and Dempsey, P.J. (2005) ADAM10 mediates ectodomain shedding of the betacellulin precursor activated by *p*-aminophenylmercuric acetate and extracellular calcium influx. *J. Biol. Chem.* 280 (3), 1826–1837.
- [23] Schlessinger, J. (2002) Ligand-induced, receptor-mediated dimerization and activation of EGF receptor. *Cell* 110 (6), 669–672.
- [24] Sibilina, M. and Wagner, E.F. (1995) Strain-dependent epithelial defects in mice lacking the EGF receptor. *Science* 269 (5221), 234–238, [published erratum appears in *Science* 1995 August 18;269(5226):909].
- [25] Strachan, L., Murison, J.G., Prestidge, R.L., Sleeman, M.A., Watson, J.D. and Kumble, K.D. (2001) Cloning and biological activity of epigen, a novel member of the epidermal growth factor superfamily. *J. Biol. Chem.* 276 (21), 18265–18271.
- [26] Sunnarborg, S.W., Hinkle, C.L., Stevenson, M., Russell, W.E., Raska, C.S., Peschon, J.J., Castner, B.J., Gerhart, M.J., Paxton, R.J., Black, R.A. and Lee, D.C. (2002) Tumor necrosis factor- α converting enzyme (TACE) regulates epidermal growth factor receptor ligand availability. *J. Biol. Chem.* 277 (15), 12838–12845.
- [27] Threadgill, D.W., Dlugosz, A.A., Hansen, L.A., Tennenbaum, T., Lichti, U., Yee, D., LaMantia, C., Mourton, T., Herrup, K. and Harris, R.C., et al. (1995) Targeted disruption of mouse EGF receptor: effect of genetic background on mutant phenotype. *Science* 269 (5221), 230–234.
- [28] Weskamp, G., Cai, H., Brodie, T.A., Higashiyama, S., Manova, K., Ludwig, T. and Blobel, C.P. (2002) Mice lacking the metalloprotease-disintegrin MDC9 (ADAM9) have no evident major abnormalities during development or adult life. *Mol. Cell Biol.* 22 (5), 1537–1544.
- [29] Yarden, Y. and Sliwkowski, M.X. (2001) Untangling the ErbB signalling network. *Nat. Rev. Mol. Cell Biol.* 2 (2), 127–137.
- [30] Zheng, Y., Saftig, P., Hartmann, D. and Blobel, C. (2004) Evaluation of the contribution of different ADAMs to TNF α shedding and of the function of the TNF α ectodomain in ensuring selective stimulated shedding by the TNF α convertase (TACE/ADAM17). *J. Biol. Chem.* 279, 42898–42906.
- [31] Zhou, B.B., Peyton, M., He, B., Liu, C., Girard, L., Caudler, E., Lo, Y., Baribaud, F., Mikami, I., Reguart, N., Yang, G., Li, Y., Yao, W., Vaddi, K., Gazdar, A.F., Friedman, S.M., Jablons, D.M., Newton, R.C., Fridman, J.S., Minna, J.D. and Scherle, P.A. (2006) Targeting ADAM-mediated ligand cleavage to inhibit HER3 and EGFR pathways in non-small cell lung cancer. *Cancer Cell* 10 (1), 39–50.