Estrogens and Human Papilloma Virus Oncogenes Regulate Human Ether-à-go-go-1 Potassium Channel Expression

Lorenza Díaz,1 Irais Ceja-Ochoa,3 Iván Restrepo-Angulo,4 Fernando Larrea,1 Euclides Avila-Chávez,1 Rocio García-Becerra,1 Elizabeth Borja-Cacho,1 David Barrera,1 Elías Ahumada, Patricio Gariglio,5 Elizabeth Álvarez-Rios,3 Rodolfo Ocadiz-Delgado,1 Enrique García-Villa,3 Elizabeth Hernández-Gallegos,4 Ignacio Camacho-Arroyo,6 Angélica Morales,1 David Ordaz-Rosado,1 Ethel García-Latorre,3 Juan Escamilla,1 Luz Carmen Sánchez-Peña,4 Milena Saqui-Salces,28 Armando Gamboa-Dominguez,2 Eunice Vera,4 Marisela Uribe-Ramírez,4 Janet Murbartíñ,4 Cindy Sharon Ortiz,4 Claudia Rivera-Guevara,4 Andrea De Vizcaya-Ruiz,6 and Javier Camacho1

1Departamento de Biología de la Reproducción and 2Departamento de Patología, Instituto Nacional de Ciencias Médicas y Nutrición Salvador Zubirán; 3Departamento de Inmunología, Escuela Nacional de Ciencias Biológicas, Instituto Politécnico Nacional; Pharmacology Section, Department of Genetics and Molecular Biology, and 4Toxicology Section, Centro de Investigación y de Estudios Avanzados del I.P.N., Pharmacology Section, Avenida Instituto Politécnico Nacional 2508, Mexico D.F., Mexico 07360. Phone: 52-55-57473800, ext. 5416; Fax: 52-55-53430106; E-mail: fcmacho@cinvestav.mx.

Abstract
Ether-à-go-go-1 (Eag1) potassium channels are potential tools for detection and therapy of numerous cancers. Here, we show human Eag1 (hEag1) regulation by cancer-associated factors. We studied hEag1 gene expression and its regulation by estradiol, antiestrogens, and human papillomavirus (HPV) oncogenes (E6/E7). Primary cultures from normal placentas and cervical cancer tissues; tumor cell lines from cervix, chorioncarcinoma, keratinocytes, and lung; and normal cell lines from vascular endothelium, keratinocytes, and lung were used. Reverse transcription-PCR (RT-PCR) experiments and Southern blot analysis showed Eag1 expression in all of the cancer cell types, normal trophoblasts, and vascular endothelium, in contrast to normal keratinocytes and lung cells. Estradiol and antiestrogens regulated Eag1 in a cell type–dependent manner. Real-time RT-PCR experiments in HeLa cells showed that Eag1 estrogenic regulation was strongly associated with the expression of estrogen receptor-α. Eag1 protein was detected by monoclonal antibodies in normal placenta and placental blood vessels. Patch-clamp recordings in normal trophoblasts treated with estradiol exhibited potassium currents resembling Eag1 channel activity. Eag1 gene expression in keratinocytes depended either on cellular immortalization or the presence of HPV oncogenes. Eag1 protein was found in keratinocytes transfected with E6/E7 HPV oncogenes. Cell proliferation of E6/E7 keratinocytes was decreased by Eag1 antibodies inhibiting channel activity and by the nonspecific Eag1 inhibitors imipramine and astemizole; the latter also increased apoptosis. Our results propose novel oncogenic mechanisms of estrogen/antiestrogen use and HPV infection. We also suggest Eag1 as an early indicator of cell proliferation leading to malignancies and a therapeutic target at early stages of cellular hyperproliferation. [Cancer Res 2009;69(8):3300–7]

Introduction
Ether à-go-go (EAG) potassium channels possess oncogenic properties (1); human Eag1 (hEag1) mRNA shows restricted distribution in healthy tissues expressed mainly in brain; slightly in placenta, testis, and adrenal gland; and transiently in myoblasts (1–3). Interestingly, Eag1 is abundantly expressed in tumor cells, including cervical, lung, breast, colon, and prostate cancer (2, 4); therefore, Eag1 is suggested as a cancer marker. In addition, an association of Eag1 amplification with reduced overall survival has been observed in patients with colon carcinoma (5). Inhibition of Eag1 gene expression decreases tumor cell proliferation (1, 6, 7), and inhibition of Eag1 channel activity by imipramine or astemizole has been suggested to decrease cancer cell proliferation (6–8). Specific block of Eag1 with monoclonal antibodies inhibits tumor cell growth both in vitro and in vivo (9). Thus, Eag1 is also suggested as a cancer therapeutic target. Because no obvious side effects were observed in the animals treated with monoclonal antibodies (9), the potential therapeutic value of Eag1 channels seems to be very high.

High-risk human papillomavirus (HR-HPV) is the major risk factor for cervical cancer (10), and estrogen use is suggested as a likely factor contributing to this cancer (11). Actually, estrogen receptors (ER) or aromatase enzymes provide advantages for proliferation of tumor cells derived from mammary gland, lung, and cervix (12, 13). Nevertheless, tamoxifen stimulates proliferation of some cancer cells (14–16).

We reported Eag1 expression in normal cervical samples from women with negative pap smears, including a patient with HPV infection (4). In addition, Eag1 mRNA was detected in the tumor-free mammary gland surrounding the breast carcinoma tissue (2), in human diverticulitis (which has the potential to change into colonic cancer), and in crypt cells of a colon cancer mouse model (5). These observations suggest Eag1 expression as an early sign of cellular hyperproliferation.

Despite the potential clinical relevance of Eag1, its regulation by cancer etiologic factors is poorly understood. Here, we studied hEag1 expression and regulation by some cancer-associated factors, namely, estrogens, antiestrogens, and HPV oncogenes in normal and tumor cells. We studied cervical cancer cells obtained from primary cultures and cell lines from different histogeneses.
“La Raza,” following the local ethical considerations. Tissue was placed in liquid nitrogen to obtain mRNA or fixed in paraformaldehyde for immunohistochemistry. For cytotrophoblast culturing, tissue was washed with saline solution and immediately processed. Neonatal foreskins from patients registered at Hospital “Gabriel Mancera” were collected following the local ethical considerations and used to obtain normal keratinocytes primary cultures.

Cell culture and reagents. Cytotrophoblasts were isolated and cultured as described (18, 19). Villous tissue was enzymatically dispersed; cytotrophoblasts were separated on a Percoll gradient, plated in DMEM-HG with 20% fetal bovine serum (FBS) and incubated at 37°C (95% humidity and 5% CO2 atmosphere). Human choriogenic gonadotrophin hormone (hCG) concentration was measured with an immunoassay kit (Immunometrics Ltd.). Human cervical cancer cells were obtained from previously established primary cultures (4). Tumor cell lines (HeLa, SiHa, CaSki, INBL, and C33A from cervix; JEG-3 and A-549 from choriocarcinoma and lung, respectively), as well as bronchial epithelial cells (BEAS) and human umbilical vascular endothelial cells (HUVEC) from normal lung and umbilical cord, respectively, were obtained from American Type Culture Collection and cultured according to manufacturer’s instructions. Cell treatments were performed, as follows, to avoid participation of exogenous estrogens present in serum or medium: cells were washed with HBSS 24 h after plating and incubated in supplemented medium (DMEM-HG without phenol red plus 5% charcoal-stripped FBS and antibiotics). Cells were incubated with 17β-estradiol (Sigma Chemical Co.) and/or the antiestrogens ICI 182,780 (Zeneca Pharmaceuticals) or 4-hydroxy-tamoxifen (Sigma Chemical Co.) during 24 h; ethanol was used as vehicle, and incubations were stopped by aspirating the culture media and adding Trizol reagent (Invitrogen) for RNA extraction. Normal keratinocytes were prepared from neonatal foreskins and grown in the keratinocyte serum-free medium (Invitrogen) supplemented with 20 mg/mL bovine pituitary extract and 0.1 ng/mL of epidermal growth factor (Invitrogen); transformed human keratinocytes (HaCat cells) provided by Dr. Lutz Gissmann [German Cancer Research Center (DKFZ)] were cultured in the same medium. Primary human keratinocytes immortalized by amphotrophic retroviruses encoding E6, E7, or E6/E7 oncoproteins of HPV-16 (provided by Dr. Frank Rösl, DKFZ) were grown in a keratinocyte growth medium (Invitrogen) and cultured as described (20).

Transient human Erα transfection and ER Western blot. Expression vector for human ER-α (pCMV-α-hERα) to transfect HeLa cells was provided by Dr. A.J. Cooney (Baylor College of Medicine). Cells were transfected using PolyFect (Qiagen, Inc.) as described (21). Transcriptional activity of transfected ERα was confirmed by a chloramphenicol acetyltransferase (CAT) reporter assay (21). Western blots were performed to detect ERα in HeLa, A-549, BEAS, and cervical cancer cells with the primary antibody anti-ERα (Santa Cruz). HeLa cells expressing ERα (HeLa-ERα) were subjected to the same treatments as described above.

PCR amplifications and Southern blot analysis. Total RNA was isolated from tissues and cell cultures with Trizol reagent. PCR was reversed transcribed, and PCR amplifications were performed with the following primers: 5′-GCTTTTGAACGCTGAGTGCAGGAG-3′ and 5′-CGAAAGTGGTGCCATAGAGGACAG-3′, which yielded 475-bp hEag1 reverse transcription-PCR (RT-PCR) products. In some cases, Eag amplification was performed by using the following sense and antisense primers: 5′-TGGTCTCTGCTTGTGATGGAGGACAG-3′ and 5′-AACGAGGAGATGATGACAGGACAG-3′. These amplifications yielded a 187-bp hEag1 product. Human Eag1-transfected Chinese hamster ovary (CHO) cells (provided by Walter Stühmer, Max-Planck-Institut für Experimentelle Medizin) were used as positive control. Cyclophilin and β2-microglobulin genes were used as constitutive genes and amplified with the following primers: 5′-CCCACCACGCGTGGCACAATGATGATGAGGACAG-3′ and 5′-AACGAGGAGATGATGACAGGACAG-3′ for cyclophilin yielding a 453-bp product and 5′-ACCCACCACGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGAGA
as previously described and also confirmed by sequence (4). In all cases, filters were washed after 18 h of hybridization and exposed to X-ray films.

**Real-time PCR amplifications.** SYBR Green real-time PCR was performed with 1 μl of cDNA obtained as described above. SYBR Green reaction was conducted using a QuantiTect SYBR Green PCR reagents kit (Qiagen) following the manufacturer's instructions. The following primers were used: 5′-TGT CTC TGC TGG TGT GTG-3′ (forward), 5′-ACA ACG AGG AGA TGT AGA CAG-5′ (reverse) for Eag1 (4) and 5′-ACC CCC ACT GAA AAA GAT GAG TAT-3′ (forward), 5′-ATG ATG CTG TTCA TGT CTC GAT-3′ (reverse) for β2-microglobulin (used as constitutive gene and to analyze relative Eag1 expression). Data analysis was performed by the 2−ΔΔCt method.

**Eag1 immunochemistry.** Specific anti-Eag1 antibodies were kindly provided by Walter Stühmer and Luis Pardo (Max Planck Institute). This antibody has been validated and shown to be very specific; it does not bind to hErg channels and discriminates between Eag1 and Eag2 (9). With this antibody, we already reported Eag1 channel expression in human cervical biopsies, cervical cancer cells from primary cultures, and CHO cells transfected with Eag1 in opposite to the absence of Eag1 in nontransfected CHO cells (4). Placental biopsies were fixed in a buffered ethanol. After washing with TBS/Tween (pH 7.4), slides were immersed in EDTA buffer [0.01 mol/L (pH 8.0)] and boiled for antigen retrieval. Slides were blocked for 2 h with levamisole and incubated in the presence of 1:50 anti-Eag1 antibody (6b001 single-chain antibody coupled with alkaline phosphatase) for 2 h at room temperature. The slides were washed with TBS/Tween, and the specific staining reaction was completed by incubating the slides in the presence of 5-bromo-4-chloro-3-indolyl phosphate/nitroblue tetrazolium (Boehr) in a buffer solution for 1 h at room temperature, protected from light, and observed as a dark blue-violet staining. Sections were counterstained with eosin. Slides were observed with a Nikon Eclipse E600 microscope using a Nikon Plan Apo 10×/0.45 objective lens. Images were acquired with a DMI1200 camera and the Nikon ACT-1 acquisition software at room temperature. Keratinocytes expressing HPV oncoproteins (K-E6, K-E6/E7) were processed in a very similar manner. After antigen retrieval with EDTA, slides were blocked with endogenous peroxidase and phosphatase blocker (Dako) for 10 min and then incubated in the presence of 1:100 anti-Eag1 antibody for 1 h at room temperature. The slides were then incubated with MACH 4 mouse probe (Biocare) in TBS/Tween for 10 min and then incubated with MACH 4 horseradish peroxidase polymer (Biocare) in TBS/Tween for 10 min. The specific staining reaction was completed by incubating the slides in the presence of diaminobencidine in buffer reaction solution (Dako) and observed as a brown staining. Sections were counterstained with hematoxylin (Dako), observed with a Nikon Eclipse E600 microscope using a Nikon Plan Apo 40×/0.45 objective lens, and analyzed as above described for the placental sections.

![Figure 2](image)

**Figure 2.** Eag1 regulation by E2 in cultured human syncytiotrophoblast and vascular endothelial cells. Southern blot analysis from RT-PCR experiments shows that E2 induced Eag1 mRNA expression in syncytiotrophoblasts with no detectable basal Eag1 expression (A) and antiestrogenic treatment with ICI 182,780 (ICI) prevented such up-regulation and decreased Eag1 levels in a syncytiotrophoblast primary culture with basal Eag1 expression (B). Eag1 is endogenously expressed in HUVEC and up-regulated by E2, and antiestrogenic treatment prevented such up-regulation (C) as in trophoblasts. Columns, Eag1 mRNA relative expression after normalization with cyclophilin (A–C); Eag1 expression in vehicle given the value of 1 in B and C. D, whole-cell patch-clamp experiments showed outward potassium currents in syncytiotrophoblasts treated with E2 (top) and untreated choriocarcinoma JEG-3 cells (bottom). Currents elicited at +60 mV were preceded by negative prepulses (−140 or −60 mV) and displayed different activation kinetics, suggesting Eag1 channel activity. Eh = −80 mV, unsubtracted traces. Figures are representative of at least three separate experiments.
Mannheim GmbH]. Cells were incubated during 96 h in culture medium
2,5-diphenyltetrazolium bromide (MTT) cell proliferation kit I, Boehringer
dehydrogenase activity inactivates mitochondria [3-(4,5-dimethylthiazol-2-yl)-
on the conversion of the tetrazolium salts to formazan crystals by
plates, and cell proliferation was assayed by the colorimetric method based
performed at room temperature (20–22
Eag1 channels in normal human placenta and vascular
endothelium, especially in the nucleus (Fig. 1A, dark blue-violet staining). Interestingly, we also observed Eag1 channels
in the vascular endothelium, especially in the nucleus (Fig. 1A). Whereas Eag1 protein expression pattern was very similar among
placentas, relative Eag1 mRNA levels were very different. Figure 1B
shows some placentas with low Eag1 mRNA expression and some
with higher levels. Despite such differences in mRNA levels, we
observed both Eag1 protein and mRNA expression in all of the
placentas studied.

Unexpectedly, Eag1 mRNA was not detected in most of the
trophoblasts primary cultures but was induced by estradiol. Figure 2A
shows Eag1 mRNA up-regulation by E2 at picomolar concentrations
whereas a higher E2 concentration originated only a faint Eag1 signal. The antiestrogen ICI 182,780 prevented
such up-regulation. In cultures displaying endogenous Eag1
mRNA (Fig. 2B), E2 induced a slight increase in Eag1 expression
and antiestrogen treatment down-regulated endogenous Eag1
expression both in the presence and absence of E2 (Fig. 2B). As
expected, we also found endogenous Eag1 expression in the
placental choriocarcinoma cell line JEG-3; however, in this case, we
did not find a significant estrogenic regulation (data not shown).
Eag1 channel expression in vascular endothelium prompted us to
study Eag1 mRNA expression and regulation by estradiol in
endothelial cells. Endogenous Eag1 mRNA was found in normal
HUVECs supplemented with 10% FBS (Fig. 2C). Eag1 was up-
regulated by E2; this effect was inhibited by ICI 182,780, which also
down-regulated endogenous Eag1 levels (Fig. 2C). The effect of
estrogens and antiestrogens on Eag1 expression was very similar in
both normal cell types (trophoblasts and vascular endothelium).

Endogenous Eag1 channel activity has not been reported for
most of the normal tissues where it is expressed, including the
brain. Therefore, we investigated if Eag1 channel activity could be
recorded in placental-derived cells. Whole-cell patch-clamp record-
ings showed no outward voltage-activated potassium currents in
trophoblast primary cultures in the absence of E2 (data not shown).
However, when incubated with E2 (1 pmol/L), normal human
trophoblasts displayed noninactivating outward currents resem-
bling Eag1 channel activity (Fig. 2D, top). Eag1 channels display a
strong Cole-Moore shift (the current elicited with a depolarizing
pulse is slower at a more negative prepulse voltage) and a very slow

**Electrophysiology.** Whole-cell recordings were acquired from isolated
cells with the patch-clamp technique (22) using an EPC-9 amplifier
(HEKA Electronics) and analyzed with Igor Pro (WaveMetrics). Patch
pipettes (2–3 M

**Metabolic activity and apoptosis.** K-E6/E7 cells were seeded in 96-well
plates, and cell proliferation was assayed by the colorimetric method based
on the conversion of the tetrazolium salts to formazan crystals by
dehydrogenase activity in active mitochondria [3-(4,5-dimethylthiazol-2-yl)-
2,5-diphenyltetrazolium bromide (MTT) cell proliferation kit I, Boehringer
Mannheim GmbH]. Cells were incubated during 96 h in culture medium
alone or in the presence of astemizole (10 μM). MTT (5 mg/mL) and 10 μmol/L
DMSO as vehicle (all of these reagents were purchased from Sigma
Chemical Co.), or the anti-Eag1 monoclonal antibody 56 (133 nmol/L, also
provided by Walter Stühmer and Luis Pardo) known to inhibit Eag1 channel
activity (9). MTT (0.5 mg/mL) was added 4 h before completing the whole
incubation time. Absorbance data were obtained from the resulting colored
solution with a microplate photometer (Sunrise Touchscreen). Apoptosis was
determined with the Annexin V-FITC kit (Invitrogen Co.) binding to
phosphatidylserine and DNA staining by propidium iodide (PI). Campto-
thein (apoptosis inducer) and methanol (necrosis inducer) were used as
controls. Experiments were carried out with the flow cytometer FACS-SYAN
ADP with nine colors (DAKO). Percentages of viable (FITC and PI negative),
apoptotic (FITC positive and PI negative), and late apoptotic (FITC and PI
positive) cells were obtained by quadrant analysis using WinDMI software
version 2.8.

**Statistical analysis.** Student’s t-test or ANOVA, followed by Dunnett’s or
Tukey-Kramer test, was used to compare data between different groups;
P values of <0.05 or <0.01 for the respective tests were considered to be
statistically significant. Analysis was made using GraphPad Prism software
version 3.0.

**Results**

**Regulation of Eag1 by Estradiol in Normal and Tumor Cells**

Eag1 channels in normal human placenta and vascular
endothelium and their regulation by estradiol. We investigated
Eag1 protein expression in normal human placenta and studied the
likely regulation of Eag1 gene expression by 17β-estradiol (E2) in
primary cultures from normal human trophoblasts. Eag1 channels
were strongly expressed in the syncytiotrophoblast layer in both
the cytoplasm and the nucleus in normal placenta (Fig. 1A, dark blue-violet staining). Interestingly, we also observed Eag1 channels
in the vascular endothelium, especially in the nucleus (Fig. 1A). Whereas Eag1 protein expression pattern was very similar among
placentas, relative Eag1 mRNA levels were very different. Figure 1B
shows some placentas with low Eag1 mRNA expression and some
with higher levels. Despite such differences in mRNA levels, we
observed both Eag1 protein and mRNA expression in all of the
placentas studied.

However, when incubated with E2 (1 pmol/L), normal human
trophoblast primary cultures in the absence of E2 (data not shown).
These trophoblasts displayed noninactivating outward currents resem-
bling Eag1 channel activity (Fig. 2D, top). Eag1 channels display a
strong Cole-Moore shift (the current elicited with a depolarizing
pulse is slower at a more negative prepulse voltage) and a very slow

![Figure 3. Estrogenic regulation of Eag1 expression in HeLa cells and participation of ERα.](https://example.com/figure3.png)

**Figure 3.** Estrogenic regulation of Eag1 expression in HeLa cells and participation of ERα. A, real-time RT-PCR experiments show that wild-type HeLa
cells display endogenous Eag1 expression (as previously reported in ref. 1), but
E2 up-regulates Eag1 expression at some concentrations without the effect of
antiestrogens. However, when HeLa cells were forced to express ERα, Eag1
was strongly up-regulated by both E2 and antiestrogens (B). Columns, mean;
age, SD. *, P < 0.05 compared with control (no E2 treatment).

**Potassium Channels and Cancer Risk Factors**
activation in the presence of extracellular magnesium (23). Figure 2D shows that outward currents elicited at +60 mV are slower when preceded by a very negative prepulse (−140 mV) compared with a more positive prepulse (−60 mV), recordings were obtained in the presence of 10 mmol/L MgCl₂. Because no other potassium channels have been reported to display such a strong Cole-Moore shift, our data suggest Eag1 channel activity in normal human trophoblasts incubated with E₂. Similar currents were elicited in the choriocarcinoma JEG-3 cells in the absence of estradiol (Fig. 2D, bottom), although, in this case, the current was not that accelerated with a more positive prepulse, as in normal human trophoblasts, despite of a lower MgCl₂ concentration (2 mmol/L) used.

**Eag1 regulation in cancer cells and the participation of Eₐrx.** We studied estrogenic regulation of Eag1 in HeLa cells by real-time RT-PCR. We found Eag1 regulation by E₂ only at two-hormone concentrations (Fig. 3A) with no effect of the antiestrogens in these HeLa wild-type cells (Fig. 3A). ER-α mRNA expression in these cells was detected by RT-PCR; however, Western blot experiments failed to show the presence of ERα or ERβ (data not shown). Therefore, we transfected these cells with human ERα (HeLa-ERα cells) and studied again Eag1 regulation by E₂, ER-α-mediated transcription was confirmed by CAT assays (21) in HeLa-ERα cells cotransfected with a CAT reporter plasmid (data not shown). Figure 3B shows a remarkable Eag1 up-regulation by E₂ in HeLa-ERα cells. ICI 182,780 and tamoxifen, alone or in combination with E₂, produced a very high Eag1 up-regulation (Fig. 3B). These results suggest ERα activation as one of the mechanisms of the estrogenic regulation of Eag1.

Estrogenic regulation was also studied in cervical cancer cells from three human cervical biopsies. Lung cell lines A549 and BEAS-2B from cancer and normal tissue, respectively, were used to study both Eag1 expression and estrogenic regulation in cells from a very common cancer influenced by estrogenic signaling (12) but histogenetically different from placental or cervical tissue. Western blot analysis showed that cervical and lung cells express ERα (data not shown). Cervical cancer cells from primary cultures were previously characterized to express Eag1, HPV, and cytokeratins (4), supporting their cancer epithelial nature. Table 1 shows screening of Eag1 estrogenic regulation in these cells. Effect of E₂ and antiestrogens on Eag1 expression in primary cultures from cervical cancer was similar between two patients (cervical cancer 1 and 2); interestingly, in a sample from another patient (cervical cancer 3), such regulation occurred in the opposite direction in all of the treatments studied. As expected, Southern blot analysis showed the absence of Eag1 gene expression in the normal human lung cells (BEAS-2B). Eag1 was not induced by E₂ or antiestrogens in these cells (data not shown). In contrast, Eag1 was present in the lung cancer cell line A549 and up-regulated with most treatments, especially by antiestrogens (Table 1). Thus, E₂ also regulates Eag1 expression in cancer cells in a cell type–dependent manner. Then, we wondered whether a well-identified etiologic factor for some cancers could also affect Eag1 expression.

**Expression and Potential Role of Eag1 in Cells Expressing HPV Oncogenes**

**Eag1 in cervical cancer cell lines and keratinocytes expressing HPV oncogenes.** We studied hEag1 gene expression in normal keratinocytes and keratinocytes immortalized with the oncogenes E6, E7, or both (K-E6, K-E7, K-E6/E7), as well as in immortalized keratinocytes lacking HPV and cervical cancer cell lines presenting or lacking HR-HPV.

Normal keratinocytes did not express Eag1 (Fig. 4A); however, a prominent Eag1 expression was found in keratinocytes immortalized with HR-HPV oncogenes, with K-E7 showing the highest expression. Eag1 was also found in spontaneously transformed keratinocytes lacking HR-HPV (HaCat cells). These data suggest that Eag1 might be regulated by different oncogenic pathways. In accordance, Eag1 expression was found in cervical cancer cell lines expressing either HPV-16 (CaSkii, SiHa) or HPV-18 (INBL) and in a cell line lacking HPV (C33A).

**Potential role of Eag1 channels in cell proliferation and apoptosis of keratinocytes expressing HPV oncogenes.** Immunocytochemistry experiments showed an important Eag1 channel protein expression in keratinocytes immortalized with HPV oncogenes (Fig. 4B, brown staining). We wondered whether Eag1 channels might have a role in the proliferation and apoptosis of these cells. Cell proliferation (assayed by metabolic activity studies) was decreased in K-E6/E7 cells by astemizole and imipramine, two widely used nonspecific Eag1 inhibitors (Fig. 4C). Specific Eag1 inhibition can be achieved by incubating the cells with the monoclonal Eag1 antibody 56. Because this antibody does not have an effect on hErg channels or even on the more closely Eag1-related protein, namely Eag2 (9), this is a very fine and specific tool to study potential physiologic roles of Eag1 channels. This antibody also decreased metabolic activity of K-E6/E7 cells (Fig. 4C). Astemizole increased K-E6/E7 apoptosis (Fig. 4D).

**Discussion**

Eag1 is a potential tool for cancer detection and therapy (1, 2, 4, 9), and several findings suggest Eag1 as an early marker for breast, cervical, and colon cancer (2, 4, 5).

### Table 1. Relative Eag1/cyclophilin expression in cancer cells treated with E₂ and/or antiestrogens (from Southern blot analysis)

<table>
<thead>
<tr>
<th>Cell type</th>
<th>E₂ (10 nmol/L)</th>
<th>E₂ + ICI 182,780</th>
<th>E₂ + Tx</th>
<th>ICI 182,780 (100 nmol/L)</th>
<th>Tx (100 nmol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cervical (1)</td>
<td>1.42</td>
<td>1.24</td>
<td>0.62</td>
<td>1.44</td>
<td>0.93</td>
</tr>
<tr>
<td>Cervical (2)</td>
<td>1.21</td>
<td>2.95</td>
<td>0.08</td>
<td>1.26</td>
<td>0.95</td>
</tr>
<tr>
<td>Cervical (3)</td>
<td>0.21</td>
<td>0.61</td>
<td>1.11</td>
<td>0.74</td>
<td>1.03</td>
</tr>
<tr>
<td>Lung (A549)</td>
<td>1.59</td>
<td>0.94</td>
<td>1.48</td>
<td>2.83</td>
<td>2.35</td>
</tr>
</tbody>
</table>

NOTE: Relative Eag1/cyclophilin expression, in comparison with vehicle-treated cells which were given an arbitrary value of 1. Abbreviation: Tx, tamoxifen.
Placental development resembles malignant tumor behavior (17). We found Eag1 protein in the syncytiotrophoblast layer and vascular endothelium of placental villi at the plasma membrane, in the cytoplasm, and in the nucleus. This distribution was expected because Eag1 has a bipartite nuclear targeting signal in its carboxy terminus (24) and perinuclear localization of Eag1 channels has been observed in tumors (2, 6). A COOH terminal fragment of a voltage-gated calcium channel translocates to the nucleus and angiogenesis in tumors (29). The effect of other angiogenic factor on Eag1 expression in both normal and cancer cells remains to be elucidated. We show the first recordings suggesting Eag1 channel activity in normal human trophoblasts, but more pharmacologic studies are needed to determine the potential contribution of other potassium channels to the outward currents recorded in placental cells.

Human ERα is necessary for a clear estrogenic regulation of Eag1 gene expression in HeLa cells. Only when forced to express ER-α did estradiol and antiestrogens clearly up-regulated Eag1. Actually, this is a potential explanation for the lack of estrogenic regulation of Eag1 in JEG-3 cells, because these cells express very low amounts of ER-α (30, 31). Thus, concerning ER-α expression, JEG-3 cells could be compared with HeLa wild-type cells not transfected with ER-α.

When screening estrogenic regulation of Eag1 mRNA in cells from cervical cancer primary cultures derived from three patients, we found similar effects in two cases but opposite effects in another. Accordingly, tamoxifen opposite effects have been reported in cervical cancer. Tamoxifen treatment inhibited growth of cervical cancer cell lines, including HeLa cells (32); but in the cervical cancer cell line SFR lacking ERs, tamoxifen stimulated HPV-16 gene expression and cell proliferation (16). Cervical cancer biopsies that Eag1 promotes vascular endothelial growth factor secretion and angiogenesis in tumors (29). The effect of other angiogenic factors on Eag1 expression in both normal and cancer cells remains to be elucidated. We show the first recordings suggesting Eag1 channel activity in normal human trophoblasts, but more pharmacologic studies are needed to determine the potential contribution of other potassium channels to the outward currents recorded in placental cells.

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(16%) from patients treated with tamoxifen had a significant decrease in the number of mitotic figures (33). Thus, the variable estrogenic regulation of Eag1 in cervical cancer primary cultures might have several explanations, including treatment conditions, differences in HPV copy number, and different amounts of ERs or ER phosphorylation; actually, tamoxifen can switch from ERα antagonist to ERα agonist if ERα is phosphorylated (34).

Estrogens stimulate growth and progression of lung tumors (35), and aromatase inhibitors suppress tumor growth in mice with A-549 lung xenografts (12). Eag1 was not found in BEAS-2B cells in accordance with the absence of Eag1 in normal bronchial epithelium (2). We found Eag1 expression in A-549 cells in compliance with the findings in lung cancer biopsies (2); in these cells, almost all treatments up-regulated Eag1. A combined therapy of antiestrogens and epidermal growth factor receptor (EGFR) inhibitor has been suggested for lung cancer (36) because of the functional linkage between estrogens and EGFRs (37). Therefore, Eag1 up-regulation by antiestrogens might be related to the cross-talk between different signal transduction pathways.

Different cervical cancer cell types and keratinocytes expressing HPV oncoproteins displayed Eag1 expression in contrast to normal keratinocytes. HPV oncoproteins E6 and E7 influence cell proliferation by targeting p53 and Rb proteins, respectively (38). The cell lines used present different molecular alterations. HeLa cells overexpress c-Myc and Bcl-2 proteins, SiHa cells have high levels of pRb and BclXL proteins (39), and keratinocytes expressing E7 display high c-Myc levels (20). Eag1 was also found in transformed keratinocytes lacking HPV (HaCat and C33A cells). Interestingly, p53 and Rb are mutated in C33A cells (40) and HaCat cells have two mutations in p53 (41). Probably Eag1 is down-regulated, at least, through p53 and Rb pathways. Because Eag1 was found in cells presenting or lacking HPV, these results suggest that Eag1 gene expression is regulated by different factors, which is in accordance with the Eag1 overexpression observed in very different types of tumors (2, 4–6); our results also offer possible alternative explanations for the oncogenic mechanisms of HPV infection. Eag1 protein was found in K-E6/E7 and K-E6 cells, and Eag1 channel inhibitors affected cell proliferation and apoptosis. Astemizole was more effective than imipramine in inhibiting cell proliferation and increasing apoptosis in keratinocytes expressing HPV oncoproteins. Both drugs have other targets different from Eag1; thus, a plausible explanation is a higher affinity of other proteins participating in cell proliferation/apoptosis to astemizole. One of such proteins might be hERγ channels, which are strongly inhibited by astemizole and have also been suggested to play a role in tumorigenesis (42–43). Further mechanistic studies are required to understand the effect of astemizole on cell proliferation and apoptosis. Nevertheless, despite of some nonspecific effects of imipramine and astemizole that might be involved, the effect of these drugs and the monoclonal Eag1 antibody on proliferation and/or apoptosis suggests Eag1 as a target at early stages of cell hyperproliferation, for example, in cells initially transformed by HPV.

Eag1 channel activity is increased by arachidonic acid in IGRI melanoma cells (46), and insulin-like growth factor-I increases both channel activity and gene expression of Eag1 in MCF-7 breast cancer cells (47). Here, we show for the first time Eag regulation by cancer risk factors in normal cells. A highlighted feature in this study was that Eag1 can be regulated by both estrogens and HPV oncoproteins. Eag1 up-regulation by E2 in HeLa cells and some cervical cancer primary cultures suggest that estrogens and HPV might have a synergistic effect on Eag1 expression. Actually, it has been shown that estrogens contribute to the onset, persistence, and malignant progression of cervical cancer in a HPV-transgenic mouse model (48). A very interesting issue to address is to know the potential participation of Eag1 channels in the mouse cervical cancer model mentioned. Another interesting issue is to investigate the differential concentration-dependent effect of estrogens. Concentration-dependent dual effects of estrogens have been already observed, for example, on growth hormone synthesis and interleukin-induced proteoglycan synthesis (49, 50).

Our experiments unravel novel potential oncogenic mechanisms of estrogen/antiestrogen use and HPV infection. This proposes that Eag1 might be expressed in early stages potentially leading to cervical transformation, for example, in patients infected with HPV or those undergoing estrogen treatment or subjects with low-grade intraepithelial lesions.

The data presented herein suggest Eag1 as an early marker of cellular proliferation leading to malignancies, enhancing potential benefits of using Eag1 in early detection programs. Because cancer is a multifactorial disease, detecting the expression of oncogenic genes or proteins regulated by several cancer risk factors, like Eag1, might lead to improved diagnosis methods and early detection of malignancies. Finally, our pharmacologic experiments propose Eag1 as a therapeutic target at early stages of cell hyperproliferation.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Acknowledgments

References

Estrogens and Human Papilloma Virus Oncogenes Regulate Human Ether-à-go-go-1 Potassium Channel Expression


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