Extracellular AGR3 regulates breast cancer cells migration via Src signaling

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Human anterior gradient proteins AGR2 and AGR3 are overexpressed in a variety of adenocarcinomas and are often secreted in cancer patients' specimens, which suggests a role for AGR proteins in intra and extracellular compartments. Although these proteins exhibit high sequence homology, AGR2 is predominantly described as a pro-oncogene and a potential prognostic biomarker. However, little is known about the function of AGR3. Therefore, the aim of the present study was to investigate the role of AGR3 in breast cancer. The results demonstrated that breast cancer cells secrete AGR3. Furthermore, it was revealed that extracellular AGR3 (eAGR3) regulates tumor cell adhesion and migration. The current study indicated that the pharmacological and genetic perturbation of Src kinase signaling, through treatment with Dasatinib (protein kinase inhibitor) or investigating cells that express a dominant-negative form of Src, significantly abrogated eAGR3-mediated breast cancer cell migration. Therefore, the results indicated that eAGR3 may control tumor cell migration via activation of Src kinases. The results of the present study indicated that eAGR3 may serve as a microenvironmental signaling molecule in tumor-associated processes.

Abstract. Human anterior gradient proteins AGR2 and AGR3 are overexpressed in a variety of adenocarcinomas and are often secreted in cancer patients' specimens, which suggests a role for AGR proteins in intra and extracellular compartments. Although these proteins exhibit high sequence homology, AGR2 is predominantly described as a pro-oncogene and a potential prognostic biomarker. However, little is known about the function of AGR3. Therefore, the aim of the present study was to investigate the role of AGR3 in breast cancer. The results demonstrated that breast cancer cells secrete AGR3. Furthermore, it was revealed that extracellular AGR3 (eAGR3) regulates tumor cell adhesion and migration. The current study indicated that the pharmacological and genetic perturbation of Src kinase signaling, through treatment with Dasatinib (protein kinase inhibitor) or investigating cells that express a dominant-negative form of Src, significantly abrogated eAGR3-mediated breast cancer cell migration. Therefore, the results indicated that eAGR3 may control tumor cell migration via activation of Src kinases. The results of the present study indicated that eAGR3 may serve as a microenvironmental signaling molecule in tumor-associated processes.

Introduction

Anterior gradient protein 3 (AGR3) is a homologue of the pro-oncogenic AGR2. AGR3 and AGR2 share a 71% sequence identity and lie adjacent to one another at chromosomal position 7p21 (1). Functionally, they belong to the protein disulfide isomerases (PDIs) family, which act as endoplasmic reticulum (ER)-resident molecular foldases involved in the maintenance of cellular homeostasis. AGR2 is part of the protein folding machinery within the ER, it is regulated by the ER stress response (2,3) and it is known to be involved in mucin production in intestinal, pulmonary and pancreatic tissues (4-6). Similarly, AGR3 is also an ER resident protein, which is required for the regulation of ciliary beat frequency and mucociliary clearance in the airway epithelium (7). Deregulation of AGR2 and AGR3 proteins expression has been associated with several clinical entities, including cancer. We and others have shown similar expression patterns of AGR2 and AGR3 in non-pathological tissue samples as well as carcinomatous ones, including that of breast, liver and ovary (8-11), which suggests their cognate physiological function and role in pathology. Numerous studies have linked AGR2 with pro-tumoral characteristics that promote cancer aggressiveness and pertain to poor prognoses (12-15). Although AGR2 and AGR3 harbor an ER retention signal sequence (KTEL and QSEL, respectively), they were present in extracellular media such as gastrointestinal mucus, blood or urine (16-19). Intriguingly, we and others have recently demonstrated an emerging role of AGR2 in the maintenance of the tumor microenvironment [including properties of cancer migration (20), invasion (21), chemoresistance (22) and epithelial-to-mesenchymal transition (EMT) (23)], which clearly indicates that extracellular AGR2 (eAGR2) protein assumes a gain-of-function role. AGR3 is a less characterized homologue of AGR2, with similar but apparently not identical function in the regulation of breast cancer cell migration via Src signaling.
of tumor-associated processes (11). So far, AGR3 was shown to interact with dystroglycan-1 (DAG-1) and metastasis-associated C4.4A protein (1), indicating its potential as a driver of metastasis. Moreover, AGR3 mediates cisplatin resistance in xenograft models of ovarian cancer (8). These findings collectively make AGR3 a potential promising target for anti-tumor therapy. Elevated AGR3 expression levels were reported in some cancer types, including breast (19,24,25), liver (9), prostate (26) and ovary (8,27). However, the precise role of AGR3 in tumorigenesis has not been investigated so far. AGR3 was identified among a set of breast cancer-associated membrane proteins (24) and later its presence was reported in sera from breast cancer patients (19). Therefore, in the present work we aim to investigate whether extracellular AGR3 (eAGR3) could have a gain-of-function within the extracellular space to promote cancer aggressiveness.

Materials and methods

Cell lines and culture reagents. Human breast carcinoma cell lines MCF-7, T-47D, BT-474, SK-BR-3 and BT-549 were purchased from American Type Culture Collection (ATCC). All cells were maintained in high glucose Dulbecco's Modified Eagle's medium (DMEM), supplemented with 10% fetal bovine serum (FBS) and 300 µg/ml L-glutamine at 37°C in humidified atmosphere with 5% CO₂. Datasatinib was obtained from Selleckchem, 7-amino-actinomycin D (7-AAD) and Annexin V-PE were from BD Biosciences. To inhibit EsR signaling, 10 nM 17β-estradiol, 1 µM tamoxifen and 0.5 nM fulvestrant (all from Sigma-Aldrich) were used for 24 h.

Purification of recombinant AGR3 protein. The sequence coding for mature AGR3 (NP_789783, amino acids 22-166) was cloned into a vector containing N-terminal His₆-GST tag, cleavable by tobacco etch virus (TEV) protease. Recombinant fusion protein His₆-GST-AGR3 was produced in BL21-CodonPlus (DE3)-RIPL cells (Agilent) according to a protocol described previously (28) with some minor modifications. In order to exclude the potential impact of bacterial endotoxins on cellular signaling (29), purified glutathione S-transferase (His₆-GST) protein served as a control in all the experiments. Briefly, cells were lysed in buffer containing 50 mM HEPES pH 7.4, 150 mM NaCl, 1 mM PMSF, 1 mg/ml lysozyme. His₆-GST-AGR3 fusion protein was captured on a GSTrap glutathione-agarose column (GE Healthcare), eluted with 20 mM glutathione and subjected to TEV protease cleavage. To remove His₆-GST and His₆-TEV, proteins were applied to HisTrap column (GE Healthcare). The purity and appropriate size of AGR3 protein was analyzed by Coomassie blue staining of 10% SDS-PAGE gels (data not shown). For all experiments, purified recombinant AGR3 protein was diluted in DMEM + 10% FBS to a final concentration of 5 ng/ml or 50 ng/ml followed by media filtration.

Collection of conditioned media and western blot analysis. For detection of secreted AGR3, conditioned media were collected after 48 h of cell culture in serum-free DMEM, centrifuged at 13,000 rpm for 10 min, followed by overnight precipitated with cold acetone (at 80% final concentration). For cellular proteins detection, cells were lysed in lysis buffer (50 mM TrisHCl, pH 7.4, 150 mM NaCl, 5 mM EDTA, 50 mM NaF, 1 mM Na₃VO₄, 1% Nonidet P40) containing protease inhibitor cocktail and phosphatase inhibitor cocktail 2 (both Sigma-Aldrich). For detection of tyrosine-phosphorylated proteins, the aforementioned lysis buffer was supplemented with 100 µM sodium orthovanadate (Sigma). The primary antibodies used were as follows: Mouse monoclonal anti-tubulin (Sigma), goat monoclonal anti-actin (Santa Cruz Biotechnology), mouse monoclonal anti-GAPDH (Santa Cruz Biotechnology), in-house mouse monoclonal anti-AGR3 (8,25), Py-Plus™-HRP mouse anti-phosphotyrosine (Invitrogen), rabbit monoclonal anti-c-Src and anti-phospho-c-Src (both Cell Signaling Technology), mouse monoclonal anti-Gapdh (clone 6C5) (Millipore), mouse monoclonal anti-VCP (p97) (BD Biosciences) and rabbit monoclonal anti-EsRalpha antibody (Abcam).

Cell detachment assay. Confluent cells were seeded in the quadruplet on 24-well plates and were incubated with 5 ng/ml and 50 ng/ml eAGR3 protein for 24 h. After, cells were washed with 0.5% EGTA and trypsin was used to detach cells from plate surface (for MCF-7, 0.0025% trypsin for 3 min; for T-47D, 0.125% trypsin for 3 min). The remaining cells were washed with PBS, fixed with 4% paraformaldehyde in PBS and stained with 5 mg/ml crystal violet. Number of attached cells was quantified by absorbance measurement on the microplate reader (Tecan Group Ltd.) at 595 nm.

Wound healing assay. Confluent cells were scraped using a sterile micropipette tip to create an in vitro wound and subsequently incubated in serum-free DMEM with or without eAGR3 as indicated. For SRC family kinases inhibition, cells were additionally treated with 1 µM dasatinib or equivalent concentration of DMSO as control. Alternatively, cells were transfected with wild-type or dominant negative (K298R) Src constructs (30) to further document the impact of Src signaling on eAGR3-induced migration. Transient transfections of MCF-7 cells seeded in 12-well plates (at a density of 4x10⁵ cells/well) were performed using Fugene 6 (Promega) according to the manufacturer’s recommendations using a 1:3 ratio of DNA:Fugene 6 in Opti-MEM (Invitrogen Life Technologies). Time-lapse acquisition of the wound closure was analyzed with Nikon eclipse Ti-E system at 10x magnification. The pictures were captured in three randomly chosen fields within the wounded region every 20 min for 24 h. The migration rate was assessed using TScratch software (31) (CSE Lab, ETH) by quantification of the cell-free area 16 h post-scratching.

Flow cytometry. Cells were treated with tyrosine kinase inhibitor dasatinib ranging from 10 to 0.01 µM for 24 h. Following treatment, cells were washed with PBS 2% FBS and analyzed by flow cytometry using a FACS-Canto II flow cytometer (BD Biosciences). The population of interest was gated according to its FSC/SSC criteria. The dead cell population was determined using 7-amino-actinomycin D (7AAD) and annexin V-PE staining (both BD Biosciences). Data were analyzed using the FACS-Diva (BD Biosciences).

Statistical analyses. Graphs and statistical analyses were done using GraphPad Prism 7.0 software. According to
the experiments, either a student t-test was applied using a two-tailed distribution of two conditions of unequal or equal variances on groups of data obtained in experiments, or an ANOVA following a Tukey's multiple comparisons test was used. P<0.05 was considered to indicate a statistically significant difference.

Results

AGR3 is secreted from breast cancer cells. To test whether AGR3 protein could be found both intracellularly (iAGR3) and extracellularly (eAGR3), we first monitored AGR3 expression levels in cell extracts and in the conditioned media of a set of distinct breast cancer cell lines including MCF-7, T-47D, BT-474, SK-BR-3 and BT-549. We found that iAGR3 protein is expressed only in MCF-7 and T-47D cells (Fig. 1A) and is secreted (eAGR3) in the extracellular milieu by these two cell lines (Fig. 1A-B). We also evaluated the relative concentration of eAGR3 using Western blotting. This was done by comparing the intensity of the immunoreactive bands obtained from purified recombinant AGR3 protein ranging from 50 to 0.05 ng/ml (herein referred to as eAGR3) to that of eAGR3 acetone-precipitated from MCF-7 and T-47D conditioned culture media. We found that in vitro breast cancer cells secrete eAGR3 in nanomolar quantities (Fig. 1B). Therefore, to investigate the biological consequences of eAGR3 secretion, we further used recombinant AGR3 protein at the concentration of 5 and 50 ng/ml. As demonstrated here, AGR3 is only expressed in estrogen receptor (EsR) positive breast cancer cell lines, which is in line with previous works showing the positive correlation between AGR3 and EsR status in breast tumor tissues (1,19,25). As such, we investigated the effect of EsR signaling attenuation on AGR3 expression using the EsR ligands, namely 17β-estradiol, tamoxifen and fulvestrant. As a result, we found that none of the used drugs affected intra- or eAGR3 expression in both cell lines tested, indicating that the EsR pathway does not control AGR3 secretion (Fig. 1C).
Regulates tumor migration and adhesion. Given that the only report pertaining to AGR3 function in cancer links AGR3 with metastasis (1), we investigated whether eAGR3 could regulate cancer cell migration and/or adhesion, one of the key steps required for tumor cell metastasis. Firstly, we studied the effect of eAGR3 on cell migration using a wound healing assay and found a significant increase in migratory properties of both MCF-7 and T-47D upon eAGR3 exposure (5 ng/ml; Fig. 1D). Next, we determined the effect of eAGR3 on cell adhesion using a cell detachment assay. To this end, MCF-7 and T-47D cells were compared for their ability to bind to plastic substratum upon treatment with eAGR3. Both MCF-7 and T-47D cells exposed to low concentrations of trypsin were more prone to stay attached to the substratum when cultivated in the presence of eAGR3 (Fig. 1E). These results demonstrate that eAGR3 plays an extracellular role in regulating, tumor-associated processes, cell-adhesion and migration in breast cancer cells.

Supports cell migration by inducing the phosphorylation of tyrosine kinases. To investigate the intracellular signaling mechanism(s) responsible for eAGR3-dependent migration, we then analyzed protein tyrosine phosphorylation patterns in control MCF-7 cells and cells treated with 5 ng/ml eAGR3 using Western blot with anti-phosphotyrosine antibodies. To enhance the detection of tyrosine-phosphorylated proteins, cells were also treated with 15 µM bpV(phen), an inhibitor of protein phosphotyrosine phosphatases. As shown in Fig. 2, we detected an increase in tyrosine phosphorylation corresponding to proteins with molecular weight of about 65, 80 and 100 kDa. This observation suggested that eAGR3 might induce the tyrosine phosphorylation of a major protein of a molecular weight compatible with the Src family kinases, key actors in cell migration (32). Thus, this result indicated that eAGR3 might possibly act through Src signaling to control cell migration. This hypothesis was further supported by a study showing that AGR2, a pro-tumorigenic homologue of AGR3, impacts on Src signaling, since AGR2 silencing in breast cancer cells resulted in decreased c-Src phosphorylation with no impact on total c-Src levels (33).

Acts through the c-Src signaling pathways. Therefore, to confirm our observation, dasatinib, a tyrosine kinase inhibitor targeting Src kinases, was used and cell migration upon treatment with eAGR3 was analyzed using wound healing assays. Before the analysis, the toxicity of gradient dasatinib concentrations ranging from 10 to 0.01 µM was measured by flow cytometry using Annexin V and 7-amino-actinomycin D (7-AAD) double staining, which confirmed that dasatinib alone does not affect cell survival at any tested concentrations (Fig. 3A). We then investigated the migration rate of T-47D cells stimulated or not with eAGR3 (from 0.5 to 50 ng/ml) and treated or not with 1 µM dasatinib. Cell migration was significantly downregulated upon dasatinib treatment in both control and eAGR3-stimulated cells (Fig. 3B). Western blot analysis also revealed the induction of Src phosphorylation in MCF-7 cells following exposure to eAGR3, which was consistently blocked in dasatinib-treated cells (Fig. 3C). This result confirmed our initial hypothesis that eAGR3 could signal through Src to promote cell migration.

To further demonstrate that eAGR3 exerts its pro-migratory functions on breast cancer cells by activating c-Src signaling, we investigated the effect of eAGR3 on MCF-7 cells over-expressing wild-type (WT) or dominant negative mutant of c-Src protein, namely K298R (Fig. 4A) (34). We found that control (Mock, empty vector) and c-Src WT-overexpressing cells migrated significantly faster towards in vitro wound...
upon treatment with eAGR3 compared to their non-stimulated counterparts (Fig. 4B-C, E). Strikingly, cells transfected with plasmid coding for kinase dead K298R mutant did not respond to eAGR3 and consequently completely lost the migratory advantage of eAGR3 stimulation (Fig. 4D-E). Taken together, these results demonstrate the involvement of c-Src in breast cancer cell migration and support our previous observations that the kinase activity of c-Src is necessary for eAGR3-mediated tumorigenic properties.

Discussion

AGR2 and AGR3 proteins are highly expressed in breast tumors, where their expression levels correlate with estrogen receptor (EsR) positivity and predict patient outcome (1,25,35,36). Accordingly, we found that AGR3 was mainly expressed in the EsR-positive cell lines (MCF-7 and T-47D), while it was absent in EsR-negative (SK-BR-3 or BT-549) cells, suggesting its EsR-dependent regulation.
However, the selective inhibition of EsRα did not affect intra- or eAGR3 levels, indicating a more complex regulation of AGR3 expression in breast cancer, which is not solely dependent on EsR signaling. AGR2 is an emerging drug target in breast cancer as it promotes growth, survival and dissemination of the metastatic cells as well as resistance to treatment by modulating tumor-associated signaling pathways and overcoming ER stress (14). In addition, AGR2 has been shown to be secreted by various cancer cell lines as well as in tumors tissues (17,18,37,38). Follow-up studies indicated that AGR2 can also act ‘from the outside’, as eAGR2, either through binding to membrane receptors or through incorporating within the cytoplasm of target cells (21,22). Despite high similarity between the two homologues- AGR2 and AGR3, there is no reported evidence of eAGR3 extracellular activity. Recent findings have demonstrated a significantly elevated level of eAGR3 in sera from breast cancer patients compared to healthy controls, which is of a diagnostic and prognostic importance (19). However, the biological consequences of eAGR3 secretion remain elusive.

In the current study, we showed for the first time that eAGR3 exerts pro-tumoral functions in breast cancer by impacting on the adhesive and migratory properties of breast cancer cells. These findings further support the hypothesis that AGR3 may be involved in metastatic processes either through a direct interaction with metastasis-related proteins (such as C4.4A protein and DAG-1 (1)) and/or by the induction of pro-metastatic signaling pathways. In line with this, we previously demonstrated that the AGR3 gene may be co-expressed with genes coding for claudin 3 and hepatocyte cell adhesion molecule (HEPACAM) (11), both reported to regulate the metastatic potential of cancer cells (39,40). Herein we uncover that eAGR3 acts through the activation of c-Src signaling pathway and that eAGR3-dependent migration can be inhibited by dasatinib and by dominant negative Src. In addition to EsR and progesterone receptor signaling (25), this is the first...
pro-oncogenic pathway linked to the AGR3 protein. However, since dasatinib did not completely abolish the AGR3-mediated increase in cell migration, it is plausible that collateral signaling pathways are involved in this process. Secreted AGR2 has been recently demonstrated to promote colorectal cancer migration and metastasis through non-canonical Wnt signaling, involving Ca^{2+}/Calmodulin-dependent protein kinase II (CaMKII) and JNK pathways (20). However, whether this is true for extracellular eAGR3 warrants further investigation. Interestingly, the effect of eAGR3 does not seem to be dose-dependent. This might be explained by the fact that high abundance of AGR3 protein might promote formations of homodimers, which, as we recently demonstrated for AGR2, are not secreted and therefore lack extracellular activity (41).

The mechanism of action of extracellular AGR proteins is in general poorly characterized and so far, it is not clear how their signal is transduced within the cells. In line with the existence of a cell surface receptor mediating extracellular AGR proteins signaling both AGR2 and AGR3 are human orthologues of the Xenopus laevis secreted XAG-2 protein (1). XAG-2 participates in frog embryogenesis and amphibian limb regeneration by interacting with the Prod-1 receptor of Ly6 superfamily (42). Although there is no human homologue of Prod-1, AGR2 was shown to interact with another Ly6 receptor family member, C4.4A, which is a GPI-anchored glycoprotein (22). Interestingly, blocking the binding of AGR2 to C4.4A reduced pancreatic tumor growth and metastasis in mice and improved mouse survival. This suggests that secreted AGR2, at least partially, exerts its pro-tumorigenic functions in a receptor-dependent manner. Given a scarce number of reports describing the role of AGR3 in cancer and its high homology with AGR2, we speculate that eAGR3 may act similarly to eAGR2 and therefore could directly bind to surface receptors thereby triggering the activation of the Src pathway. Our hypothesis is also reinforced by the reported link between AGR2 expression and Src phosphorylation in breast cancer (33).

So far, the role of AGR3 in breast cancer biology has been ambiguous, since we and others have reported the opposite effect of elevated AGR3 expression on clinical outcomes (19,25). However, the present work points towards rather pro-oncogenic properties of eAGR3 such as migration and adhesion. This is of particular importance, since AGR2 and AGR3 are co-expressed in breast cancer tissues (25), have been shown to be secreted in breast cancer (19) and as reported here, eAGR3 plays an extracellular function as a signaling molecule in the tumor microenvironment, as we previously described for eAGR2 (23). Therefore, our work highlights the importance of AGR3 function and its prognostic significance in breast cancer.

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Availability of data and materials

The datasets used and/or analyzed during the present study are available from the corresponding author on reasonable request.

Authors’ contributions

JO, LS, MD, TA, FI, DS and DF carried out the experiments and related analyses. RH and SP provided the reagents, designed the experiments and critically revised the manuscript. JO, EC, FD and DF designed the study and wrote the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Patient consent for publication

Not applicable.

Competing interests

The author EC is a founder of Cell Stress Discovery Ltd.

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