Aromatase within the breast

W Yue1, R J Santen1, J-P Wang1, C J Hamilton2 and L M Demers2

1Department of Internal Medicine, University of Virginia School of Medicine, Charlottesville, Virginia 22908, USA
2Department of Pathology, Hershey Medical Center, Pennsylvania State University, Hershey, Pennsylvania 17033, USA

(Requests for offprints should be addressed to W Yue)

Abstract

In situ aromatization and enhanced uptake of estradiol from plasma are two potential mechanisms for maintenance of high concentrations of estradiol found in breast tumors of postmenopausal patients. To test the relative importance of these two mechanisms, a nude mouse model was established by inoculating aromatase (A+) and/or sham (A−) transfected MCF-7 cells into ovariectomized mice. Postmenopausal hormonal status was simulated by providing estradiol Silastic implants which clamped plasma estradiol levels at 5-20 pg/ml. We demonstrated that in situ aromatization rather than the uptake mechanism is the key determinant of tumor estradiol levels and tumor growth rate under conditions reflecting the postmenopausal state. The importance of intratumoral aromatase was also suggested by the findings that long-term estrogen deprivation increases sensitivity to estradiol and enhances aromatase activity in MCF-7 cells. The results of our in vivo and in vitro studies suggest that complete blockade of in situ aromatization in the breast would provide added benefit to postmenopausal breast cancer patients, especially those who relapse from antiestrogen therapy.

Introduction

Estrogen is mitogenic to the breast and plays an important role in the growth of hormone-dependent breast cancer. In premenopausal women, the major source of circulating estradiol (E2) is the ovaries. Following the menopause, extraglandular sites in adipose tissue, liver, muscle, brain and breast then become the primary sources of estrogen production. Cessation of ovarian estrogen synthesis leads to a significant reduction in plasma estrogen levels. A parallel decrease of E2 levels in plasma and in the breast would be expected at the time of menopause. However, the concentrations of E2 in malignant breast tissue in postmenopausal patients are much higher than expected and similar to those in premenopausal patients despite the large differences in plasma levels (van Landeghem et al.1985).

Previous studies have shown that aromatase is present in both normal and malignant breast tissues with varying activities (Perel et al.1982, Lipton et al.1987, Reed et al. 1989, 1990, Silva et al.1989, Miller et al. 1990, Bulun et al.1993, Koos et al.1993, Lu et al. 1996). While breast cancer cells can uptake estrogens from plasma, high tissue E2 concentrations in postmenopausal breast cancer cannot be adequately explained by the uptake mechanism. This conclusion is based upon both indirect and direct data.

Indirect data from previous studies suggested that in situ aromatization contributes preferentially to the estrogen content of breast tumors. However, no direct biologic data to support this hypothesis are yet available. Direct proof of the importance of in situ estrogen production is impossible to obtain in studies of postmenopausal breast cancer patients. Both peripheral and in situ aromatization take place, a finding which confounds interpretation. Therefore, an appropriate model system is required. Ideally, this model should be able to distinguish between in situ and peripheral aromatization and directly correlate the amount of E2 produced locally with the biologic response observed. In this study, we chose to use xenografts of aromatase or sham transfected MCF-7 breast cancer cells (Zhou et al. 1990) grown in ovariectomized nude mice. Using this model, we demonstrated that in situ synthesis predominates over uptake from plasma as a means of maintaining breast tissue E2 concentrations under the circumstances of the postmenopausal state.
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Methods

Cell culture
MCF-7 cells stably transfected with the human placental aromatase gene (A+) or plasmid vector alone (A−) (Zhou et al. 1990) were cultured in Eagle’s minimum essential medium containing 5% fetal bovine serum (FBS) and neomycin (600 μg/ml; Gibco, Bethesda, MD, USA). Wild type MCF-7 cells were cultured in IMEM with 5% FBS. Long term estrogen deprived (LTED) MCF-7 cells were cultured phenol red-free IMEM containing 5% dextrancoated charcoal stripped FBS. The culture medium was changed twice weekly.

Athymic mice
Female athymic mice 5 weeks of age were obtained from Harlan Sprague-Dawley (Indianapolis, IN, USA). The animals were housed in a pathogen-free environment under controlled conditions of light and humidity and received food and water ad libitum. Ovariectomy was performed under flurothyl anesthesia 1-3 days before cell inoculation. Inoculation of A+ or A−cells was carried out according to the procedures described previously (Yue et al. 1994, 1998a).

Preparation of Silastic estradiol implants
Silastic E2 implants were prepared using Silastic brand tubing with an inner diameter of 0.078” (Dow Corning, Midland, MI, USA) according to the method previously described (Masamura et al. 1995, Smith et al. 1977). The complete implant was 0.5 cm in length. E2 doses were adjusted by mixing E2 with cholesterol at ratios of 1:79-1:19 in weight. Based on extrapolations from our previous data (Masamura et al. 1995), predicted plasma E2 concentrations produced by these E2 implants were 5, 7, 10 and 20 pg/ml respectively.

Measurement of tissue estradiol levels in tumors
Tumor samples were maintained at ≈80 °C before radioimmunoassay (RIA) of E2. Tumors were homogenized in PBS with a Polytron homogenizer at 4 °C. Total E2 was extracted with diethyl ether and the E2 was isolated using celite column chromatography. E2 was measured using a high titer E2 antibody and iodinated E2 trace obtained from ICN (Costa Mesa, CA, USA). The inter- and intra-assay coefficients of variation were 12 and 9% respectively at a mean concentration of 50 pg/ml.

Growth assay
Cells were plated in six-well plates in corresponding culture medium. The medium was replaced with phenol red-free IMEM with or without charcoal stripped serum 2 days after plating. At 4 days after plating, medium containing vehicle or treatment compound was applied. The final concentration of vehicle was 0.1-0.2%. The media were changed every 3 days. At the end of treatment, cells were rinsed twice with saline. Nuclei were prepared using sequential addition of 1 ml Heps-MgCl2 solution (Hepes 10 mM and MgCl2 1.5 mM) and 0.1 ml ZAP solution (ethylhexadeyledimethylammonium bromide 0.13 M and glucosic acid 3 ml/100 ml), and counted using a Coulter Counter.

Radiometric aromatase assay
(3H2O release assay)
Confluent wild type MCF-7 or LTED cells grown in 60-mm dishes were rinsed with Hanks’ solution and incubated at 37 °C for 6 h with 1.5 ml serum-free IMEM containing approximately 1.5 μCi [1β-3H]androstenedione (specific activity 24.5 Ci/mmol; DuPont NEN, Boston, MA, USA). After incubation, the medium was transferred to a test tube and 3 ml chloroform were added to each tube to extract unconverted substrate and other steroids. An aliquot of 0.7 ml aqueous phase was treated with 2.5% activated charcoal suspension to remove residual steroids. Tritiated water (3H2O) formed during aromatization of [1β-3H]androstenedione to estrogen was measured in a scintillation counter.

Statistical analysis
Data were analyzed by one-way ANOVA followed by Duncan’s multiple range test.

Results

Detection of peripheral aromatization in ovariectomized nude mice
To validate our animal model, two issues needed to be clarified: whether there is peripheral aromatization in ovariecetomized nude mouse and, if so, could this peripheral aromatization produce a sufficient amount of estrogen to stimulate the growth of hormone-dependent breast cancer cells? To answer these questions, we evaluated the growth of aromatase transfected MCF-7 cells (A+) and sham transfected cells (A−) in response to aromatase substrate, androstenedione (Δ4A), in ovariecetomized mice. Mice bearing either A+ or A− cells on both flanks were called homointransplants. These two groups were tested in situ and peripheral aromatization respectively. Animals with A+ cells on one flank and A− cells on the other were called heterointransplants. This group minimized individual differences between the animals when comparing the effect of E2 from different sources.
During the 49-day treatment with $\Delta^4$A, $A^-$ cells did not grow in either the homoimplant or the heteroimplant groups. In contrast, $A^+$ cells grew rapidly. The total volume of $A^+$ tumor increased 5-6-fold. The growth rate

Figure 1 Growth curves of $A^+$ and $A^-$ tumors in ovariectomized nude mice receiving $\Delta^4$A. A total of 25 ovariectomized mice were divided into three groups. Group 1 ($n=8$) was inoculated with $A^-$ cells (2.5×10^6 cells/site; four sites/mouse). Group 2 ($n=8$) was inoculated with $A^+$ cells at the same cell concentration and number of sites as group 1. Group 3 ($n=9$) was inoculated with $A^-$ cells on one flank (two inoculation sites) and $A^+$ cells on the other (two inoculation sites). All three groups of mice were injected with $\Delta^4$A (0.1 mg/mouse, s.c.) once a day. Tumor volume was measured weekly. Tumor growth was expressed as percentage of initial total tumor volume of each group (Yue et al. 1998a).

Figure 2 $E_2$ levels in $A^+$ and $A^-$ tumors in ovariectomized nude mice receiving $\Delta^4$A. One tumor from each mouse mentioned in Fig. 1 was homogenized and $E_2$ concentration was measured as described in ‘Materials and Methods’. $^aP<0.01$ compared with $A^-$ tumor from the homoimplant group; $^bP<0.01$ compared with $A^-$ tumor from the heteroimplant group (Yue et al. 1998a).
however, was similar in both homoi implant and heteroimplant groups (Fig. 1). As expected, tissue E₂ concentrations corresponded to tumor growth. In situ aromatization of Δ₄,A significantly increased tissue E₂ levels that were 3–4-fold higher than A⁻ tumors in the heteroimplant group (Fig. 2). These results directly demonstrate that there is no detectable peripheral aromatization in ovariectomized nude mice and that in situ aromatization is a key determinant of tumor E₂ content and growth stimulation.

**Predominance of the in situ synthesis over the uptake mechanism**

To determine the relative importance of in situ aromatization versus the estrogen uptake mechanism under the conditions reflecting the estrogen hormonal status in postmenopausal women, we implanted E₂-containing Silastic tubing to ovariectomized mice to ‘clamp’ plasma E₂ levels at approximately 5–20 pg/ml. Growth of A+ cells and tumor E₂ levels in these animals were compared with those animals receiving Δ₄,A for in situ aromatization.

To monitor plasma levels of E₂ resulting from the Silastic implants, uterine weight measurements were used as a bioassay. A dose-dependent increase in uterine weight in the mice treated with E₂ implants was observed as a reflection of increased serum E₂ levels. Uterine weights from all the mice receiving E₂ implants were similar to or higher than that of intact mice (Table 1). These data suggest that serum E₂ levels achieved by Silastic implants are either at or above the physiologic concentrations normally found in the mouse. In animals receiving the substrate Δ₄,A, uterine weights were also increased, indicating that E₂ made in situ in A+ tumors re-entered plasma and stimulated the uterus. The degree of stimulation, however, was consistent with lower circulating levels of E₂ when compared with intact mice and the mice with E₂ implants.

The concentration of E₂ in the tumor tissue was significantly increased by in situ aromatization. In contrast, the three lower E₂ doses of the Silastic implants did not enhance the levels of E₂ in the tumor even though plasma levels were increased (Table 1). Only the highest dose of the E₂ implant produced a tissue E₂ level comparable to that resulting from in situ aromatization. However, the predicted plasma E₂ level achieved by this dose of E₂ is higher than the level of postmenopausal women.

Finally, we assessed tumor growth rate as a means of determining the biologic effects of E₂ found in the tumor. The weight of the tumor was the highest in the mice receiving Δ₄,A. These tumors were 5-fold larger than those with 5 pg/ml E₂ implant (Table 1). These data demonstrate that the in situ aromatization provides higher local tissue E₂ levels and thus greater stimulation of tumor growth than that observed with the estrogen uptake mechanism.

**Utilization of endogenous androgen substrate for in situ aromatization**

To mimic postmenopausal breast cancer more closely, studies using ovariectomized nude mice without supplementation of exogenous Δ₄,A were carried out. In these animals, A+ tumors grew more slowly than in those given exogenous Δ₄,A, as noted in prior experiments. However, in the absence of exogenous Δ₄,A, the growth rate of A+ tumors was higher than that of the A⁻ tumors. The average weight was 88±9.7 and 35.8±2.8 mg for A+ and A⁻ tumor respectively. Tissue E₂ concentration was 3.8-fold higher in A+ tumors than in A⁻ tumors. Treatment of the mice bearing A+ tumors with the aromatase inhibitor, YUE et al.: Breast aromatase

<table>
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<tr>
<th>Source of E₂</th>
<th>Treatment</th>
<th>Estimated plasma E₂ (pg/ml)</th>
<th>Uterine weight (mg)</th>
<th>Tumor E₂ concentration (pg/g)</th>
<th>Tumor weight (mg)</th>
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<tr>
<td>In situ</td>
<td>OVX control</td>
<td>9.7±1.9</td>
<td>461.4±4.4</td>
<td>30.4±4.0</td>
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<td>aromatization</td>
<td>Androstenedione</td>
<td>64.4±4.6²</td>
<td>1132.6±221.3³</td>
<td>449.4±70.2²</td>
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<tr>
<td>Uptake</td>
<td>E₂ implant</td>
<td>5.0±5.4²</td>
<td>548.6±19.0</td>
<td>84.3±10.2</td>
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<td></td>
<td>7</td>
<td>107.1±4.2²</td>
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<td>87.4±7.7</td>
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<td>1060.7±120.3³</td>
<td>231.4±30.2³</td>
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</table>

²P<0.05 compared with OVX control.
4-hydroxyandrostenedione (OHA), reduced tissue E2 to the levels found in A− tumors and tumor growth was inhibited. These results suggest that endogenous steroids provided sufficient substrate to allow biologically meaningful amounts of estrogen to be produced in situ which could locally stimulate tumor growth.

Growth characteristics of MCF-7 cells after long-term estrogen deprivation

Our laboratory and others have established a subline of MCF-7 cells by culturing the cells in phenol red-free medium supplemented with 5% charcoal stripped FBS (Masamura et al. 1995). In this medium, MCF-7 cells stop growing initially and re-gain their growth ability without the addition of E2. At 6 months, the growth rate is as high as that of wild type MCF-7 cells maximally stimulated with E2. The basal growth rate of these cells can be inhibited by the antiestrogen, ICI 182,780 (Fig. 3). Rescue experiments showed that, in the presence of ICI 182,780 (10−9 M), the growth curve of deprived cells in response to E2 was shifted to the left by three orders of magnitude compared with that of wild type MCF-7 cells (Fig. 4). This demonstrated that long-term estrogen deprivation causes the development of hypersensitivity to E2 in MCF-7 cells. These cells adapt themselves to a low estrogen environment and require much lower amounts of E2 for growth stimulation.

Aromatase activity in long-term estrogen deprived MCF-7 cells

We measured aromatase activity in wild type and long-term estrogen deprived cells using the tritiated water release assay. We observed that aromatase activity was 4-5 fold higher in deprived cells when compared with wild type cells (Fig. 5). Treatment with the phorbol ester phorbol 12-myristate 13-acetate (PMA) (10 ng/ml) for 24 h stimulated aromatase activity in both types of cells with higher stimulation observed in the deprived cells (Fig. 6).

Discussion

We have established an animal model to examine the relative importance of in situ aromatization in the maintenance of high tissue E2 concentrations in the breast of postmenopausal women. The key advantage of our animal model is the lack of appreciable peripheral aromatization in nude mice. Therefore, it can distinguish the effect of estrogen from different origins. To validate the model, exogenous Δ4A was given to ovariectomized mice to provide sufficient substrate to determine whether peripheral aromatization was present. Under this condition, aromatase negative cells (A−) did not grow, demonstrating that peripheral aromatization in ovariectomized mice, if any, is negligible. Aromatase positive cells (A+), in contrast, aromatized exogenous Δ4A, which led to higher tissue E2 levels and an enhanced...
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Figure 4 Rescue of ICI 182,780-induced growth inhibition by E2. Wild type (WT) and LTED MCF-7 cells were plated in six-well plates at the density of 60,000 cells/well in corresponding culture medium. At 2 days, the cells were re-fed with phenol red- and serum-free IMEM and cultured in this medium for another 2 days before treatment with ICI 182,780 (10^{-9} M) in combination of various concentrations of E2. At 5 days, nuclei prepared from each well were counted using a Coulter Counter.

Figure 5 Aromatase activity in wild type and estrogen deprived MCF-7 cells. Confluent wild type and estrogen deprived MCF-7 cells in 60-mm dishes were incubated at 37°C with [1β-3H]androstenedione plus or minus aromatase inhibitor 4-hydroxyandrostenedione (4-OHA) (10 μM) for 6 h. Radioactivity of tritiated water formed in the culture media during aromatization of [1β-3H]androstenedione was measured after chloroform extraction and charcoal treatment. Aromatase activity was expressed as fmol/mg protein/h (Yue et al. 1998b).

tumor growth rate. These data suggest that in situ aromatization is a key determinant of tissue E2 levels and tumor growth.

Demonstrating the importance of in situ aromatization does not exclude the role of an estrogen uptake mechanism to maintain high tissue E2 levels. To critically compare the biologic effects of E2 made in situ with that made available through an uptake mechanism in postmenopausal women, it was necessary to develop a model that reflected the postmenopausal hormone environment. To that end, we used Silastic E2 implants to clamp plasma E2 levels in ovariectomized nude mice at 5-20 pg/ml. These concentrations reflect free E2 levels in female plasma, because sex hormone binding globulin is not present in the mouse. As shown by uterine weight changes, the Silastic E2 implants caused dose-dependent increases in plasma E2 concentrations. Tumor E2 levels can also be enhanced through an estrogen uptake mechanism. However, the
plasma levels of $E_2$ required to increase the tissue $E_2$ to that achieved by \textit{in situ} aromatization was considerably higher than the estrogen levels usually observed in the postmenopausal individuals (Bonney \textit{et al.} 1983, Vermuelen \textit{et al.} 1986, Mehta \textit{et al.} 1987). Consistent with the higher tissue $E_2$ concentration observed with \textit{in situ} aromatization, tumor growth was maximally stimulated by estrogen synthesized \textit{in situ} when compared with that taken up from clamped levels of plasma $E_2$ produced by the Silastic implants. This study thus quantitatively demonstrates that \textit{in situ} aromatization can effectively increase tissue $E_2$ levels to a greater extent than that produced by the uptake of estrogen from the circulation under physiologic conditions that reflect the postmenopausal female.

Our studies have shown that growth of hormone-dependent breast cancer cells in a nude mouse model correlates with the levels of $E_2$ found in the tumor. Interestingly, a tendency towards an inverse correlation between tumor tissue $E_2$ concentration and aromatase activity has been observed. We found that aromatase activity in A+ tumors varied substantially, depending on whether the substrate $\Delta^4A$ was provided or not. In ovariectomized animals not supplemented with $\Delta^4A$, tumor $E_2$ levels were relatively low and the tumor growth rate was also low even though the aromatase activity in the tumor was as high as 2 pmol/mg/h. When $\Delta^4A$ was provided, tumor $E_2$ levels and tumor growth rate were enhanced, although the tumor aromatase activity dropped to levels of 0.1 - 0.4 pmol/mg/h. These results suggest that the amount of $E_2$ synthesized \textit{in situ} is determined by both intratumoral aromatase activity and availability of its substrate. Previous studies have shown that aromatase activities in breast tumors of postmenopausal patients are lower than in our model system. High concentrations of circulating $\Delta^4A$, however, could allow sufficient amounts of estrogen to be produced \textit{in situ} for growth stimulation.

The inverse correlation between tumor $E_2$ concentration and aromatase activity suggests that, in addition to well-known factors, aromatase activity might be subjected to regulation by $E_2$ and/or aromatase substrate through other unknown mechanism(s). Several lines of evidence support this hypothesis. We observed that aromatase activity in MCF-7 human breast cancer cells increased 4-8-fold after more than 6 months of culture under estrogen deprived conditions. Treatment of A+ cells in culture with $E_2$ caused a dose-dependent reduction of aromatase activity within a certain range (data not shown). Rubin \textit{et al.} (1998) have shown that estrogen treatment of adipose stromal cells reduces aromatase activity due to differentiation of stromal cells to adipocytes.

This kind of regulation of aromatase activity would also be expected to take place \textit{in vivo} in postmenopausal patients. Reduction of circulating $E_2$ levels following the menopause might result in an up regulation of aromatase activity in the breast. High concentration of circulating $\Delta^4A$ in postmenopausal women would then provide
sufficient substrate for in situ aromatization. Further elevation of aromatase activity could occur following antiestrogen therapy, which causes estrogen deprivation. On the other hand, we have shown that breast cancer cells become more sensitive to the mitogenic effect of E2 after long-term estrogen deprivation. Once hypersensitivity develops, these cells will need much smaller amounts of E2 to grow. If these concepts are indeed correct, utilization of potent aromatase inhibitors to completely block in situ rather than peripheral aromatization, might provide added benefit to postmenopausal patients, especially those who relapse from previous antiestrogen therapy.

References


