Aromatase within the breast

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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 (E\textsubscript{2}) 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 E\textsubscript{2} levels in plasma and in the breast would be expected at the time of menopause. However, the concentrations of E\textsubscript{2} 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 \textit{et al.} 1985).

Previous studies have shown that aromatase is present in both normal and malignant breast tissues with varying activities (Perel \textit{et al.} 1982, Lipton \textit{et al.} 1987, Reed \textit{et al.} 1989, 1990, Silva \textit{et al.} 1989, Miller \textit{et al.} 1990, Bulun \textit{et al.} 1993, Koos \textit{et al.} 1993, Lu \textit{et al.} 1996). While breast cancer cells can uptake estrogens from plasma, high tissue E\textsubscript{2} 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 E\textsubscript{2} 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 \textit{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 E\textsubscript{2} concentrations under the circumstances of the postmenopausal state.
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 in phenol red-free IMEM containing 5% dextran-coated 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 flurothane 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 1:19 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 to a tissue concentration of 50 mg/ml. The tissue homogenates were 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 (Heps 10 mM and MgCl2 1.5 mM) and 0.1 ml ZAP solution (ethylhexadecyldimethylammonium bromide 0.13 M and glacial acetic 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 Hank’s 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 ovariectomized 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 (Δ4-A), in ovariectomized mice. Mice bearing either A+ or A− cells on both flanks were called homoiimplants. 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 heteroimplants. This group minimized individual differences between the animals when comparing the effect of E2 from different sources.
During the 49-day treatment with Δ4A, 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

![Growth curves of A+ and A− tumors in ovariectomized nude mice receiving Δ4A.](image1)

**Figure 1** Growth curves of A+ and A− tumors in ovariectomized nude mice receiving Δ4A. A total of 25 ovariectomized mice were divided into three groups. Group 1 (n=8) was inoculated with A− cells (2.5×10⁶ 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 Δ4A (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).

![E2 levels in A+ and A− tumors in ovariectomized nude mice receiving Δ4A.](image2)

**Figure 2** E2 levels in A+ and A− tumors in ovariectomized nude mice receiving Δ4A. One tumor from each mouse mentioned in Fig. 1 was homogenized and E2 concentration was measured as described in ‘Materials and Methods’. ²P<0.01 compared with A− tumor from the homoimplant group. ²P<0.01 compared with A+ tumor from the heteroimplant group (Yue et al. 1998a).
however, was similar in both homoimplant and heteroimplant groups (Fig. 1). As expected, tissue E$_2$ concentrations corresponded to tumor growth. In situ aromatization of Δ$^4$A significantly increased tissue E$_2$ 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 E$_2$ 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 E$_2$-containing Silastic tubing to ovariectomized mice to ‘clamp’ plasma E$_2$ levels at approximately 5-20 pg/ml. Growth of A+ cells and tumor E$_2$ levels in these animals were compared with those animals receiving Δ$^4$A for in situ aromatization.

To monitor plasma levels of E$_2$ 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 E$_2$ implants was observed as a reflection of increased serum E$_2$ levels. Uterine weights from all the mice receiving E$_2$ implants were similar to or higher than that of intact mice (Table 1). These data suggest that serum E$_2$ levels achieved by Silastic implants are either at or above the physiologic concentrations normally found in the mouse. In animals receiving the substrate Δ$^4$A, uterine weights were also increased, indicating that the E$_2$ 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 E$_2$ when compared with intact mice and the mice with E$_2$ implants.

The concentration of E$_2$ in the tumor tissue was significantly increased by in situ aromatization. In contrast, the three lower E$_2$ doses of the Silastic implants did not enhance the levels of E$_2$ in the tumor even though plasma levels were increased (Table 1). Only the highest dose of the E$_2$ implant produced a tissue E$_2$ level comparable to that resulting from in situ aromatization. However, the predicted plasma E$_2$ level achieved by this dose of E$_2$ is higher than the level of postmenopausal women.

Finally, we assessed tumor growth rate as a means of determining the biologic effects of E$_2$ found in the tumor. The weight of the tumor was the highest in the mice receiving Δ$^4$A. These tumors were 5-fold larger than those with 5 pg/ml E$_2$ implant (Table 1). These data demonstrate that the in situ aromatization provides higher local tissue E$_2$ 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 Δ$^4$A were carried out. In these animals, A+ tumors grew more slowly than those given exogenous Δ$^4$A, as noted in prior experiments. However, in the absence of exogenous Δ$^4$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− tumors respectively. Tissue E$_2$ concentration was 3.8-fold higher in A+ tumors than in A− tumors. Treatment of the mice bearing A+ tumors with the aromatase inhibitor,

<table>
<thead>
<tr>
<th>Source of E$_2$</th>
<th>Treatment</th>
<th>Estimated plasma E$_2$ (pg/ml)</th>
<th>Uterine weight (mg)</th>
<th>Tumor E$_2$ concentration (pg/g)</th>
<th>Tumor weight (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OVX control</td>
<td></td>
<td>9.7±1.9</td>
<td>46.1±4.4</td>
<td>30.4±4.0</td>
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<tr>
<td>In situ aromatization</td>
<td>Androstenedione</td>
<td>64.4±4.6$^a$</td>
<td>63.9±221.3$^a$</td>
<td>449.4±70.2$^a$</td>
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<tr>
<td>Uptake</td>
<td>E$_2$ implant</td>
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<td>90.6±5.4$^a$</td>
<td>548.6±19.0</td>
<td>84.3±10.2</td>
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<td></td>
<td></td>
<td>7</td>
<td>107.1±4.2$^a$</td>
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<td></td>
<td>10</td>
<td>114.7±4.9$^a$</td>
<td>629.9±74.1</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>126.0±14.1$^a$</td>
<td>1060.7±120.3$^a$</td>
<td>231.4±30.2$^a$</td>
</tr>
</tbody>
</table>

$^a$P<0.05 compared with OVX control.
4-hydroxyandrostenedione (OHA), reduced tissue E$_2$ 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 E$_2$. At 6 months, the growth rate is as high as that of wild type MCF-7 cells maximally stimulated with E$_2$. 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 E$_2$ 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 E$_2$ in MCF-7 cells. These cells adapt themselves to a low estrogen environment and require much lower amounts of E$_2$ 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 E$_2$ 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 Δ$^4$A 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 Δ$^4$A, which led to higher tissue E$_2$ levels and an enhanced...
tumor growth rate. These data suggest that in situ aromatization is a key determinant of tissue E_2 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 E_2 levels. To critically compare the biologic effects of E_2 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 E_2 implants to clamp plasma E_2 levels in ovariectomized nude mice at 5-20 pg/ml. These concentrations reflect free E_2 levels in female plasma, because sex hormone binding globulin is not present in the mouse. As shown by uterine weight changes, the Silastic E_2 implants caused dose-dependent increases in plasma E_2 concentrations. Tumor E_2 levels can also be enhanced through an estrogen uptake mechanism. However, the
plasma levels of E2 required to increase the tissue E2 to that achieved by in situ aromatization was considerably higher than the estrogen levels usually observed in the postmenopausal individuals (Bonney et al. 1983, Vermeulen et al. 1986, Mehta et al. 1987). Consistent with the higher tissue E2 concentration observed with in situ aromatization, tumor growth was maximally stimulated by estrogen synthesized in situ when compared with that taken up from clamped levels of plasma E2 produced by the Silastic implants. This study thus quantitatively demonstrates that in situ aromatization can effectively increase tissue E2 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 E2 found in the tumor. Interestingly, a tendency towards an inverse correlation between tumor tissue E2 concentration and aromatase activity has been observed. We found that aromatase activity in A+ tumors varied substantially, depending on whether the substrate Δ4A was provided or not. In ovariectomized animals not supplemented with Δ4A, tumor E2 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 Δ4A was provided, tumor E2 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 E2 synthesized 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 Δ4A, however, could allow sufficient amounts of estrogen to be produced in situ for growth stimulation.

The inverse correlation between tumor E2 concentration and aromatase activity suggests that, in addition to well-known factors, aromatase activity might be subjected to regulation by E2 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 E2 caused a dose-dependent reduction of aromatase activity within a certain range (data not shown). Rubin 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 in vivo in postmenopausal patients. Reduction of circulating E2 levels following the menopause might result in an up regulation of aromatase activity in the breast. High concentration of circulating Δ4A in postmenopausal women would then provide
sufficient substrate for \textit{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 $E_2$ after long-term estrogen deprivation. Once hypersensitivity develops, these cells will need much smaller amounts of $E_2$ to grow. If these concepts are indeed correct, utilization of potent aromatase inhibitors to completely block \textit{in situ} rather than peripheral aromatization, might provide added benefit to postmenopausal patients, especially those who relapse from previous antiestrogen therapy.

\textbf{References}


