Plasma and urinary oestrogens in breast cancer patients on treatment with 4-hydroxyandrostenedione

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Summary Plasma and urinary oestrogens were measured in nine breast cancer patients (eight postmenopausal women and one man) before and during treatment with the aromatase inhibitor 4-hydroxyandrostenedione. Urinary oestrogens were measured by using a highly specific GC-MS method. Plasma levels of oestrone, oestradiol and oestrone sulphate were suppressed by 66.6% (± 3.6%), 57.7% (± 5.1%) and 51.8% (± 6.4%) respectively (P < 0.005 for all). The twenty-four hour urinary excretion of total oestrogens, oestradiol, oestrone, 2-hydroxyoestrone, 16α-hydroxyoestrone and the minor metabolites 16β - and 15α-hydroxyoestrone were all suppressed by mean values ranging from 60% to 82%, (oestradiol: P < 0.025, otherwise P < 0.005). There were no significant changes in the ratios between the different plasma oestrogens. The finding of sustained plasma and urinary oestrogens at 20–40% compared to their control levels indirectly support a hypothesis of alternative oestrogen sources in postmenopausal breast cancer patients on treatment with 4-hydroxyandrostenedione.

The aim of contemporary endocrine treatment of advanced breast cancer is to reduce oestrogen stimulation to the tumour cell. This could be achieved either by blocking oestrogen action at the receptor level with antiestrogens or by reducing the oestrogen supply to the tumour cell.

The major pathway of oestrogen production in postmenopausal women is peripheral conversion (aromatisation) of circulating androstenedione (A) into oestrone (Oe) (Grodin et al., 1973). Aromatase inhibition is a successful approach to achieve plasma oestrogen suppression and tumour shrinkage in postmenopausal women suffering from breast cancer. The ‘classic’ aromatase inhibitor, aminoglutethimide (Orimet®), has been in clinical use for more than two decades (Lønning & Kvinnsland, 1988). The toxic side effects caused by this drug has prompted the development of new and more selective aromatase inhibitors (Lønning et al., 1990).

4-Hydroxyandrostenedione (Formestane®, Ciba-Geigy) is a second generation aromatase inhibitor (Brodie et al., 1977), first reported to cause tumour shrinkage in breast cancer patients in 1984 (Coombes et al., 1984). In contrast to aminoglutethimide, 4-hydroxyandrostenedione seems to act specifically on the aromatase enzyme (Brodie et al., 1981; Dowsett et al., 1989). The drug causes few side-effects, and results from phase I and II trials including more than 500 patients have revealed an overall response rate of 26% among unselected patients (Lønning, 1992).

The biochemical action of aromatase inhibitors in vivo is still incompletely understood. Different aromatase inhibitors like aminoglutethimide, 4-hydroxyandrostenedione (Formestane®, Ciba-Geigy) and CGS 16949 (Fadrazole®, Ciba-Geigy) inhibit aromatisation by 82–98% (Dowsett et al., 1985; Jones et al., 1992; Lønning et al., 1991; Reed et al., 1990; Santen et al., 1978 ). Despite this, several investigators have reported sustained plasma oestrogens at about 30–50% of their control values in treated patients (Dowsett et al., 1989; Dowsett et al., 1990; Lønning et al., 1989b; Santen et al., 1982; Santen et al., 1989; Vermeulen et al., 1983). Some aromatase inhibitors may act on plasma oestrogen by mechanisms other than aromatase inhibition; aminoglutethimide has been shown to stimulate the metabolism of plasma oestrone sulphate (Oe,S) by enhancing the production of 16α-hydroxylated metabolites (16α-hydroxyoestrone and oestradiol) (Lønning et al., 1987; Lønning et al., 1989a; Lønning & Skulstad, 1989).

So far most studies have evaluated the influence of aromatase inhibitors on plasma oestrogens. However, due to the low levels of plasma oestrogens in patients on treatment with aromatase inhibitors, these steroids can be measured with less sensitivity only, in which case there is a risk of non-specific interactions in the assay. About 60–70% of the oestrogen metabolites are excreted in the urine (Fishman et al., 1966; Zumoff et al., 1968), and the concentration of urinary oestrogen metabolites is about 100 times the concentration of plasma oestrogens. These urinary oestrogen metabolites may therefore be measured by highly specific GC-MS methods (Fotsis & Adlercreutz, 1987).

To our knowledge neither plasma Oe,S nor urinary oestrogen metabolites have previously been reported in patients treated with 4-hydroxyandrostenedione. This study was designed to test whether sustained plasma Oe,S and Oe levels in breast cancer patients treated with 4-hydroxyandrostenedione are accompanied by sustained plasma Oe,S and urinary oestrogen metabolite excretion. By comparing plasma and urinary oestrogen suppression, non specific interactions in the RIA assay or alteration in oestrogen disposition not related to aromatase inhibition might be reflected in conflicting results.

Patients and methods

Patients
Nine patients with advanced breast cancer (one man and eight postmenopausal women) who were to receive 4-hydroxyandrostenedione because of progressive disease were included in this study. All gave their verbal informed consent. The mean age was 72 years (range 62 to 79 years). No patients were smokers, and none of them received any other hormonal treatment or drugs known to influence drug metabolism. The liver enzymes and plasma creatinine were within the normal range in all patients, indicating normal liver and renal function.

All patients had previously been treated with two or more different endocrine regimens (range two to eight, median...
three regimens). Any previous hormonal therapy was terminated at least 4 weeks before commencing 4-hydroxyandrostenedione. Two patients had received previous treatment with aminoglutethimide, in which case aminoglutethimide was terminated 4 and 8 weeks before commencing on 4-hydroxyandrostenedione.

Treatment schedule and sampling protocol
All patients had i.m. injections of 4-hydroxyandrostenedione 250 mg. The injections were given weekly for the first 6 weeks, thereafter at 2-weekly intervals. Blood and urine sampling were performed before commencing on 4-hydroxyandrostenedione and after 36 to 80 days on treatment. The time interval from the last injection of 4-hydroxyandrostenedione to blood and urine collection in the on-treatment test situation ranged from 2 to 13 days with a median of 7 days.

Twenty-four hour urine was collected in dark glass bottles containing ascorbic acid (final concentration >4 g l\(^{-1}\)) to prevent the catechol-oestrogens from undergoing oxidation (Gelbke, 1973). The urine was pooled, one aliquot was obtained for urinary creatinine measurement, and two aliquots of 50 ml were frozen and stored at -20°C until processing.

Heparinised blood samples were obtained on the morning of the urine collection period between 8 a.m. and 9 a.m. after an overnight fast. Plasma was separated by centrifugation and stored at -20°C until processing.

Analytical methods
Plasma oestrogens were measured by modification of RIA methods previously described (Dowsett et al., 1987; Lenning et al., 1989a). The sensitivity limit for Oe1, Oe2 and Oe3S was 2.1 pM, 6.3 pM and 25.9 pM respectively, and the CV within assay were 4.3% 3.9% and 6%.

The analytical method for the determination of the urinary oestrogen profile based on capillary gas chromatography-mass spectrometry (GC/MS) in the selected ion monitoring (SIM) mode has been published (Fotsis & Adlerscreutz, 1987). A significant improvement in the accuracy and precision of the method included the addition of deuterated \((d_5)\)ethoxime derivatives (Wähäus et al., 1987) of all ketonic oestrogens as internal standards immediately after hydrolysis of the urine extract. In this way stable-isotope dilution mass spectrometry could be used for all ketonic oestrogens. The final determination was carried out using a Hewlett Packard 5995B quadruple instrument equipped with a 0.2 mm x 12.4 m bonded phase BP 1 (equivalent to silicone SE-30) capillary silica column directly connected to ion source. The coefficients of variation for all fractions and other details regarding the reliability of the procedure have been published (Fotsis & Adlerscreutz, 1987; Bannwart et al., 1988). The following oestrogens were determined: Oestrone (Oe1), Oestradiol (Oe2), 2-hydroxyoestrone (2-OH-Oe1), 2-hydroxyoestradiol (2-OH-Oe2), 2-methoxyoestrone (2-MeOe1), 4-hydroxyoestrone (4-OH-Oe1), oestriol (Oe3), 16α-hydroxyoestrone (16α-OH-Oe1), 16β-hydroxyoestrone (16β-OH-Oe1), 15α-hydroxyoestrone (15α-OH-Oe2) and 16-keto-oestradiol (16-Keto-Oe2).

Creatinine in urine and serum was measured by the method of Jaffé. As none of the patients had any significant change in plasma creatinine values during the investigation period, it was found feasible to use the creatinine clearance value as a 'recovery standard' for urine collection. Thus, to correct for any difference in urine losses between the two test situations, the amount of urinary oestrogens excreted was calculated using the ratio between the highest and the actual creatinine clearance for each patient as a correction factor.

Statistical methods
Plasma and urinary oestrogen levels before and during treatment were compared using the Wilcoxon Matched Pair Signed Rank Test. All \(P\)-values were expressed as two-tailed.

Results

Plasma oestrogens
Plasma oestrogen levels before and during treatment are given in Table I and Figure 1. Treatment with 4-hydroxy-androstenedione suppressed plasma levels of Oe1, Oe2 and Oe3S in all patients \((P<0.005)\). The mean percentage of suppression \((\pm\) s.e.m.) was 66.5\% \((\pm\) 3.6\%) for Oe2, 57.7\% \((\pm\) 5.1\%) and 51.8\% \((\pm\) 6.4\%) for Oe1, Oe2 and Oe3S respectively. While the Oe2/Oe1 ratio decreased in eight of nine patients, this was not of statistical significance (a ratio of 0.213 ± 0.031 and 0.163 ± 0.027 before and during treatment respectively, \(P = 0.080\)). There was no change in the Oe2/Oe3S ratio \((0.042 ± 0.006\) before and \(0.037 ± 0.004\) during treatment, \(P>0.20\)), but a small increase in the Oe2/Oe3S ratio \((P = 0.054)\).

Urinary oestrogens
Urinary excretion of total oestrogens and the different oestrogen metabolites is shown in Table II and in Figure 2a and 2b. The results may be summarised as follows:

1. Urinary excretion of total oestrogens was suppressed by a mean value of 66%.
2. All urinary metabolites except for 2-OH-Oe2 and 4-OH-Oe1 were significantly suppressed (mean values of suppression ranging from 60% to 82%). The urinary concentration of 4-OH-Oe1 was below the sensitivity limit of the assay in the control situation. Thus, the result obtained for this metabolite should be interpreted with caution.
3. No significant alterations in the ratio of the 16α-hydroxylated metabolites (16α-OH-Oe1 and Oe2) or 2-OH-Oe1 relative to Oe1 were found.

Comparison of plasma and urinary oestrogen suppression
The relative suppressions of urinary and plasma oestrogens were of the same magnitude. A suppression of total urinary oestrogen by 66\% \((\pm\) 5.6\%) corresponds well to a suppression of plasma Oe1, Oe2 and Oe3S of 66.6\% \((\pm\) 3.6\%), 57.7\% \((\pm\) 5.1\%) and 51.8\% \((\pm\) 6.4\%) respectively.

Table I

|             | Mean values in pmol l\(^{-1}\) (\pm\) s.e.m.) and mean percentual suppression (\pm\) s.e.m.) before and during treatment with 4-hydroxyandrostenedione | \(P\) |
|-------------|-------------------------------------------------------------------------------------------------|------|
|             | Before | During | \% suppression |  |
| Plasma Oe2  | 15.4 ± 3.4 | 5.5 ± 0.7 | 57.8 ± 5.1 | <0.005 |
| Plasma Oe1  | 70.6 ± 10.8 | 21.0 ± 1.5 | 66.6 ± 3.6 | <0.005 |
| Plasma Oe3S | 456.0 ± 131.1 | 197.0 ± 83.5 | 51.8 ± 6.4 | <0.005 |
| Ratio Oe2/Oe1S | 0.042 ± 0.006 | 0.037 ± 0.004 | ns |  |
| Ratio Oe2/Oe1 | 0.212 ± 0.022 | 0.260 ± 0.029 | 0.054 |
| Ratio Oe1/Oe1S | 0.213 ± 0.031 | 0.163 ± 0.027 | 0.080 |
Figure 1 Individual plasma levels of oestradiol P-Oe2, oestrone (P-Oe1) and oestrone sulphate (P-Oe1S) before and during treatment in 9 breast cancer patients (8 postmenopausal women: O, and 1 man: □) treated with 250 mg 4-hydroxyandrostenedione i.m. fortnightly.

Discussion

Plasma levels of Oe1, Oe2 and Oe1S obtained in our patients before treatment were in the same range as previously reported by us and others for postmenopausal breast cancer patients but plasma Oe1S was in the low normal range (Dowsett et al., 1989; Lenning et al., 1989b; Vermeulen et al., 1989). The amount of different urinary oestrogen metabolites excreted during 24 h was in the same range as previously reported in breast cancer patients (Aldercreutz et al., 1991).

The relative suppression of plasma Oe1 and Oe2 obtained by 4-hydroxyandrostenedione was of the same magnitude as previously reported by others (Dowsett et al., 1989; Reed et al., 1990). To our knowledge, plasma Oe1S and urinary oestrogen metabolite excretion have not been measured in patients on treatment with 4-hydroxyandrostenedione previously. Oestrone sulphate has been suggested to play an important role as an oestrogen source to the tumour cell (Santner et al., 1986; Pasqualini et al., 1989), and the influence of aromatase inhibitors on plasma Oe1S levels may be of significant biological importance.

Aromatase is a key enzyme in postmenopausal oestrogen synthesis. Current opinion is that peripheral aromatisation of circulating A and testosterone (T) into Oe1 and Oe2 respectively accounts for total postmenopausal oestrogen synthesis.

Table II Mean values in nmol 24 h⁻¹ (± s.e.m.) and mean percentual suppression (± s.e.m.) of 24 h urinary metabolites before and during treatment with 4-hydroxyandrostenedione

| Metabolite   | Before          | During         | % suppression | P       |
|--------------|-----------------|----------------|---------------|---------|
| 2-OHOe1      | 4.64 ± 1.47     | 1.09 ± 0.25    | 70.8 ± 5.2    | <0.005  |
| 4-OHOe1      | 0.54 ± 0.15     | 0.43 ± 0.12    | 13.5 ± 16.0   | >0.2    |
| 2-OHOe2      | 2.27 ± 0.39     | 1.44 ± 0.37    | 14.2 ± 39.2   | >0.1    |
| Oe2          | 1.57 ± 0.27     | 0.44 ± 0.11    | 59.7 ± 17.4   | <0.025  |
| Oe1          | 5.86 ± 1.26     | 1.90 ± 0.35    | 63.6 ± 5.3    | <0.005  |
| 2-methoxyOe1 | 1.13 ± 0.22     | 0.28 ± 0.07    | 72.9 ± 4.2    | <0.005  |
| 16-OHOe1     | 1.91 ± 0.26     | 0.42 ± 0.07    | 78.1 ± 2.3    | <0.005  |
| 15-OHOe1     | 0.35 ± 0.12     | 0.10 ± 0.02    | 60.2 ± 8.2    | <0.005  |
| 16-OHOe2     | 1.30 ± 0.33     | 0.23 ± 0.12    | 81.8 ± 7.9    | <0.005  |
| Oe3          | 7.62 ± 1.90     | 1.92 ± 0.41    | 68.3 ± 8.3    | <0.005  |
| Total oestrogens | 28.24 ± 4.48 | 8.47 ± 1.37   | 66.2 ± 5.6    | <0.005  |
Aromatase inhibition is a successful treatment approach in postmenopausal breast cancer. Treatment with different aromatase inhibitors like aminoglutethimide, 4-hydroxyandrostenedione and CGS 16949A all cause effective suppression of plasma oestrogens and CGS 16949A as well as urinary oestrogens (Santen et al., 1982; Santen et al., 1989; Dowsett et al., 1989; Dowsett et al., 1990) and clinical responses comparable to what may be expected from the most effective forms of endocrine treatment like anti-oestrogens and high dose progestins (Lennng et al., 1992). Thus, aromatase inhibitors differ significantly from other drugs investigated as hormone suppressors in postmenopausal breast cancer. Glucocorticoids, ketoconazole and trilostane all exert similar steroid synthesis, cause a modest suppression of plasma oestrogens, and produce clinical responses in a small number of patients (Harris et al., 1988; Harris et al., 1989; Beardwell et al., 1983; Coombe et al., 1985; Williams et al., 1987). The results obtained with these drugs compared with aromatase inhibitors indirectly suggest a dose response relationship between plasma oestrogen suppression and the chance of achieving a clinical response in postmenopausal breast cancer patients. Accordingly, a major goal is the development of oestrogen synthesis inhibitors.

The efficacy of an aromatase inhibitor may be assessed in different ways. One approach is to measure in vivo aromatase inhibition by use of isotope tracer infusions (Jacobs et al., 1991), another approach is to measure the degree of plasma oestrogen suppression. A major problem is to explain the inconsistency of the results obtained with these different methods and to interpret the finding of sustained plasma oestrogens despite subtotal aromatase inhibition. There are two possible explanations for these findings. First, they may be due to technical flaws in the tracer infusion studies or with plasma oestrogen analysis. Second, they indicate some alternative sources of plasma oestrogens in patients on treatment with aromatase inhibitors.

Considering the first possibility, tracer studies have revealed a >95% inhibition of the conversion of circulating androstenedione into oestrone during treatment with 4-hydroxyandrostenedione (Jones et al., 1992; Reed et al., 1990) as well as with other aromatase inhibitors (Lennng et al., 1991; McNeill et al., 1992; Santen et al., 1978). These methods are sensitive enough to detect aromatase inhibition down to 98–99% (Jacobs et al., 1991). Any non-specific interaction in the chromatograms may be expected to cause an underestimation of the degree of inhibition. Thus, it is not likely that these studies may have overrated the efficacy of those compounds. While the possibility of non-specific interactions in the radioimmunoassays is a more likely explanation of an internal consistency between the relative suppression of plasma oestrogens measured by RIA techniques and the suppression of urinary oestrogen metabolites measured by a specific GC-MS method provides indirect evidence this may not be the case.

The possibility of alternative oestrogen sources in breast cancer patients on treatment with aromatase inhibitors should be considered. These could be enzymatic pathways not inhibited by current drugs or, alternatively, that the oestrogen synthesis could partly take place in compartments not equilibrating with circulating androstenedione or not penetrated by aromatase inhibitors. So far there is no direct evidence pointing to any such a pathway. Alternatively, plasma oestrogens could be derived from residual tissue oestrogens, like Oe1 or lipidal oestrogen conjugates (Larner et al., 1992) which may have a slow turnover and could be sustained in the tissue for a long time even when their production is inhibited. While this possibility can not be excluded, we found no correlation between plasma oestrogen suppression and the duration of 4-hydroxyandrostenedione treatment among patients investigated in this study. Results by others (Dowsett et al., 1985b) as well as unpublished data from our laboratory suggest plasma oestrogens to be sustained also in patients who have been on aminoglutethimide treatment for more than 6 months. While it is not possible at this stage to draw any conclusion considering possible sources of these oestrogens, our finding of an internal consistency between the relative suppression of plasma and urinary oestrogens in breast cancer patients treated with 4-hydroxyandrostenedione add indirect support to a hypothesis that the sustained plasma oestrogens are real oestrogens and not technical artefacts. This finding may have significant implications for future studies on aromatase inhibitors in the treatment of breast cancer.

The major metabolic pathways of oestrogens are hydroxylation in the 2- and 16α-position (Bolt, 1979). Our results revealed no significant change in the ratio of the 16α-hydroxylated (16α-Oe1 and Oe3) or 2-hydroxylated (2-OH-Oe1) metabolites to Oe, in the urine. Thus, in contrast to aromatase inhibition (Lennng et al., 1989a; Lennng & Skullstad, 1989) 4-hydroxyandrostenedione does not seem to influence the major oestrogen metabolic pathways in vivo.

The metabolite 4-OH-Oe1, like 2-OH-Oe1, was little suppressed by treatment with 4-hydroxyandrostenedione. The possibility exists that urinary 4-OH-Oe1 could arise from aromatisation of 4-hydroxyandrostenedione. However, as the urinary level of 4-OH-Oe1 before treatment was below the detection limit of the method, the result should be interpreted with caution. The concentrations of plasma oestrogens before and during 4-hydroxyandrostenedione treatment was 1.6% and 3.8% only. Thus, under any circumstance a direct production of 4-OH-Oe1 from 4-hydroxyandrostenedione most probably would not be of a magnitude of biological importance and may not explain our finding of sustained plasma and urinary oestrogens.

The reason why 2-OH-Oe1 is relatively moderately suppressed remains unclear. At these low levels, the assay may be only very incompletely specific for this metabolite. If this metabolite was low. While there was a small increase in the plasma Oe1/Oe2 ratio, the ratio of Oe3/Oe1 in urine was slightly reduced. While previous investigations have suggested a possible influence by 4-hydroxyandrostenedione on the 17β-hydroxyoestrogen dehydrogenase in vitro (Brodie et al., 1982), our results do not suggest any influence of 4-hydroxyandrostenedione on this enzyme in vivo. Neither is there any obvious reason why 16β-OH-Oe1 was particularly effectively suppressed (mean suppression of 82%). However, it should be considered that oestrogen metabolic enzymes have been shown to be influenced by several exogenous factors (Conney, 1986), and our current knowledge of the regulation of these enzymes is incomplete.

Considering the plasma oestrogens, it may be noted that the plasma Oe1/Oe3/S ratio was reduced in 8/9 patients. This contrasts the findings obtained with aminoglutethimide in which case the Oe1/Oe3/S ratio was elevated due to enhanced secretion of Oe3/S metabolism (Lennng et al., 1989b). Our findings seem to exclude any enhancement of Oe3/S metabolism by 4-hydroxyandrostenedione, but further studies are needed to assess whether treatment with 4-hydroxyandrostenedione causes a reduction in the Oe1/Oe3/S ratio. If this should be the case, it may provide information of clinical importance. Current opinion in the literature is that there is no evidence of a direct secretion of plasma Oe3/S in postmenopausal women, as circulating Oe3/S seems to be accounted for by production from plasma Oe1 and Oe2 (Longcope et al., 1972; Lennng et al., 1989b). However, it should be recalled that patients on treatment with aromatase inhibitors have plasma oestrogens markedly lower than other postmenopausal women. Accordingly, while a small secretion of Oe3/S could be difficult to detect in postmenopausal women in general, it could be of importance in patients having their major oestrogen production pathways blocked by an aromatase inhibitor. More studies are needed to evaluate this phenomenon, but our findings underline the importance of measuring plasma Oe1/S in concert with Oe3 and Oe2 in patients treated with aromatase inhibitors.

Conclusions

4-Hydroxyandrostenedione suppresses plasma and urinary oestrogens in breast cancer patients, but the finding that both
plasma and urinary oestrogens remained at levels 30-50% of their control values supports the hypothesis that alternative oestrogen sources may exist in breast cancer patients. In contrast to amino-glutethimide, 4-hydroxyandrostenedione does not seem to have any major influence on the major pathways of oestrogen metabolism.

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