Cortical γ-Aminobutyric Acid Levels Across the Menstrual Cycle in Healthy Women and Those With Premenstrual Dysphoric Disorder

A Proton Magnetic Resonance Spectroscopy Study

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Background: There is increasing support for the hypothesis that gonadal steroids involved in the regulation of the human menstrual cycle modulate γ-aminobutyric acid (GABA) neuronal function. This study tests the hypothesis that cortical GABA neuronal function, reflected in brain GABA concentrations, fluctuates across the menstrual cycle in healthy women and those with premenstrual dysphoric disorder (PMDD) and that a menstrual cycle phase–dependent abnormality in brain GABA concentrations in women diagnosed as having PMDD would reflect altered central response to circulating gonadal and neuroactive steroids.

Methods: Fourteen healthy menstruating women and 9 women diagnosed as having PMDD were recruited from a women’s behavioral health research program located at a university-based medical center. The women underwent serial proton magnetic resonance spectroscopic measurements of occipital cortex GABA levels across the menstrual cycle (primary outcome measure) and had blood drawn for gonadal hormone and neurosteroid levels determined on each scan day (secondary outcome measure).

Results: There was a significant group × phase interaction with most of the finding explained by the reduction in cortical GABA levels during the follicular phase in those with PMDD compared with healthy controls. Cortical GABA levels declined across the menstrual cycle in healthy women, whereas women with PMDD experienced an increase in cortical GABA levels from the follicular phase to the mid luteal and late luteal phases. Significant between-group differences in the relationship between hormones and GABA were observed for estradiol, progesterone, and allopregnanolone.

Conclusions: These data strongly suggest that the GABAergic system is substantially modulated by menstrual cycle phase in healthy women and those with PMDD. Furthermore, they raise the possibility of disturbances in cortical GABA neuronal function and modulation by neuroactive steroids as potentially important contributors to the pathogenesis of PMDD.

Arch Gen Psychiatry. 2002;59:851-858

P RECLINICAL STUDIES have increasingly defined the neural targets for gonadal steroids, such as estradiol and progesterone, and their neurosteroid precursors and derivatives.1-4 For example, the 3α-reduced biosynthetic derivatives of progesterone, 3α-hydroxy-5α-pregnan-20-one (allopregnanolone) and 3α-hydroxy-5β-pregnan-20-one (pregnenolone), are potent γ-aminobutyric acid A (GABA_A) receptor facilitators, increasing the frequency and duration of the chloride ionophore channel opening.4 In healthy women, menstrual cycle–related changes in cognitive function, mood, and drug sensitivity may be attributable to fluctuations in the hormonal modulation of γ-aminobutyric acid (GABA) systems.5-7 Alterations in GABA neuronal function have been implicated in the pathophysiology of premenstrual dysphoric disorder (PMDD), a luteal phase–specific syndrome characterized by moderate-to-severe alterations in mood, behavior, and physical well-being that impairs the personal, professional, and/or social functioning of 3% to 7% of premenopausal women.8 Plasma GABA levels are reduced across the menstrual cycle in women with PMDD compared with healthy controls who experience an increase in plasma GABA levels from the follicular to luteal phases.9 Additionally, women with PMDD demonstrate a luteal phase–specific decrease in the behavioral and physiologic response to administration of GABA_A receptor agonists.6,7 Measurement of cortical excitability using transcranial magnetic stimulation demonstrates an increase in cortical inhibition in healthy controls in the mid luteal phase compared with the...
mid follicular phase to a degree comparable to that observed after administration of GABA-enhancing drugs.10 The fact that women with PMDD did not demonstrate an increase in cortical inhibition during the mid luteal phase provides additional evidence of phase-specific reduction in GABA_A receptor function11 in this population. Preclinical findings demonstrating alterations in the number of α4 subunits and sensitivity of GABA_A receptor on withdrawal of chronically administered allopregnanolone12 provide a compelling model for the mechanism by which neurosteroids may mediate GABA neuronal changes across the menstrual cycle.

Further support for a neurosteroid-GABA hypothesis in the pathogenesis of PMDD comes from treatment studies that demonstrate the preferential responsiveness of PMDD to selective serotonin reuptake inhibitors (SSRIs). The SSRI-induced increases in cerebrospinal fluid and brain allopregnanolone in patients with major depression13 and in rats,14 respectively, are likely due to the stimulatory effect of SSRIs on 3α-hydroxysteroid oxidoreductase, the rate-limiting enzyme in the biosynthesis of allopregnanolone.15 Although luteal phase deficits in allopregnanolone are associated with greater symptom severity in women with PMDD,16-17 most studies have found no difference between women with premenstrual syndrome and PMDD and their healthy counterparts with respect to luteal phase levels of gonadal steroids and allopregnanolone.17-19 Failure to demonstrate a significant effect of diagnosis on plasma neuroactive steroids does not necessarily detract from the importance of these steroids in the pathogenesis of PMDD because a dissociation between peripheral and brain levels of allopregnanolone has been demonstrated in rodents.20,21

Quantitative, localized, repeatable, noninvasive measurements of human cortical GABA levels are now possible.22 These advances in proton magnetic resonance spectroscopy (1H-MRS) permit direct tests of the hypothesis that human cortical GABA levels fluctuate across the menstrual cycle and that PMDD is associated with abnormalities in GABA neuronal function. The aims of this study are 3-fold: (1) to determine whether there are menstrual cycle phase– and diagnosis–specific fluctuations in cortical GABA levels in normal menstruating women and women with PMDD, (2) to assess menstrual cycle–related fluctuations in plasma neuroactive steroids, and (3) to examine the relationship between plasma neuroactive steroids and cortical GABA levels. We chose the occipital cortex as our region of interest for this study based on previous evidence that GABAergic-modulating substances (benzodiazepines, alcohol, vigabatrin) and psychiatric disorders (unipolar depression and panic disorder) were associated with altered GABA levels in this region.23-25

Participants and Methods

Twenty-three regularly menstruating women, 9 with PMDD (age, 26-39 years; mean age, 34.6 years) and 14 healthy controls (age, 21-43 years; mean age, 30.1 years), participated in this study after giving written informed consent using forms and procedures approved by the Yale University School of Medicine Human Investigations Committee, New Haven, Conn. All participants were recruited through local advertising and were paid for their participation. Participants had not been pregnant or taking hormonal contraceptives for at least 10 months and had not taken psychotropic drugs for more than 5 years. Two participants with PMDD had previously taken fluoxetine hydrochloride for major depressive episodes.

All participants underwent a diagnostic interview using the Structured Clinical Interview for Diagnosis based on DSM-IV.26 Women with PMDD were excluded if they had an Axis I psychiatric or substance abuse or dependence disorder within the previous 2 years or a lifetime history of bipolar disorder or psychosis. Healthy controls were without personal or family (first-degree relative) history of a confirmed psychiatric disorder (by participant report). Table 1 summarizes participant characteristics. Participants did not differ significantly with respect to age at presentation, age at menarche, parity, or menstrual cycle length.

All women were screened prospectively for 2 to 3 consecutive menstrual cycles using the Daily Record of Severity of Problems to rate severity of mood and physical symptoms.27 The Daily Record of Severity of Problems is a 24-item daily diary that solicits information regarding the severity of mood, cognitive, behavioral, and physical symptoms and level of interference in the personal, professional, and interpersonal life domains. Each symptom is rated on a scale of 1 (not present) to 6 (extreme). All women with PMDD had at least a 50% increase in severity of at least 4 mood symptoms in the luteal phase (average score for 7 days before onset of menses) compared with the follicular phase (average score days 5-11). No symptom was rated higher than a 3 (mild) on days 5 to 11, and 4 symptoms were rated at least a 4 (moderate) in severity for at least 2 of the 7 days before onset of menses.

Timing of 1H-MRS Scans

Scans were scheduled to coincide with the period of low gonadal steroid levels (days 3-8; early to mid follicular phase), highest gonadal steroid levels (3-8 days after luteinizing hormone surge; mid luteal phase), and the period of gonadal steroid withdrawal (1-5 days before onset of menses; late luteal phase). Timing of the luteinizing hormone surge was determined using a commercially available urine luteinizing hormone kit (Answer, Carter-Wallace, New York, NY). Blood was obtained for gonadal steroid and neurosteroid determination on each scan day. Serum was assayed for estradiol and progesterone levels by a commercial laboratory (Clinical Laboratory Partners, Hartford, Conn) to confirm menstrual cycle phase. The GABA data were not included in any statistical analysis that included menstrual cycle phase (operationalized group) when hormone levels could not confirm the desired phase.

Table 1. Participant Characteristics*

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>PMDD (n = 9)</th>
<th>Controls (n = 14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>34.6 ± 4.50</td>
<td>30.1 ± 6.23</td>
</tr>
<tr>
<td>Age at menarche, y</td>
<td>12.1 ± 1.62</td>
<td>11.9 ± 1.71</td>
</tr>
<tr>
<td>Age of PMDD onset, y</td>
<td>25.0 ± 4.91</td>
<td>NA</td>
</tr>
<tr>
<td>Cycle length, d</td>
<td>28.9 ± 4.81</td>
<td>28.6 ± 3.30</td>
</tr>
<tr>
<td>DSRP score, follicular</td>
<td>34.9 ± 6.5</td>
<td>25.1 ± 2.6</td>
</tr>
<tr>
<td>DSRP score, luteal</td>
<td>66.1 ± 25.4</td>
<td>25.3 ± 2.3</td>
</tr>
</tbody>
</table>

*Data are presented as mean ± SD. PMDD indicates premenstrual dysphoric disorder; DSRP, Daily Record of Severity of Problems; and NA, not applicable.
lar phase scan data from 1 participant with PMDD and 2 healthy controls were excluded from phase-specific analyses secondary to having estradiol levels of more than 100 pg/mL (367 pmol/L) (indicative of late follicular phase). Data from 2 mid-luteal phase scans (1 PMDD participant, 1 healthy control) were omitted from analyses because of a progesterone level of 299 ng/dL (9.5 nmol/L) or less.

All women participating in the study abstained from drinking alcohol for at least 48 hours before each 1H-MRS scan and had minimal (none to 3 drinks per week) alcohol use at baseline with the exception of one participant with PMDD who regularly drank 10 glasses of wine per week. One participant with PMDD reported smoking 3 to 7 cigarettes per day but abstained from smoking for at least 5 hours before each scan. Daily ratings during the scan month continued to confirm PMDD diagnosis for those included in the study.

MRS METHODS

Studies were performed with a 2.1-T magnet (Oxford Magnetic Technology, Oxford, England) with a 1-m bore and a spectrometer (Bruker Avance; Bruker Instruments, Billerica, Mass). Participants lay supine with the occipital cortex against an 8-cm surface coil tuned to the 1H-MRS frequency of 89.67 MHz. Gradient-echo scout images of the participant’s brain were obtained for participant positioning, and a 1.5 × 3 × 3-cm3 voxel centered on the midline of the occipital cortex, 1.5 cm deep from the dura, was chosen for 1H-MRS. Automated first- and second-order shimming was applied in the volume of interest. Detection of the 3.0 ppm of GABA C4 resonance was performed for 20 minutes using J-editing. Briefly, pairs of subspectra were obtained, one with a frequency selective inversion pulse applied to the GABA C3 resonance and one without the inversion pulse. The subspectra were subtracted to obtain difference spectra that contained total GABA (combined measure of GABA and the GABA-containing dipeptide homocarnosine). Localization was achieved with selective excitation, 3-dimensional, image-selected, in vivo spectroscopy, outer volume suppression, and a surface spoiler coil. The spectral acquisition parameters were as follows: repetition time, 3.39 seconds; echo time, 68 milliseconds; sweep width, 1500 Hz; and acquisition time, 510 milliseconds. The free induction decay was zero-filled to 32 K, processed with 3-Hz lorentzian broadening, zero-time, 510 milliseconds; echo time, 68 milliseconds; sweep width, 1500 Hz; and acquisition time, 510 milliseconds. The free induction decay was zero-filled to 32 K, processed with 3-Hz lorentzian broadening, zero-time, 510 milliseconds; echo time, 68 milliseconds; sweep width, 1500 Hz; and acquisition time, 510 milliseconds.

Mixed models were used to analyze the data on GABA and neurosteroid concentrations in plasma. All outcomes were checked to ensure that they resembled a normal distribution using normal probability plots and Kolmogorov-Smirnov test statistics. Log transformations were used to normalize all outcomes before analysis, except where log transformation did not improve normality of the distribution. Relations between repeated measurements on the same participant and is unaffected by data missing at random. Before analysis, all outcomes were checked to ensure that they resembled a normal distribution using normal probability plots and Kolmogorov-Smirnov test statistics. Log transformations were used when data exhibited positive skewness. Differencing in GABA levels across the 3 phases between the 2 groups (aim 1) were tested in a computer program (SAS PROC MIXED; SAS Institute, Cary, NC) by fitting a mixed model.

Serum estradiol and progesterone levels were determined in a commercial laboratory using heterogeneous competitive magnetic separation assay with a lower limit of detection (LOD) of 30.7 pmol/L and immunoassay techniques with a within-run coefficient of variation of 8.1% at the LOD for estradiol and an LOD of 0.32 nmol/L and coefficient of variation of 9.3% for progesterone. Neurosteroids, including pregnenolone, 3α-dihydroprogesterone (3α-DHP), and allopregnanolone, were determined using gas chromatography–mass spectroscopy (GC-MS) modified from Hubbard et al.29

GC-MS Conditions

The mass spectrometer was a Perkin Elmer Turbomass (negative chemical ionization mode). The gas chromatograph (GC) was an Autosystem XL (Quadrex Corp, New Haven, Conn) equipped with a methylsilicone column (15 m × 0.25 mm inside diameter) with a 0.05-m film thickness. The initial gas chromatograph oven temperature was 150°C, followed by 230°C at 30°C/min, then to 250°C at 1.0°C/min, and finally to 320°C at 30°C/min. Ultrahigh-purity helium was the carrier gas. The gas chromatograph was operated in the splitless mode for the first 0.7 min and then was switched to a split flow. The injection port flow was 1.0 mL min. Methane was used as the reagent gas for negative chemical ionization. The injector and transfer-line temperatures were maintained at 300°C and 310°C, respectively. Selected ions of m/z (mass/charge) 460, m/z 462, and m/z 466 were monitored.

Steroid Extraction and Separation

Steroids in plasma were extracted by solid phase extraction using C18 columns. For plasma samples, the internal standard solution was added, followed by an aliquot of methanol and water (proportion, 50/50), then diluted with deionized water to a final concentration of 3% methanol. Samples were then extracted with C18 columns equilibrated with methanol. The steroid fraction was eluted with methanol, then evaporated to dryness at 40°C.

Steroids were derivatized according to the method of Hubbard et al29 and were reacted in the following order: 50 µL of 2% carboxymethoxyamine hemihydrochloride in pyridine at 60°C for 45 minutes, a volume of 25 µL each of 20% pentafluorobenzyl bromide in acetonitrile and 20% disopropylethylamine in acetonitrile at 45°C for 20 minutes, and 25 µL of acetonitrile and 50 µL of bis(trimethylsilyl) trifluoroacetamide at 40°C for 30 minutes. After each step, the reaction mixture was dried under nitrogen.

All neurosteroids for participants with PMDD and healthy controls were batch run under the same laboratory conditions. The ranges of between-day coefficient of variation for duplicate repeats of samples performed throughout several months were 3.6% to 15% for 5α-DHP, 5.5% to 27% for pregnenolone, and 8.4% to 22% for allopregnanolone.

STATISTICAL METHODS

Mixed models were used to analyze the data on GABA and neuroactive steroid levels. This approach takes into account correlations between repeated measurements on the same participant and is unaffected by data missing at random. Before analysis, all outcomes were checked to ensure that they resembled a normal distribution using normal probability plots and Kolmogorov-Smirnov test statistics. Log transformations were used when data exhibited positive skewness. Differencing in GABA levels across the 3 phases between the 2 groups (aim 1) were tested in a computer program (SAS PROC MIXED; SAS Institute, Cary, NC) by fitting a mixed model.
with a random effect for participant and fixed effects for group, phase, and group × phase interaction. If the group × phase interaction effect was significant at the .05 level, follow-up individual comparisons between the groups at each phase were performed. Bonferroni correction was used for multiple post hoc comparisons.

Similarly, overall and phase between-group differences for each gonadal steroid and neurosteroid (aim 2) were tested by fitting a separate mixed-effects model with the same fixed and random effects described herein. Because phase was an effect in these models, the analyses were performed on the operationalized sample (the results were essentially the same for the entire sample).

The relationship between GABA and each steroid (aim 3) was estimated by fitting a separate mixed model with GABA as the response variable, with a random effect for participant and fixed effects for group, steroid, and group × steroid interactions. Because phase and steroids are usually highly correlated, phase was not used as an effect in this model, and the analysis was performed on the entire sample. When a significant difference in the relationship between GABA and a gonadal steroid or neurosteroid was observed (a significant steroid interaction), a graph with regression line for phase interaction was given in Table 2 (Table 2). Examining GABA data by group, healthy menstruating women experienced a significant decrease in cortical GABA levels from the follicular phase to both the mid luteal phase (F1,25 = −0.20, P = .41) and late luteal phase (F1,25 = 1.67, P = .001) when age was added as a covariate or when those undergoing scanning in an alternate sequence were removed from the analysis. There were no significant group differences in the mid luteal phase (t11 = 0.69, P = .51) and late luteal phase (t8 = 1.67, P = .13) scans with respect to the number of days after luteinizing hormone surge.

**MENSTRUAL CYCLE FLUCTUATIONS IN GABA LEVELS**

Mean GABA, gonadal steroid, and neurosteroid levels are given in Table 2. For the operationalized sample, there was a significant group × phase interaction (F2,27 = 17.9, P < .001) for the cortical GABA data, explained mainly by a significant difference in follicular phase GABA levels (F1,27 = 27.8, P < .001) (Figure 2). These findings continued to be significant when age was added as a covariate or when those undergoing scanning in an alternate sequence were removed from the analysis. There were no significant group differences in the mid luteal phase (F1,25 = −0.20, P = .65) or the late luteal phase (F1,25 = 0.71, P = .41) (Table 2).

Examining GABA data by group, healthy menstruating women experienced a significant decrease in cortical GABA levels from the follicular phase to both the mid luteal phase (F1,25 = 18.2, P < .001) and the late luteal phase (F1,25 = 21.2, P < .001). In contrast, a signific-

### Table 2. Cortical γ-Aminobutyric Acid (GABA) and Peripheral Gonadal Hormone and Neurosteroid Levels Across the Menstrual Cycle in Women With Premenstrual Dysphoric Disorder (PMDD) and Healthy Controls*

<table>
<thead>
<tr>
<th></th>
<th>PMDD</th>
<th>Controls</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GABA, mmol/kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Follicular</td>
<td>0.78 ± 0.23</td>
<td>1.67 ± 0.25</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Mid luteal</td>
<td>1.27 ± 0.55</td>
<td>1.15 ± 0.32</td>
<td>.65</td>
</tr>
<tr>
<td>Late luteal</td>
<td>1.27 ± 0.32</td>
<td>1.12 ± 0.40</td>
<td>.41</td>
</tr>
<tr>
<td>Group × phase analysis</td>
<td>...</td>
<td>...</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Progesterone, nmol/L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Follicular</td>
<td>2.51 ± 1.48</td>
<td>2.41 ± 1.37</td>
<td>.92</td>
</tr>
<tr>
<td>Mid luteal</td>
<td>31.34 ± 11.73</td>
<td>44.59 ± 25.79</td>
<td>.37</td>
</tr>
<tr>
<td>Late luteal</td>
<td>23.37 ± 13.27</td>
<td>8.94 ± 8.38</td>
<td>.01</td>
</tr>
<tr>
<td>Group × phase analysis</td>
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<td>...</td>
<td>.01</td>
</tr>
<tr>
<td>Estradiol, pmol/L</td>
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</tr>
<tr>
<td>Follicular</td>
<td>183.04 ± 95.08</td>
<td>180.81 ± 59.08</td>
<td>.89</td>
</tr>
<tr>
<td>Mid luteal</td>
<td>436.35 ± 230.66</td>
<td>463.39 ± 169.41</td>
<td>.63</td>
</tr>
<tr>
<td>Late luteal</td>
<td>365.90 ± 134.26</td>
<td>230.06 ± 147.91</td>
<td>.02</td>
</tr>
<tr>
<td>Group × phase analysis</td>
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<td>.03</td>
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<tr>
<td>Pregnenolone, nmol/L</td>
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<tr>
<td>Follicular</td>
<td>0.82 ± 0.71</td>
<td>0.83 ± 0.80</td>
<td>.98</td>
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<tr>
<td>Mid luteal</td>
<td>1.79 ± 1.08</td>
<td>0.88 ± 0.62</td>
<td>.07</td>
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<tr>
<td>Late luteal</td>
<td>1.69 ± 1.07</td>
<td>0.54 ± 0.33</td>
<td>.01</td>
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<tr>
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<td>.03</td>
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<tr>
<td>Allopregnanolone, nmol/L</td>
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<tr>
<td>Follicular</td>
<td>1.02 ± 0.75</td>
<td>1.56 ± 0.62</td>
<td>.10</td>
</tr>
<tr>
<td>Mid luteal</td>
<td>4.75 ± 3.47</td>
<td>6.80 ± 2.83</td>
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</tr>
<tr>
<td>Late luteal</td>
<td>4.90 ± 1.67</td>
<td>4.55 ± 3.72</td>
<td>.61</td>
</tr>
<tr>
<td>Group × phase analysis</td>
<td>...</td>
<td>...</td>
<td>.33</td>
</tr>
</tbody>
</table>

*Data are presented as mean ± SD. Ellipses indicate data not applicable. To convert progesterone to ng/dL, divide by 0.0318; and estradiol to pg/mL, divide by 3.67.
cant increase in cortical GABA from the follicular phase to both the mid luteal phase ($F_{1,25}=8.9, P<.006$) and the late luteal phase ($F_{1,25}=9.2, P=.005$) occurred in the women with PMDD. There was no significant between-group difference in the absolute magnitude of the change in cortical GABA levels from the follicular to mid luteal phase ($t_{11}=0.69, P=.51$).

To examine potential effects of subtle between-group differences that may have been imposed by scanning women at different points in the luteal phase with respect to their peak hormone levels and variation in menstrual cycle length, we examined the GABA data with the day of cycle scanned standardized to a 28-day cycle (day of cycle scanned/cycle length × 28). GABA data based on the standardized day of cycle variable were analyzed using a mixed-effects model with a random intercept and a random slope for participant and fixed effects for group, day, and group by day. The findings from this analysis again demonstrated a significant group × day interaction ($F_{1,11}=39.5, P<.001$). History of major depression (n=3) did not seem to have an impact on cortical GABA levels.

**MENSTRUAL CYCLE FLUCTUATIONS IN GONADAL STEROIDS AND NEUROSTEROIDS**

Sufficient data were obtained for estradiol, progesterone, pregnenolone, 5αDHP, and allopregnanolone to allow for meaningful analysis of impact on cortical GABA levels and/or between-group differences in hormone levels. All variables except 5αDHP were log transformed to eliminate positive skewness. Results for progesterone, estradiol, pregnenolone, and allopregnanolone are given in Table 2. With respect to between-group differences in hormone levels, significant group × phase interaction occurred for pregnenolone ($F_{2,26}=3.7, P=.03$), progesterone ($F_{2,25}=5.0, P=.01$), and estradiol ($F_{2,25}=3.96, P=.03$). Between-group differences for these hormones occurred in the late luteal phase (pregnenolone: $F_{1,25}=7.9, P=.009$; progesterone: $F_{1,25}=10.3, P=.004$; and estradiol: $F_{1,25}=6.77, P=.02$), although the late luteal difference in estradiol did not pass the conservative Bonferroni correction. Analysis of between-group difference in 5αDHP levels was limited to the mid luteal phase secondary to limited sensitivity of the assay to detect follicular phase levels. Women with PMDD had significantly higher levels of 5αDHP in the mid luteal phase than healthy controls ($F_{1,12}=5.3, P=.04$).

**RELATIONSHIP BETWEEN PLASMA NEUROACTIVE STEROIDS AND CORTICAL GABA LEVELS**

Significant between-group differences in the relationship between hormones and GABA were observed for estradiol ($F_{1,31}=13.1, P=.001$), progesterone ($F_{1,31}=13.8, P=.001$), allopregnanolone ($F_{1,31}=8.7, P=.01$), and the progesterone-allopregnanolone ratio ($F_{1,31}=5.9, P=.02$). Pregnenolone and the pregnenolone-allopregnanolone ratio had no significant overall or by group impact on GABA levels. As follow-up to the significant interaction tests, separate regression lines were estimated for healthy controls and participants with PMDD and are shown in Figure 3. Estradiol ($β=−.23$; 95% confidence interval [CI], −.42 to −.05), progesterone ($β=−.12$; 95% CI, −.21 to −.04), and allopregnanolone ($β=−.19$; 95% CI, −.34 to −.05) were significantly negatively associated with GABA levels in healthy controls, whereas estradiol and progesterone were significantly positively associated with GABA levels in participants with PMDD (for estradiol: $β=.36$; 95% CI, .08-.63; and for progesterone: $β=.13$; 95% CI, .02-.25). The relationship between cortical GABA levels and allopregnanolone in the PMDD group was not significant ($β=.12$; 95% CI, −.04 to .28).

**COMMENT**

To our knowledge, this report presents the first direct measurement of the cortical level of a neurotransmitter across the menstrual cycle in healthy women and women with PMDD. The most striking finding in this study was the effect of diagnosis on the menstrual cyclicity seen in cortical GABA levels in both groups. Cortical GABA levels decreased across the menstrual cycle in healthy women, whereas the opposite occurred in women with PMDD. These findings were not altered by participant age, whether the data were analyzed for the operationalized group or for the entire sample, or whether the data were analyzed based on day of cycle instead of menstrual cycle phase. Women with PMDD have reduced cortical GABA levels during the follicular phase, but they are not significantly different from healthy counterparts during the mid or late luteal phase. These findings are consistent with those of Schmidt et al,32 who suggest that the pathophysiologic processes responsible for the symptoms associated with PMDD may not be restricted to the late luteal phase. Furthermore, the magnitude of the change in GABA levels from follicular to mid luteal phase was significant in both groups, suggesting that most of the group × phase finding cannot be accounted for by cortical GABA changes in one participant group alone.

Factors other than diagnosis or menstrual cycle phase that may have influenced our findings include potential for instability in the GABA measurement or, alternatively, the presence of a first scan effect. Each of these alternative explanations is improbably based on previ-
changed when women who underwent scanning in an alternate sequence were removed from the analysis.

The decline in cortical GABA levels from the follicular to luteal phase seen in healthy controls in the present study is in contrast to the plasma GABA findings of Halbreich et al. and suggests that peripheral measures of GABA function may not accurately reflect central function. Likewise, we did not detect a difference in cortical GABA levels in those women with PMDD and a history of major depression compared with those without such history; however, our sample size may have been a limiting factor.

The relationship between cortical GABA levels and symptoms in PMDD is in contrast to that of major depression and panic disorder, where symptomatic episodes are associated with reduced occipital cortex GABA. Our follicular phase GABA levels in the PMDD group (mean±SD, 0.78±0.23 mmol/kg brain) were substantially lower than those reported for women with major depression (melancholic subtype) (1.10±0.66 mmol/kg brain) and a group of men and women with panic disorder (1.08±0.30 mmol/kg). In contrast, during the mid and late luteal phases when our participants were symptomatic, their GABA levels were not unlike those of the healthy controls in the present study. Although these findings suggest that follicular phase GABA levels distinguish women with PMDD from those with major depression and support the diagnostic distinction between major depression and PMDD, these findings need to be confirmed in a study of cortical GABA levels in MDD in which menstrual cycle phase is clearly defined. Of interest, our finding of a decrease in cortical GABA levels in healthy controls as the endogenous levels of the neurosteroid GABA agonists rise is consistent with 1H-MRS findings demonstrating a reduction in cortical GABA levels in healthy controls after a single oral dose of 0.5 mg of the GABA agonist clonazepam.

The fact that allopregnanolone levels did not distinguish women with PMDD from healthy counterparts is consistent with most studies but not all. Our finding of higher late luteal phase estradiol and progesterone levels in the PMDD group can be contributed to having studied a greater proportion of these women (50% vs 33%) more than 3 days before the onset of menstrual flow.

In the present study, the relationship between gonadal steroids and cortical GABA levels in healthy women was opposite to that seen in those with PMDD. For healthy women, the rise in estradiol, progesterone, and allopregnanolone levels in the mid luteal phase signaled a decrease in cortical GABA levels that persisted, despite hormonal declines in the late luteal phase. This pattern would be consistent with the hypothesis that these or related hormones directly or indirectly depress GABA synthesis, perhaps via their facilitation of GABA function. However, cautious interpretation of this finding is warranted for several reasons. First, it is curious that estradiol, which is a GABA antagonist and would be expected to oppose the GABA neuronal effects of the 3α-reduced progesterone metabolites, appeared in this study to have either the same directional effect or a weaker antagonistic effect on GABA levels. Second, the gonadal steroid levels, which were determined in a commercial laboratory,
are known to increase in a predictable fashion from the follicular to mid luteal phase. These expected hormonal fluctuations may have enhanced the likelihood of obtaining a significant correlation between hormones and GABA levels, giving the appearance of driving the GABA levels down or up in the healthy controls and participants with PMDD, respectively.

With these caveats considered, the rise in cortical GABA levels across the menstrual cycle and the positive correlation between gonadal steroid levels and cortical GABA levels in participants with PMDD could have several explanations. First, PMDD may be associated with an abnormality in GABA, receptor function that conveys attenuated GABA neuronal sensitivity to the inhibition-enhancing effects of agents that typically facilitate GABA, receptor function. This hypothesis would be consistent with the literature suggesting a luteal phase-specific decrease in cortical inhibition and reduced sensitivity to the behavioral and physiologic effects of a benzodiazepine and the neurosteroid pregnanolone administration in women with PMDD. Our finding that allopregnanolone had a significant impact on cortical GABA levels in healthy controls but not those with PMDD is consistent with these findings. Preclinical studies suggest this phenomenon may be secondary to allopregnanolone-induced expression of the α4 subunit of GABA, which conveys reduced sensitivity to the facilitatory effects of agonists for this receptor.

This study parallels other human studies that indicate that benzodiazepine administration and inhibition of GABA catabolism depress GABA levels, presumably by depression of the expression or function of the GABA synthetic enzyme glutamic acid decarboxylase (GAD67). Continuing with this theory, these findings suggest that feedback inhibition of GAD67 by GABA, receptor agonists outweighs the stimulatory effects of estradiol on GAD67 activity reported in some brain regions in rodents. For example, the rise in cortical GABA levels across the menstrual cycle could reflect the induction of factors that reduce GABA, receptor function in the luteal phase and contribute to anxiety in patients with PMDD.

However, this study has several limitations that influence interpretation of its results. This study was unable to differentiate whether fluctuations in cortical GABA levels reflect changes in GABA synthesis or GABA turnover. This distinction may become possible as carbon 13 MRS techniques are developed for directly measuring these processes. The naturalistic design of this study limits the ability to determine the impact of individual hormones on cortical GABA levels. This could be rectified by conducting H-MRS studies in menstruating women using gonadotropin-releasing hormone agonists with add-back paradigm to isolate the effects of individual hormones on cortical GABA levels. Finally, although the occipital cortex receives input from many cortical and limbic regions, it is not generally implicated in the pathogenesis of mood disorders. Therefore, the findings of this study may be “downstream” from the neural circuitry of mood regulation.

In summary, this study documented menstrual cycle-related changes in cortical neurotransmitter chemistry in healthy women. Future studies will be needed to further characterize the nature and functional consequences of this phasic GABAergic modulation in healthy women. This finding also highlights the importance of incorporating menstrual cycle phase within clinical research designs involving menstruating women.

This study also begins the important and complicated process of mapping the neurochemical determinants of PMDD. Premenstrual dysphoric disorder presents unique challenges to the study of brain chemistry. Postmortem studies of cortical neurotransmitter systems in PMDD are probably impossible for several reasons: (1) valid diagnosis requires prospective assessment during multiple menstrual cycles; therefore, retrospective assessments from unintentional deaths are not likely to be useful; (2) life-threatening illnesses generally impair the regulation of the menstrual cycle and therefore prevent the use of brain tissue collected from young women; and (3) the onset of menopause prevents the use of brain tissue collected from elderly patients. Therefore, in conjunction with a solid foundation in preclinical research, molecular brain imaging, despite its limitations, seems uniquely suited for exploring the neurochemistry of PMDD.

Submitted for publication October 19, 2001; final revision received March 7, 2002; accepted March 15, 2002.

This study was funded in part by the National Institute of Mental Health (grant K23 MH01830-01) (Dr Epperson); the National Alliance for Research in Schizophrenia and Depression (Young Investigator Award) (Dr Weiss, Epperson, and Mason); and the National Institute of Neurological Disorders and Stroke (grant T32 NS07416-01) (Dr Haga). Additional support for this study came from the Department of Veterans Affairs (National Center for Posttraumatic Stress Disorder, Alcohol Research Center) and the National Institute of Alcohol Abuse and Alcoholism (grants P50 AA12870-01 and KO2 AA 00261-01).

Dr Epperson thanks Peter Schmidt, MD, and Robert H. Purdy, PhD, for their insightful mentorship. In addition, we thank Kathryn Czarkowski, MS, for her help in recruiting and managing participants and Shani Osbourne, BA, for her technical support.

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