

# Depression: The Case for a Monoamine Deficiency

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The monoamine hypothesis of depression predicts that the underlying pathophysiologic basis of depression is a depletion in the levels of serotonin, norepinephrine, and/or dopamine in the central nervous system. This hypothesized pathophysiology appears to be supported by the mechanism of action of antidepressants: agents that elevate the levels of these neurotransmitters in the brain have all been shown to be effective in the alleviation of depressive symptoms. However, intensive investigation has failed to find convincing evidence of a primary dysfunction of a specific monoamine system in patients with major depressive disorders. Understanding of the etiology of depression has been hampered by the absence of direct measurements of monoamines in humans. However, the monoamine depletion paradigm, which reproduces the clinical syndrome, allows a more direct method for investigating the role of monoamines. Results from such studies show that antidepressant responses are transiently reversed, with the response being dependent on the class of antidepressant. In contrast, monoamine depletion does not worsen symptoms in depressed patients not taking medication, nor does it cause depression in healthy volunteers with no depressive illness. In conclusion, it is clear that antidepressant agents in current use do indeed require intact monoamine systems for their therapeutic effect. However, some debate remains as to the precise role that a deficiency in monoamine system(s) may play in depression itself.

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The monoamine hypothesis of depression proposes that there is a depletion in the levels of serotonin, norepinephrine, and/or dopamine in the central nervous system.<sup>1</sup> In the 1950s, reserpine, which depletes central stores of monoamines, was shown to induce depression. Reserpine was also shown to induce aspects of depression such as motor retardation and sedation in animal models. In contrast, the monoamine oxidase inhibitor iproniazid produced an antidepressant effect when administered to tubercular patients; iproniazid was later found to improve mood in depressed nontubercular patients.

For many years, the neurobiological basis of depression has been linked to the mechanism of action of antidepressants. Newer antidepressants that elevate levels of serotonin (5-hydroxytryptamine, or 5-HT), norepinephrine,

and/or dopamine in the brain have been shown to alleviate effectively the symptoms of depression. Although there is substantial evidence to support a role for the monoamine systems in the mechanism of action of antidepressants,<sup>2</sup> intensive investigation has failed to find convincing evidence of a primary dysfunction of a specific monoamine system in patients with major depressive disorders.<sup>3</sup>

Understanding the relationship of monoamine systems to therapeutic antidepressant responses and the neurobiology of depression has been hindered by the lack of direct measurements of monoamines in humans. The monoamine depletion paradigm provides a more direct method for investigating the role of monoamines in drug action and mental illness, since the primary outcome measure is the capacity to reproduce the clinical syndrome itself.<sup>4-6</sup>

## INDIRECT EVIDENCE FOR THE ROLE OF MONOAMINES IN DEPRESSION

### Serotonin

Substantial indirect evidence supports the hypothesis that a dysfunctional serotonergic system may play a role in depression. Levels of the major serotonin metabolite 5-hydroxyindoleacetic acid (5-HIAA) have been reported to be lower than normal in the cerebrospinal fluid (CSF) of patients with depression<sup>7</sup>; however, this is not a consistent observation.<sup>8</sup> In addition, low concentrations of 5-HIAA in the CSF have been found to correlate with violent sui-

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cide.<sup>9,10</sup> The number of serotonin transporter sites and the uptake of serotonin are both reduced in the platelets of antidepressant-naïve depressed patients, a model for neuronal serotonin receptors.<sup>11,12</sup> Interestingly, there was no alteration in the number of transporter sites in patients with panic disorder, mania, Alzheimer's disease, fibromyalgia, or atypical depression, suggesting a specificity for major depression.<sup>12</sup> Chronic antidepressant treatment with imipramine or fluoxetine has been shown to produce a significant reduction (40%–50%) in serotonin transporter messenger RNA in the raphe nuclei.<sup>13</sup>

Several investigators have also reported an increase in the density of postsynaptic 5-HT<sub>2</sub> receptor binding sites in the frontal cortices of depressed suicide victims and unmedicated depressed patients.<sup>14,15</sup> These observations correlate well with recent observations of increased numbers of 5-HT<sub>2A</sub> and 5-HT<sub>2</sub> receptors on platelets of patients with major depression and suicidal patients, respectively.<sup>16,17</sup> It has been suggested that up-regulation of cortical 5-HT<sub>2</sub> receptors in depression is an adaptive response to reduced synaptic serotonin.<sup>12</sup>

### Norepinephrine

Although levels of the major norepinephrine metabolite 3-methoxy-4-hydroxyphenylglycol (MHPG) have been measured in urine, plasma, and CSF of patients with depression, there is little correlation between MHPG levels and depressive symptoms. Indeed, increased, decreased, and unchanged urinary MHPG concentrations have all been reported in depressed patients.<sup>18–22</sup> However, patients with low urinary MHPG levels have been reported to be responsive to imipramine treatment,<sup>18</sup> and patients with low urinary MHPG levels respond more robustly to treatment with tricyclic and tetracyclic antidepressants than do patients with high MHPG levels.<sup>23–25</sup> The binding of [<sup>3</sup>H]-nisoxetine (a ligand for the norepinephrine reuptake transporter) has been reported to be significantly reduced in the locus ceruleus obtained postmortem from suicide victims and patients with depression compared with control subjects.<sup>26</sup> Chronic administration of desipramine has also been reported to decrease [<sup>3</sup>H]-nisoxetine binding in several brain areas, including the hippocampus.<sup>27</sup>

Presynaptic  $\alpha_2$ -adrenoceptors may also play an important physiologic role in the regulation of the release of norepinephrine.<sup>28</sup> Enhanced autoreceptor activity and the subsequent decrease of norepinephrine could be involved in the etiology of depression: the density and affinity of  $\alpha_2$ -adrenoceptors are increased in the frontal cortex and, to a lesser extent, in the hypothalamus, amygdala, hippocampus, and cerebellum of depressed suicide victims.<sup>29</sup> In addition, an increase in the affinity and density of  $\alpha_2$ -adrenoceptors on isolated human platelets from depressed patients has also been reported.<sup>30</sup> Antidepressant drug treatment and electroconvulsive therapy are associated with a decrease in the density of  $\alpha_2$ -adrenoceptors and

in the affinity of ligands at these receptors in platelets from depressed patients.<sup>31</sup> Measurement of the up-regulation of  $\beta$ -adrenoceptors in patients with depression has been shown to be reproducible, and their down-regulation is regarded as a marker of antidepressant efficacy.<sup>32</sup>

## RATIONALE FOR MONOAMINE DEPLETION STUDIES

If the underlying pathophysiology of depression is indeed a deficiency in specific central neurotransmitter systems as predicted by the monoamine hypothesis, then depletion of monoamines should have specific effects on depressive symptoms in particular groups of patients. By reducing the central levels of a particular neurotransmitter in a transient and reversible manner, we can investigate its importance in mental illness.

Since the synthesis of serotonin is entirely dependent on the availability of its precursor amino acid tryptophan, manipulation of tryptophan levels in the central nervous system will affect serotonin transmission. Tryptophan is an essential amino acid and humans must obtain it from dietary sources; therefore, it is a relatively straightforward process to deplete brain serotonin stores by administration of a tryptophan-free amino acid drink. This effect has been demonstrated in animal studies.<sup>33,34</sup>

The manipulation of central norepinephrine has been approached in a slightly different fashion, although the principle remains the same. The first and rate-limiting step in the synthesis of catecholamines is the conversion of tyrosine to L-3,4-dihydroxyphenylalanine (L-dopa) by the enzyme tyrosine hydroxylase. This step can be inhibited reversibly by the administration of  $\alpha$ -methyl-*p*-tyrosine (AMPT), which therefore inhibits the production of norepinephrine (and dopamine).

## PREDICTIONS FOR THE RESULTS OF DEPLETION STUDIES

The indirect evidence outlined above suggests that a dysfunction in the serotonergic and/or noradrenergic systems may be implicated in the etiology of depression. Assuming the monoamine hypothesis holds true, what might we expect to observe when monoamines are depleted in humans with or without depression?

### Depressed Patients in Remission on Antidepressant Treatment

Since many current antidepressants function by inhibiting the reuptake of norepinephrine or serotonin, or both neurotransmitters, it seems straightforward to predict that depletion of serotonin with a tryptophan-free drink will exacerbate or cause a return to depressive symptoms in patients treated with selective serotonin reuptake inhibitors (SSRIs), and that treatment with AMPT will worsen

**Table 1. Predictions for the Recurrence of Depressive Symptoms During Depletion Studies, Based on the Monoamine Hypothesis of Depression<sup>a</sup>**

Subjects	Serotonin Depletion	Catecholamine Depletion
Healthy	++	++
Depressed, no medication	+	+
Recovered while taking SSRI	+++	-
Recovered while taking NRI	-	+++
Recovered while taking NaSSA	+++	+++

<sup>a</sup>Abbreviations: NaSSA = norepinephrine and specific serotonergic antidepressant, NRI = norepinephrine reuptake inhibitor, SSRI = selective serotonin reuptake inhibitor. Symbols represent grades of response (arbitrary units).

depressive symptoms in patients taking norepinephrine reuptake inhibitors (NRIs) (Table 1). Patients who are in remission and taking an agent such as a norepinephrine and specific serotonergic antidepressant (NaSSA) that inhibits reuptake in both systems might be expected to experience an increase in depressive symptoms when either monoamine is depleted.

#### Patients With Depression But Not Taking Medication

In this group of patients, the monoamine hypothesis predicts that patients would feel more depressed during monoamine depletion, although the actual change in depressive symptomatology might depend on the remaining level of functioning of the neurotransmitter system in question.

#### Healthy Subjects

If a deficiency of one or other of the monoamine neurotransmitter systems underlies depression, then depletion of monoamines might be expected to induce depressive symptoms in healthy subjects.

### RESULTS OF MONOAMINE DEPLETION STUDIES

The results of monoamine depletion studies undertaken by our group are summarized in Table 2.

#### Depressed Patients in Remission on Antidepressant Treatment

Our first study of the effects of tryptophan depletion showed that 14 (67%) of 21 patients responding to antidepressant medication in the 2 weeks prior to testing experienced a relapse of depressive symptoms (50% increase in Hamilton Rating Scale for Depression [HAM-D] with total score  $\geq 17$ ) within 5 to 7 hours of tryptophan depletion, but not during control treatment.<sup>4</sup> Symptoms were reported by the patients to be the same as those experienced prior to antidepressant therapy. Patients who had responded successfully to the relatively selective norepinephrine reuptake inhibitor desipramine were much less

**Table 2. Observed Results of Monoamine Depletion Studies: Recurrence of Depressive Symptoms During Depletion<sup>a</sup>**

Subjects	Serotonin Depletion	Catecholamine Depletion
Healthy	-	$\pm$
Depressed, no medication	-	-
Recovered while taking SSRI	++++	+
Recovered while taking NRI	+	++++
Recovered while taking NaSSA	++++	++++

<sup>a</sup>Data from references 4, 35–43. Symbols: - = no effect,  $\pm$  = mild effects in some subjects, + = 20%–25% of patients, ++++ = 50%–80% of patients.

likely to relapse (20% relapse rate) than those who had responded to an SSRI or monoamine oxidase inhibitor (90% relapse rate). These results have been confirmed in a study of patients who were either antidepressant treatment-naïve or who had previously responded successfully to treatment.<sup>35</sup> These patients were depleted of tryptophan in a double-blind manner after having responded for at least 2 weeks to treatment with either desipramine or fluoxetine. Six (46%) of the 13 responders to fluoxetine experienced a relapse, while only 1 desipramine responder (8%) of 13 relapsed.

In a similar study, we investigated the effects of catecholamine depletion in depressed patients randomly assigned to either desipramine or fluoxetine.<sup>36,37</sup> Thirteen (81%) of 16 desipramine responders relapsed during AMPT testing, whereas only 1 (6%) relapsed during testing with diphenhydramine as active control. In contrast, 4 (19%) of 21 fluoxetine responders relapsed during catecholamine depletion, as did 3 (14%) during control treatment.

We have also investigated the effects of monoamine depletion in patients maintained on treatment with mirtazapine, an antidepressant with effects on both the serotonergic and noradrenergic systems. In a crossover study, tryptophan and catecholamine depletion were equally as likely to cause relapse in these patients.<sup>38</sup>

#### Patients With Depression But Not Taking Medication

We depleted 43 drug-free depressed patients of tryptophan in a double-blind, placebo-controlled crossover study.<sup>39</sup> In contrast to changes seen in patients on antidepressant treatment, there was only minimal change in the HAM-D score on the day of the test, and, on the day following the test, some patients experienced a worsening of symptoms, while others actually experienced an improvement. Also, there was no correlation between plasma tryptophan levels and change in HAM-D score on any day of the test.

We noted a similar lack of exacerbation of symptoms during catecholamine depletion in 50 drug-free depressed patients.<sup>40</sup> There was minimal change in mood during or after depletion, and there were no significant differences in HAM-D scores between AMPT and placebo testing.

## Healthy Subjects

Tryptophan depletion caused minimal symptoms in healthy subjects with no personal or family history of depression.<sup>41–43</sup>

## Monoamine Depletion and Vulnerability to Depression

In contrast to their results with healthy patients, Benkelfat et al.<sup>41</sup> reported that about 30% of subjects with a family history of affective disorders showed an increase in depressive symptoms during tryptophan depletion. We have investigated this effect further in a study of history-positive subjects who were currently remitted, but who were not taking any antidepressant medication.<sup>42,43</sup> Tryptophan depletion caused a significant increase in HAM-D score in all 12 history-positive subjects, although only 25% of the history-positive subjects actually relapsed. No significant changes in HAM-D scores in the 12 control subjects were found.

Similar results were observed in a study of women who had recovered from recurrent episodes of major depression, but who were not taking medication.<sup>6</sup> In the majority of subjects, tryptophan depletion induced a return of their depressive symptoms.

## DISCUSSION

The results of monoamine depletion studies in depressed patients currently on drug treatment can be interpreted as providing support for the hypothesis that depression is a dysfunction of the central neurotransmitter(s) norepinephrine and/or serotonin, and that restoration of neurotransmitter function by reuptake inhibition provides an effective method to treat depression. However, it is also clear from the depletion studies in medication-free symptomatic patients and healthy subjects that this is not the complete picture. The failure to exacerbate or precipitate depressive symptoms in these subjects implies that a simple lesion in the serotonergic and/or noradrenergic systems is unlikely to be the simple cause of depression. For instance, if the dysfunction in the monoamine system is not at the level of neurotransmitter (i.e., presynaptic), but in the ability of the neuronal system to recognize and/or use the neurotransmitter, alterations in the levels of monoamine would not affect depressive symptoms. It is well known that the response to antidepressant therapy is delayed and that improvement in mood is not observed until several days or weeks following treatment. This suggests that antidepressant effects may involve an alteration of the ability or sensitivity of the postsynaptic neurons to respond to monoamines.<sup>3,44</sup> Only after this had occurred would changes in the monoamine levels have any effect. Possible subcellular loci for a dysfunction of the postsynaptic receptors are discussed by Leonard (this supplement).<sup>45</sup>

Determination of the precise pathophysiology of depression therefore requires considerable further research.

However, it seems likely that a shift of focus toward understanding the adaptive changes induced by antidepressants may yield further insights into the underlying neurobiological basis of depression.

*Drug names:* desipramine (Norpramin, Pertofram and others), diphenhydramine (Benadryl and others), fluoxetine (Prozac, Fluctin), mirtazapine, (Remeron, Zispin, and others), reserpine (Serpassil and others).

*Disclosure of off-label usage:* The author has determined that, to the best of his knowledge, no investigational information about pharmaceutical agents has been presented in this article that is outside U.S. Food and Drug Administration–approved labeling.

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