

Article

Long-Term Oral Tamoxifen Administration Decreases Brain-Derived Neurotrophic Factor in the Hippocampus of Female Long-Evans Rats

Laura E. Been ^{1,*}, Amanda R. Halliday ¹, Sarah M. Blossom ¹, Elena M. Bien ¹, Anya G. Bernhard ¹, Grayson E. Roth ¹, Karina I. Domenech Rosario ¹, Karlie B. Pollock ¹, Petra E. Abramenko ¹, Leily M. Behbehani ¹, Gabriel J. Pascal ¹ and Mary Ellen Kelly ^{1,2}

¹ Department of Psychology and Neuroscience Program, Haverford College, Haverford, PA 19041, USA; amandarhalliday@gmail.com (A.R.H.); smblossom17@gmail.com (S.M.B.); ebien@haverford.edu (E.M.B.); anyagolombek@gmail.com (A.G.B.); grayson.roth30@gmail.com (G.E.R.); kdomenech998@gmail.com (K.I.D.R.); karlie.pollock@yahoo.com (K.B.P.); petra.abramenko@gmail.com (P.E.A.); leily.behbehani@gmail.com (L.M.B.); gabriel.pascal@jefferson.edu (G.J.P.); kellymek@sas.upenn.edu (M.E.K.)

² Neuroscience Program, University of Pennsylvania, Philadelphia, PA 19104, USA

* Correspondence: lbeen@haverford.edu; Tel.: +1-610-896-1017

Simple Summary: Tamoxifen is prescribed to premenopausal patients with estrogen-receptor-positive breast cancers for a period of 5–10 years after cancer diagnosis. This prolonged treatment regimen, though effective at preventing cancer recurrence, is often associated with unwanted cognitive and affective symptoms. To understand the clinical side effects of tamoxifen, animal studies investigating the effect of tamoxifen on the brain must model the chronic nature of tamoxifen therapy. This study describes a novel method of tamoxifen administration in female rats conducive to long-term administration of tamoxifen. Blood samples from treated rats showed levels of tamoxifen similar to levels in humans. Brain samples revealed tamoxifen-induced changes of a neurotrophic factor in the hippocampus, a structure critical to cognitive and affective processing. This study, therefore, suggests a potential mechanism that may underlie the cognitive side effects reported in patients.

Abstract: Tamoxifen, a selective estrogen receptor modulator (SERM), is commonly used as an adjuvant drug therapy for estrogen-receptor-positive breast cancers. Though effective at reducing the rate of cancer recurrence, patients often report unwanted cognitive and affective side effects. Despite this, the impacts of chronic tamoxifen exposure on the brain are poorly understood, and rodent models of tamoxifen exposure do not replicate the chronic oral administration seen in patients. We, therefore, used long-term ad lib consumption of medicated food pellets to model chronic tamoxifen exposure in a clinically relevant way. Adult female Long-Evans Hooded rats consumed tamoxifen-medicated food pellets for approximately 12 weeks, while control animals received standard chow. At the conclusion of the experiment, blood and brain samples were collected for analyses. Blood tamoxifen levels were measured using a novel ultra-performance liquid chromatography–tandem mass spectrometry assay, which found that this administration paradigm produced serum levels of tamoxifen similar to those in human patients. In the brain, brain-derived neurotrophic factor (BDNF) was visualized in the hippocampus using immunohistochemistry. Chronic oral tamoxifen treatment resulted in a decrease in BDNF expression across several regions of the hippocampus. These findings provide a novel method of modeling and measuring chronic oral tamoxifen exposure and suggest a putative mechanism by which tamoxifen may cause cognitive and behavioral changes reported by patients.

Keywords: breast cancer; hormone therapy; brain; growth factor; estrogen receptor; animal model; cognition; memory



Citation: Been, L.E.; Halliday, A.R.; Blossom, S.M.; Bien, E.M.; Bernhard, A.G.; Roth, G.E.; Domenech Rosario, K.I.; Pollock, K.B.; Abramenko, P.E.; Behbehani, L.M.; et al. Long-Term Oral Tamoxifen Administration Decreases Brain-Derived Neurotrophic Factor in the Hippocampus of Female Long-Evans Rats. *Cancers* **2024**, *16*, 1373. <https://doi.org/10.3390/cancers16071373>

Academic Editors: John R. Hawse and Andrea Manni

Received: 22 December 2023

Revised: 24 January 2024

Accepted: 29 March 2024

Published: 31 March 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Tamoxifen is a common adjuvant drug therapy used to decrease the recurrence risk of estrogen-receptor-positive breast cancers [1–3]. The mechanism of action of tamoxifen depends on its location in body tissue and the local estradiol environment [3]. Generally, tamoxifen acts as an antagonist in the presence of endogenous estradiol but is agonistic and protects against the effects of estrogen depletion in the absence of endogenous estradiol [3,4]. Thus, it has been termed a selective estrogen receptor modulator (SERM). Patients typically take tamoxifen orally for 5–10 years following or concurrent with primary cancer treatment [2].

While tamoxifen is effective at decreasing the risk of cancer recurrence due to its antagonistic effects in breast tissue [2], people undergoing chronic tamoxifen treatment report unwanted psychological side effects, such as anxiety, depression, brain fog, confusion, and memory impairment [1,3,5,6]. Long-term tamoxifen therapy has been shown to decrease performance on visuospatial, visual, and verbal memory tasks [6–9], decision-making tasks [9,10], and impair overall executive function [7,11]. However, it has been difficult to separate the effects of tamoxifen from the effects of primary cancer treatments, other adjuvant therapies, such as aromatase inhibitors [12], and the psychosocial effects of being a cancer survivor [13].

As in people, tamoxifen treatment in rodents can lead to affective and cognitive changes; however, the impact of tamoxifen on cognitive–behavioral outcomes varies depending on the hormone status of the subjects [3]. For example, tamoxifen administration to gonad-intact female rodents has been shown to increase anxiety- and depressive-like behaviors [4], decrease memory consolidation and retrieval ability on step-down avoidance tasks [14], and decrease novel object recognition ability [15]. In ovariectomized rodents, on the other hand, tamoxifen administration is protective against anxiety- and depressive-like behaviors [4] and improves working memory ability [16]. Because tamoxifen is more commonly used in premenopausal patients [2], its effects on gonad-intact female rodents are of particular interest. Notably, previous rodent studies have not modeled chronic oral tamoxifen use and instead have used a variety of tamoxifen administration methods, including long-term injections [17], short-term or one-time injections [14,16,18], and short-term gavages [15].

The hippocampus is a strong putative candidate to mediate some of the cognitive side effects of tamoxifen therapy. First, the hippocampus expresses α - and β -estrogen receptors (ER α and ER β , respectively) across its various subregions [19–22]. Research in rodents has demonstrated that estradiol fluctuations impact hippocampal neurophysiology [22,23], which in turn affects depressive- and anxiety-like behaviors [24,25], as well as performance on spatial memory tasks [19,21]. Within hippocampal neurons, brain-derived neurotrophic factor (BDNF) may play an important role in mediating tamoxifen’s effects on cognition and emotion. As serum levels of estradiol increase, BDNF expression in the hippocampus increases as well [20,26,27]. Estrogen receptor activation influences BDNF transcription via estrogen response elements (EREs) that bind to the BDNF gene [20,21,28,29]. Finally, estradiol has been shown to mediate both synaptogenesis [30] and long-term potentiation [21] through its interactions with BDNF.

Taken together, this evidence suggests that tamoxifen’s impact on cognition and emotion may be mediated by BDNF expression in the hippocampus. We, therefore, hypothesized that long-term oral tamoxifen administration would decrease BDNF expression in the hippocampus. To test this hypothesis, we established a model of long-term oral tamoxifen administration in adult, gonad-intact female Long-Evans rats. The need to administer tamoxifen for several weeks requires a protocol that allows for self-administration of tamoxifen, similar to that of human patients, with minimal stress. This paper will convey the adaptations made to our initial protocol that resulted in several weeks of self-administration of a clinically relevant dose of tamoxifen. Using a novel ultra-performance liquid chromatography–tandem mass spectrometry (LC-MS/MS) detection method, we found that this long-term oral administration produced serum levels of tamoxifen compa-

rable to serum levels in humans taking tamoxifen as an adjuvant therapy [31]. Brain tissue analyses found that tamoxifen-treated animals had significantly lower BDNF expression in the DG, medial CA3, and CA1. These results provide an important first step in characterizing the effect of long-term oral tamoxifen administration on the hippocampus and may increase our understanding of the cognitive and affective side effects associated with long-term tamoxifen use.

2. Materials and Methods

2.1. Subjects

For all experiments, adult female Long-Evans Hooded rats were purchased from Charles River Laboratories (Wilmington, Massachusetts) at 3–4 months of age. Animals were housed in pairs in standard cages (17.7 × 9.4 in × 8.26 in; Allentown LLC, Allentown, NJ, USA) containing standard TekFresh cellulose low-dust rat bedding (Teklad 7099; Inotiv, West Lafayette, IN, USA), and a Plexiglas tube (Bio-Serv, Flemington, NJ, USA) and wooden block (Bio-Serv, Flemington, NJ, USA) for enrichment. Subjects were kept on a 12 hour light–dark cycle with ad libitum food and water access.

2.2. Tamoxifen Self-Administration

Animals were divided into two experimental groups: tamoxifen ($n = 20$) and control ($n = 16$). Animals in the tamoxifen group consumed tamoxifen ad libitum for 10–13 weeks via medicated food pellets (Envigo, Indianapolis, IN, USA) that were custom developed to simulate the standard dose of tamoxifen prescribed to premenopausal people diagnosed with breast cancer (20 mg daily), while control animals received an ingredient-matched rodent feed (16% protein, 55% carb, and 3.4% fat) that did not contain tamoxifen (Envigo) [31]. The composition of the feed was identical between the two groups, except for the addition of tamoxifen, red food coloring, and sucrose to enhance palatability in the medicated food pellets (Table 1). Importantly, the base pellet that both experimental groups received (2016, Teklad Global 16% Protein Rodent Diet) did not contain alfalfa or soybean meal, thus minimizing the occurrence of phytoestrogens in control rats during the time they were housed at Haverford College.

Table 1. Formula composition of medicated and non-medicated pellets.

	Tamoxifen Diet (g/Kg)	Control Diet (g/Kg)
2016, Teklad Global 16% Protein Rodent Diet ¹	949.75	1000
Sucrose	49.96	0.00
Tamoxifen USP	0.04	0.00
Red Food Color	0.25	0.00

¹ For detailed formulation of the 2016 Teklad Global 16% Protein Rodent Diet, see Inotiv.com.

Body weight was monitored for all animals, regardless of experimental group, throughout the drug administration period. Rats that lost more than 15% of their starting body weight, regardless of experimental group, were presented with their respective food pellets (either tamoxifen-enhanced pellets or standard chow, according to experimental group) mashed in a flavor-enhanced, nutritionally fortified gel (DietGel Recovery, Clear H2O, Portland, ME, USA), in addition to ad libitum access to chow to further enhance palatability and encourage ingestion until their weight stabilized. Starting at six weeks into the experiment, all rats in the tamoxifen group were presented with this mash daily to maintain adequate health, while also ensuring adequate consumption of tamoxifen (Figure 1). Control rats also received chow mashed in nutritionally fortified gel at several time points throughout the experiment. As an additional check on animal health, starting at 6 weeks, body condition was assessed daily with the Body Condition Scale [32] (see Supplementary Figure S1). All rats in the tamoxifen and control groups were assigned scores of 3 (well-conditioned) or above. Final weight checks were conducted prior to euthanization.

2.3. Blood Analysis

Following 10–13 weeks of access to medicated or control pellets, animals were euthanized via intracardial perfusion (see below). Blood samples were collected from the inferior vena cava immediately prior to perfusion and stored in heparin-coated vacutainer blood collection tubes (BD Medical, Franklin Lakes, NJ, USA) on ice until centrifugation. Samples were centrifuged at 2300 g at 4 °C for 20 min and serum was stored at –80 °C until the assay.

An ultra-performance liquid chromatography–tandem mass spectrometry assay with reversed-phase chromatographic separation, employing a Waters XBridge C18 (100 × 2.1 mm, 100 Å, 3.5 µm) and a runtime of 4.5 min, was used to quantify tamoxifen levels. Rat plasma samples (100 µL) were extracted with acetonitrile containing tamoxifen-d5 (5 ng/mL) and 0.1% formic acid. Two µL of the extract was injected onto the UPLC-MS/MS system for analysis.

Tamoxifen and tamoxifen-d5 were separated by ultra-performance liquid chromatography (UPLC, Sciex, Framingham, MA, USA) and detected using a triple-quadrupole mass spectrometer (API4000). Tandem mass spectrometry (MS-MS) parameters were optimized in the positive ionization mode, and multiple-reaction monitoring (MRM) transition of m/z 372.3 → 72.0 was used for tamoxifen analysis. Tamoxifen-d5 (m/z 377.3 → 72.0) was used as an internal standard. A calibration curve for tamoxifen was prepared in human plasma over the linear range of 0.1 → 250 ng/mL ($r^2 > 0.99$; Figure 2 and Table 2). Calibration standards and blanks in human plasma were extracted by protein precipitation with 400 µL of 5 ng/mL of tamoxifen-d5 in acetonitrile. Five µL of extract was injected for LC-MS/MS analysis. Tamoxifen and tamoxifen-d5 were separated on an XBridge C18 column (100 × 2.1 mm, 100 Å, 3.5 µm) using 0.1% formic acid in water and 0.1% formic acid in acetonitrile as aqueous and organic mobile phases, with a flow rate of 0.5 mL/min. Analytes were separated using a gradient elution, with a retention time of 2.68 min for tamoxifen and tamoxifen-d5. The LC-MS tamoxifen assay used here was based on assays initially developed and validated in human plasma [33,34]. Therefore, as a confirmatory assay, human plasma and rat plasma were compared using 100 ng/mL concentrations of tamoxifen and found to be comparable (Table 3).

Table 2. Summary of the tamoxifen calibration curve in plasma. A calibration curve for tamoxifen was prepared in human plasma and was linear over the range of 0.1–250 ng/mL with coefficient of regression, $r^2 > 0.99$. Data are presented as mean, standard deviation (SD), accuracy (%), and coefficient of variation (CV %).

Calibration Curve (<i>n</i> = 6)	Tamoxifen Concentration (ng/mL)									
	0.1	0.5	1	2.5	5.0	10	25	50	100	250
1	0.108	0.528	1.00	2.61	5.11	10.5	29.4	46.4	108	270
2	0.117	0.533	1.11	2.61	4.84	10.3	27.4	48.4	107	253
3	0.104	0.484	0.95	2.69	4.79	10.2	29.2	54.0	109	247
4	0.090	0.479	0.88	2.08	4.25	9.55	25.2	47.9	95.6	266
5	0.091	0.566	0.922	2.49	5.06	10.5	27.9	52.9	92.1	234
6	0.092	0.467	0.841	2.18	4.25	9.38	24.8	46.5	97.2	230
Mean	0.100	0.511	0.949	2.44	4.72	10.1	27.3	49.4	101	250
SD	0.011	0.040	0.096	2.53	0.382	0.487	1.95	3.29	7.35	16.3
Accuracy (%)	100	102	94.9	97.7	94.3	101	109	98.7	101	100
CV (%)	11.1	7.79	10.1	10.4	8.09	4.84	7.15	6.66	7.25	6.52

Table 3. Human plasma and rat plasma comparison. The tamoxifen assay was initially developed in human plasma. Human plasma and rat plasma were compared using 100 ng/mL concentrations of tamoxifen. Results were comparable between human and rat plasma. Data are presented as concentration (ng/mL), mean, standard deviation (SD), coefficient of variation (% CV), and accuracy (%).

	Concentration (ng/mL)	Mean \pm SD	% CV	% Accuracy
Human Plasma	100	101 \pm 7.35	7.25	101
Rat Plasma	100	97.62 \pm 2.01	2.06	97.6

2.4. Tissue Histology and Immunohistochemistry

Immediately following blood collection (see above), subjects were sacrificed by intracardial perfusion. Briefly, subjects were administered an overdose of sodium pentobarbital (Beuthanasia-D, 22 mg/100 g body weight, Merck Animal Health, Madison, NJ, USA) and then transcardially perfused with approximately 250 mL of 25 mM phosphate-buffered saline (PBS), followed by approximately 250 mL of 4% paraformaldehyde in PBS. Brains were immediately extracted and post-fixed in 4% paraformaldehyde overnight and then cryoprotected for 48 h in 30% sucrose in PBS. Coronal sections (35 μ m) were sectioned at -20° C on a cryostat (Leica Biosystems, Wetzlar, Germany), collected in a 1:6 series, and stored in cryoprotectant until immunohistochemical processing.

For immunohistochemistry, hippocampal sections were removed from the cryoprotectant and rinsed for 5 \times 5 min in 25 mM PBS. After PBS washes, sections were incubated in hydrogen peroxide (1:100) for 15 min to reduce endogenous peroxidase activity. Sections were then washed for 5 \times 5 min in 25 mM PBS before incubation in a rabbit monoclonal primary antibody against brain-derived neurotrophic factor (1:3000, Cat # ANT-010, Alomone Labs, Jerusalem, Israel) in 0.4% Triton-X 100 in PBS for 24 h at room temperature. This antibody has previously been validated for use in rodent tissue using inducible BDNF knockouts [35] and shBDNF-treated rats [36]. This antibody recognizes both mature BDNF and pro-BDNF [36].

After incubation in the primary antibody, sections were rinsed for 5 \times 5 min in PBS and incubated for one hour in a biotinylated secondary antibody (1:600, Biotin-SP AffiniPure Goat Anti-Rabbit IgG, Jackson Immunoresearch Labs; 111-065-003) in 0.4% Triton-X 100 in PBS. Sections were then rinsed for 5 \times 5 min in PBS and incubated in avidin–biotin complex with horseradish peroxidase (per manufacturer’s instructions, Vectastain Elite ABC-HRP Kit, Vector Laboratories, Burlingame, CA, USA). After 4 \times 5 min washes in PBS, sections were washed for 2 \times 5 min in a sodium acetate buffer and then incubated for 10 min in 3,3'-diaminobenzidine HCl (0.2 mg/mL) in nickel sodium acetate buffer (0.025 g Nickel II Sulfate/mL NaOAc) and hydrogen peroxide (0.83 μ L/mL) solution.

Stained tissue was then washed for 2 \times 5 min in sodium acetate buffer, washed for 3 \times 5 min in PBS, mounted on glass slides (SuperFrost Plus Microscope Slides, ThermoFisher Scientific, Waltham, MA, USA), and left to air-dry overnight. After drying, slides were dehydrated with alcohols, cleared with xylenes, and cover-slipped with Permount (ThermoFisher Scientific, Waltham, MA, USA).

2.5. BDNF Densitometry Analysis in Hippocampus

Images were acquired at 10X magnification using a Nikon E200 brightfield microscope (Nikon Instruments, Melville, NY, USA) with a color camera and Spot Basic software (Diagnostic Instruments, Sterling Heights, MI, USA). Five evenly spaced template images (S1, S2, S3, S4, and S5) were selected from the rat brain atlas [37] to capture the rostral to caudal extent of the hippocampus. The CA3 was split into medial and lateral regions for imaging and analysis in order to capture it fully. Twenty images were collected for each animal: five images per hippocampus region (DG, CA1, mCA3, and lCA3).

Densitometry analyses were performed by experimenters who were blind to the condition of the subject using ImageJ software (version 2.15.1, imagej.net/software/fiji; [38]).

Mean values for background optical density were collected from 36×36 -pixel regions that did not contain BDNF-ir cells using the “mean gray value” tool. Mean optical density values for regions of interest (ROIs) were calculated after tracing the hippocampus region of interest with the polygon tool (Figure 3) and analyzing with the “mean gray value” tool (Figure 4). ROIs were checked for consistency across animals by an experimenter blind to the condition of the subjects. Background optical density was subtracted from ROI optical density using the following equation: $(OD) = \log(255/(OD_{ROI} - OD_{background}))$. Because background levels were variable across sections, likely due to individual differences in perfusions, we background-subtracted OD values between sections with high background levels versus low background levels and found no significant difference between groups. This suggests that: (1) our method was effective at subtracting background, and (2) differences between treatment groups were not due to differences in background.

2.6. Statistical Analysis

All statistics were run using Jamovi (www.jamovi.org, accessed on 14 April 2022) with alpha values of 0.05. Assumptions of normality were tested using the Shapiro–Wilk normality test. Repeated-measures factorial ANOVAs were used to look for interactions and the main effects of drug condition (tamoxifen vs. control) and time (week) on body weight. Significant effects were explored using Bonferroni’s multiple comparisons tests, and the Geisser and Greenhouse method was used to correct violations of sphericity. Two-way ANOVAs were used to look for interactions and the main effects of drug condition (tamoxifen vs. control) and section level (1–5) on BDNF-ir density within each of the four ROIs (DG, CA1, mCA3, and lCA3). Individual brain regions were analyzed separately. Significant effects were explicated using Fisher’s LSD post hoc comparisons test. Individual samples were excluded from analysis if tissue damage precluded OD analysis, or if there was no adequate match for the template atlas plate. The relationship between serum tamoxifen levels and BDNF-ir density was examined using simple correlations.

3. Results

3.1. Body Weight

There was a significant interaction between time and drug condition on body weight ($F(11, 99) = 10.65, p < 0.0001$). Post hoc tests revealed that starting at Week 3, tamoxifen-fed rats weighed significantly less than control rats for the duration of the experiment (all $p < 0.001$, Figure 1).

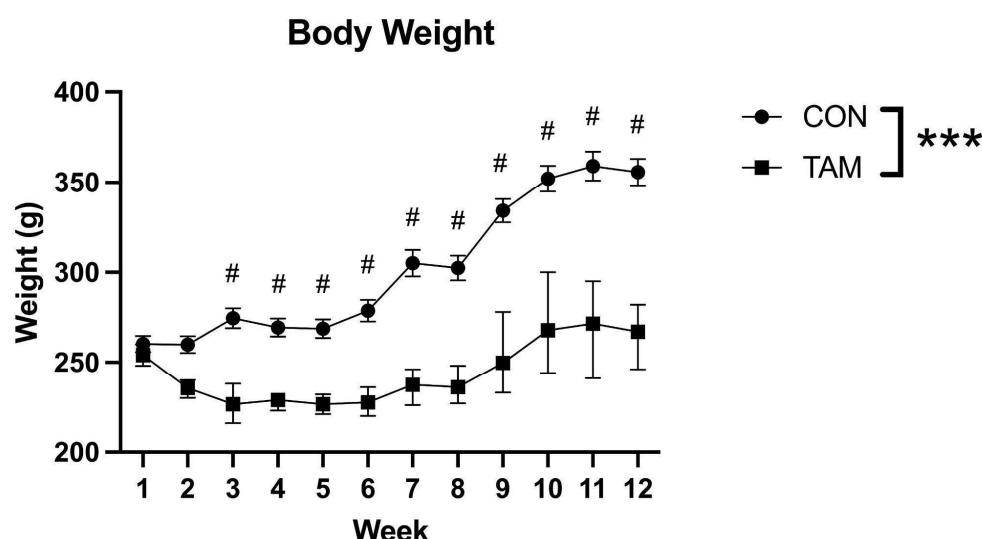


Figure 1. Body weight. Body weight was tracked throughout the course of the experiment. Starting at Week 6, tamoxifen pellets were mashed in a flavor-enhanced gel in addition to ad libitum presentation to prevent further weight loss. Repeated-measures factorial ANOVAs were used to look for interactions

and the main effects of drug condition (TAM vs. CON) and time (Week) on body weight. There was a significant interaction between drug condition and time on body weight. Post hoc tests found that starting at Week 3, TAM animals weighed significantly less than CON animals. Data were presented as mean \pm standard error, *** significant interaction, $p < 0.001$; # significant post hoc test, $p < 0.001$.

3.2. Plasma Tamoxifen Levels

Tamoxifen was not found in any control samples. In tamoxifen-treated animals, plasma concentrations ranged from 10.7 to 48.3 ng/mL ($M = 28.1$, $SD = 11.2$; Table 4). Representative chromatograms can be found in Figure 2.

Table 4. Tamoxifen levels (ng/mL) in TAM-treated rats ($n = 10$).

Subject	Measured Tamoxifen Concentration (ng/mL)
TAM 1	48.3
TAM 2	33.8
TAM 3	26.5
TAM 4	35.0
TAM 5	22.0
TAM 6	34.2
TAM 9	16.3
TAM 10	10.7
TAM 11	35.0
TAM 12	19.3

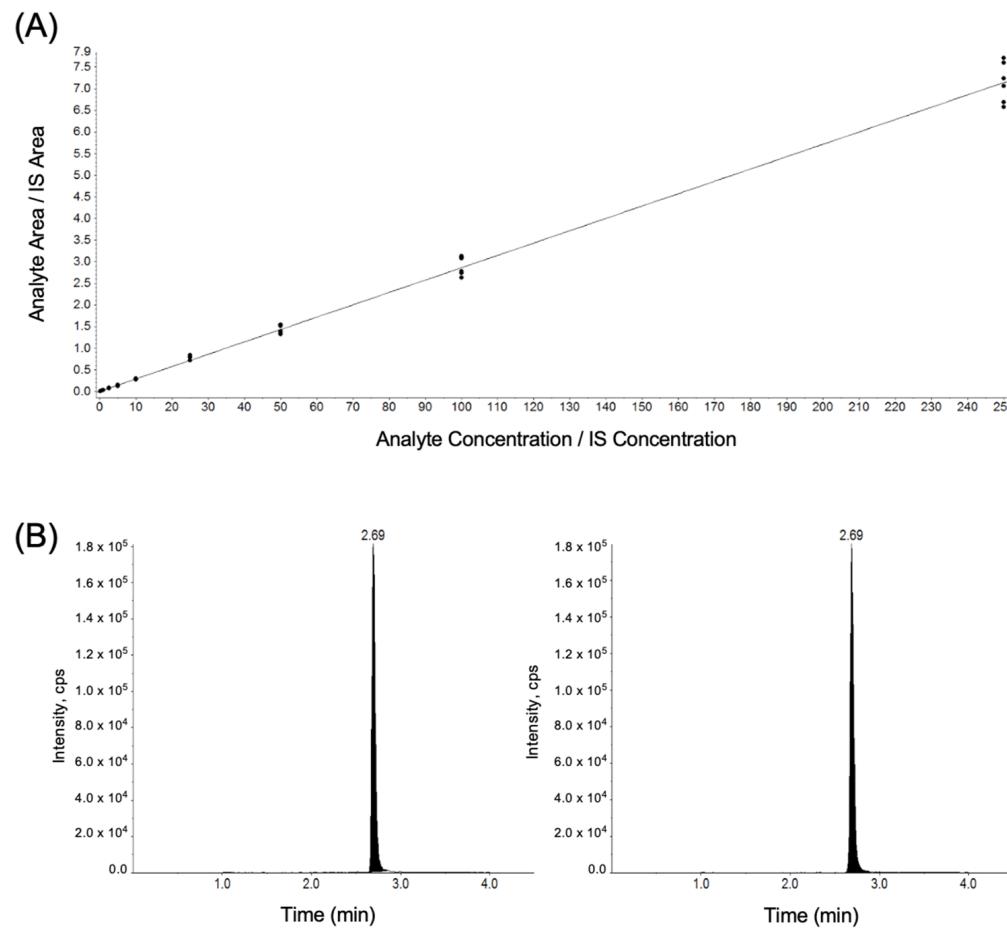


Figure 2. Cont.

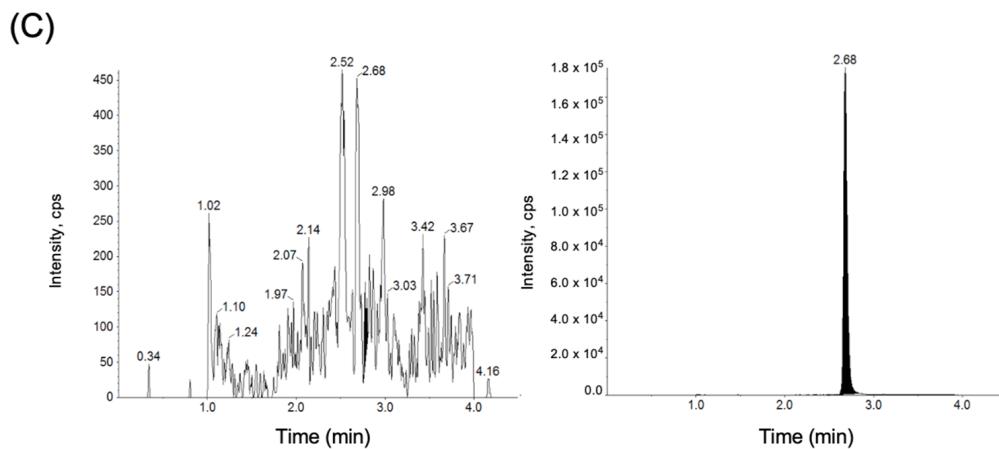


Figure 2. Mass spectrometry analysis of tamoxifen. Tamoxifen and tamoxifen-d5 were separated by ultra-performance liquid chromatography (UPLC) and detected using a triple-quadrupole mass spectrometer. Tandem mass spectrometry (MS-MS) parameters were optimized in the positive ionization mode and the multiple-reaction monitoring (MRM) transition of m/z 372.3–72.0 was used for tamoxifen analysis. Tamoxifen-d5 (m/z 377.3–72.0) was used as an internal standard. (A) A calibration curve for tamoxifen was prepared in human plasma and was linear over the range of 0.1–250 ng/mL. Analytes were separated using a gradient elution, with a retention time of 2.68 min for tamoxifen and tamoxifen-d5. (B) Representative chromatogram from tamoxifen-treated animal of tamoxifen (left) and tamoxifen-d5 (right). (C) Representative chromatogram from control-treated rat (standard chow) of tamoxifen (left) and tamoxifen-d5 (right) in plasma.

3.3. BDNF Immunoreactivity

For each brain region of interest, the density of BDNF-immunoreactive (ir) neurons in the DG, CA1, mCA3, and lCA3 was analyzed and compared between groups (Figure 3). In the DG, there was a significant main effect of drug condition on the density of BDNF-ir cells ($F(1, 146) = 9.454, p = 0.003$). Post hoc tests revealed that BDNF-ir density was lower in tamoxifen-treated animals than control animals in Section 4 ($p = 0.03$, Figure 4A). In CA1, there was a main effect of drug condition on the density of BDNF-ir cells ($F(1, 146) = 8.886, p = 0.003$). Post hoc tests revealed that BDNF-ir density was lower in tamoxifen-treated animals than control animals in Section 2 ($p = 0.04$) and Section 4 ($p = 0.02$, Figure 4B). In mCA3, there was a significant main effect of drug condition on the density of BDNF-ir cells ($F(1, 144) = 11.94, p < 0.001$). Post hoc tests revealed that BDNF-ir was lower in tamoxifen-treated animals than control animals in Section 3 ($p < 0.01$, Figure 4C). There was also a significant main effect of section on the density of BDNF-ir cells in mCA3 ($F(4, 144) = 3.302, p = 0.01$). Post hoc tests revealed that Section 2 differed from Section 4 ($p = 0.02$) and Section 5 ($p = 0.03$), and Section 3 differed from Section 4 ($p < 0.01$) and Section 5 ($p < 0.01$). Finally, in lCA3, there was no effect of drug condition ($F(1, 145) = 0.071, p = 0.79$) or section ($F(1, 145) = 0.87, p = 0.48$) on the density of BDNF-ir cells (Figure 4D).

Animals' plasma tamoxifen concentration at the time of sacrifice did not correlate significantly with BDNF-ir cells in the DG ($r = -0.4221, p = 0.2244$, Figure 5A) or CA1 ($r = -0.2053, p = 0.5693$, Figure 5B). In both medial and lateral CA3 (Figure 5C,D), there was a trend toward an increased plasma tamoxifen concentration being associated with decreased BDNF-ir cells, although these did not reach significance (mCA3 $r = -0.6112, p = 0.0604$; lCA3 $r = -0.6168, p = 0.0575$).

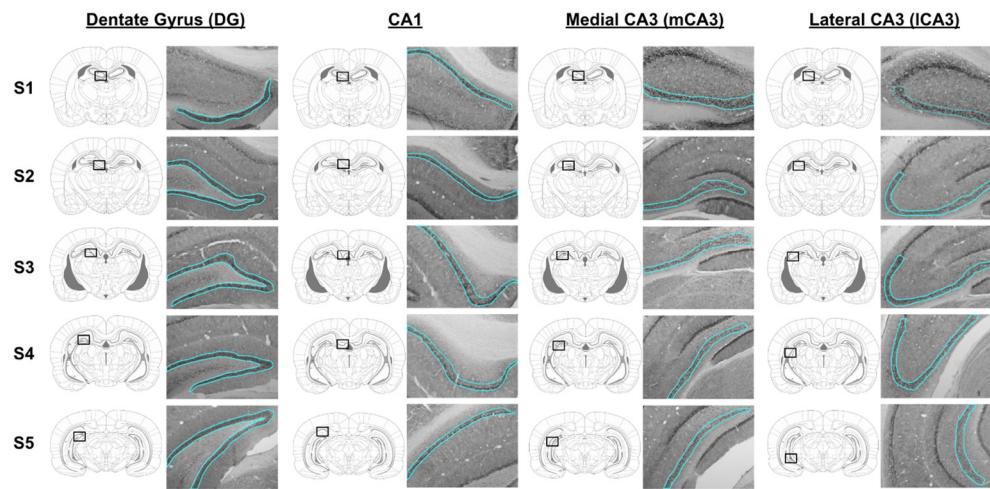


Figure 3. BDNF expression in hippocampal subregions. Representative photomicrographs showing immunohistochemical localization of BDNF in the dentate gyrus (DG), CA1, medial CA3 (mCA3), and lateral CA3 (ICA3). For each region of interest, five sections (S1–S5) capturing the rostral to caudal extent of the hippocampus were analyzed. Regions of interest are identified on the corresponding template atlas plate and are traced in cyan on the photomicrograph.

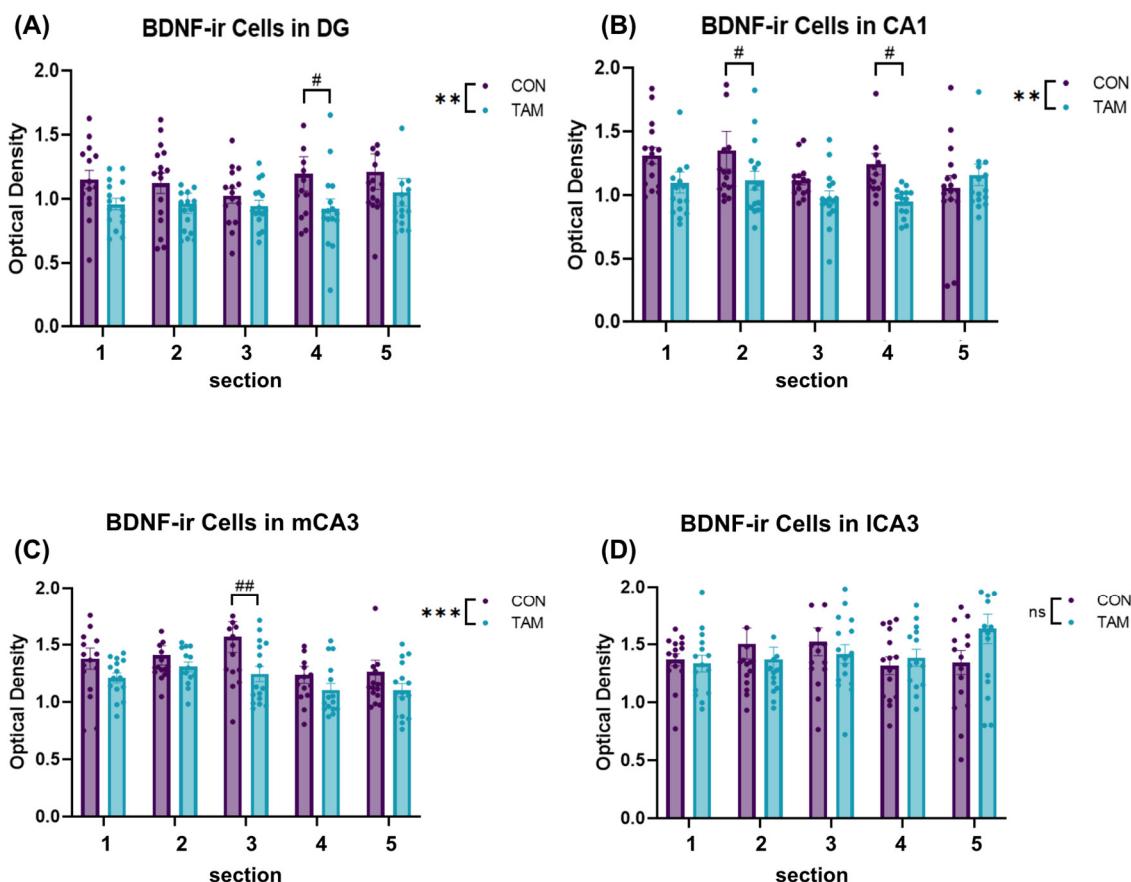


Figure 4. Quantification of BDNF optical density in hippocampal subregions. For each brain region of interest, immunohistochemical localization of BDNF was quantified using background-subtracted optical density in five sections, capturing the rostral to caudal extent of the hippocampus. Significant interactions and/or main effects of the drug condition (tamoxifen, TAM vs. control, and CON) and

section number (1–5) on BDNF optical density were detected using two-way ANOVAs. (A) In DG, there was a significant main effect of drug condition on BDNF-ir density. Post hoc tests revealed that BDNF-ir density was lower in TAM animals than CON animals in Section 4. (B) In CA1, there was a main effect of drug condition on the density of BDNF-ir cells. Post hoc tests revealed that BDNF-ir density was lower in TAM animals than CON animals in Section 2. (C) In mCA3, there was also a significant main effect of drug condition on the density of BDNF-ir cells. Post hoc tests revealed that BDNF-ir was lower in TAM animals than CON animals in Section 3. (D) Finally, in ICA3, there were no interactions or main effects of the drug condition or section level on BDNF immunoreactivity. Data are presented as mean \pm standard error, and asterisks indicate significant omnibus tests: ** $p < 0.01$, and *** $p < 0.001$. Pound signs indicate significant post hoc differences between drug conditions: # $p < 0.05$, ## $p < 0.01$.

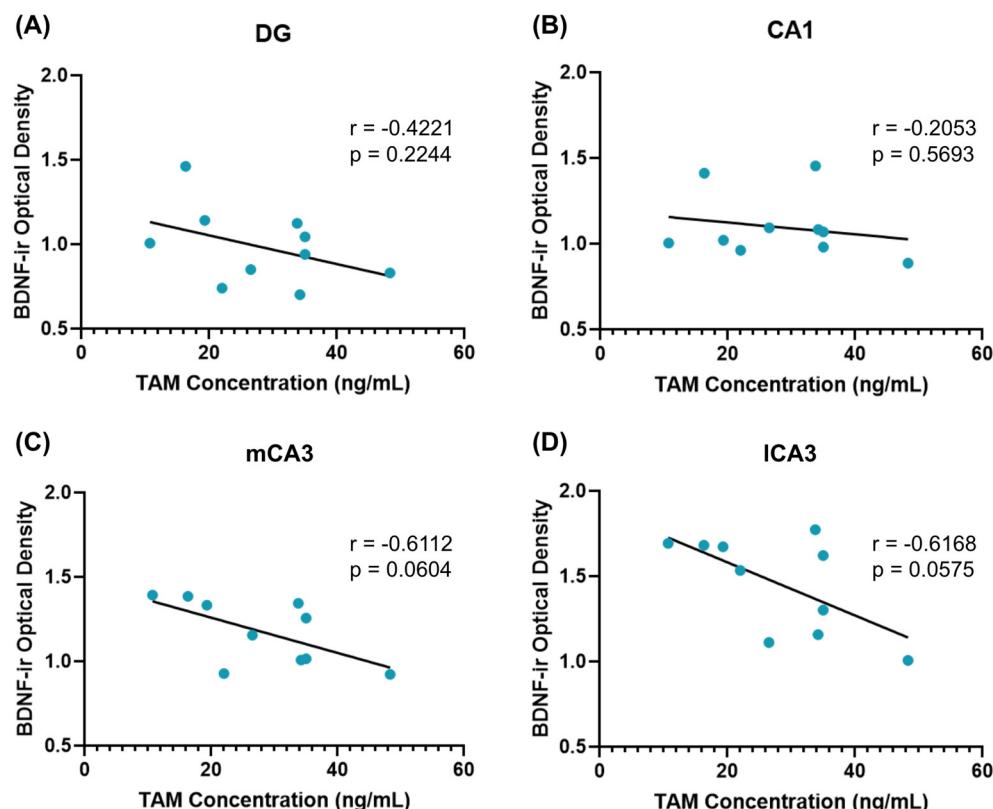


Figure 5. Plasma tamoxifen and BDNF correlations. The relationship between plasma tamoxifen levels and BDNF expression in hippocampal subregions was investigated using simple correlations. In all four brain regions of interest, plasma tamoxifen was negatively correlated with BDNF levels. Although these correlations did not reach significance in (A) DG or (B) CA1, trends toward significance were detected in (C) mCA3 and (D) ICA3. Pearson's correlation coefficient (r) and p -values for each brain area are presented.

4. Discussion

Here, we demonstrated for the first time that long-term oral tamoxifen administration decreases BDNF expression in the hippocampus of adult female Long-Evans Hooded rats. Notably, we showed that a novel administration method, long-term ad lib exposure to medicated food pellets, produced plasma tamoxifen levels that were similar to a human dose (20 mg) [31]. Further, we used a novel LC-MS/MS assay to detect tamoxifen levels in rat plasma. Together, these results provide a new way to model and measure the effects of long-term oral tamoxifen administration on the brain, which may be particularly useful for investigating mechanisms of cognitive and behavioral changes reported by patients taking tamoxifen.

Voluntary oral administration via medicated food pellets is a clinically relevant, non-invasive, and effective method for modeling the effects of tamoxifen in rodents. Tamoxifen can readily cross the blood–brain barrier [39,40], and oral self-administration is an attractive alternative to systemic injections [14,16–18], oral gavage [15], or intragastric administration [41], in that it more closely models the metabolism of tamoxifen use in patient populations and eliminates stress associated with restraint, repeated injections, or gavage as potential confounding variables. Nonetheless, there are some challenges with this method. First, there were likely differences in palatability between tamoxifen and control chow. Tamoxifen-fed animals initially lost weight and required additional intervention (food pellets mashed in flavor-enhanced gel) to prevent further weight loss, whereas control animals typically gained weight across the course of the experiment. A similar study in mice found that 15 days of exposure to tamoxifen chow also led to weight loss, particularly in female subjects, and animals did not consistently eat tamoxifen chow for the first 5 days of exposure [42]. However, an anorexic effect of tamoxifen itself cannot be ruled out, as tamoxifen injections induce anorexia in rodents [43–47]. While oral gavage would introduce stress and is, therefore, not recommended, future experiments may wish to explore mild food deprivation, pair feeding tamoxifen-treated and control animals, or administer a daily oral dose of tamoxifen to eliminate the effects of feeding differences and/or body weight as potential confounds on dependent variables.

There was also variability in individual animals' plasma tamoxifen concentrations. These differences likely resulted from differences in voluntary consumption of tamoxifen chow across animals, both throughout the experiment and specifically on the day of euthanasia. Blood draws were collected approximately 60 min after the last tamoxifen pellets were presented, but the amount of medicated pellet consumed, or the timing of consumption within the one-hour window, were not measured. Future studies should collect data about the volume and timing of food intake, particularly prior to blood collection, as well as additional bioassays that correlate with tamoxifen consumption, such as uterine weight [48].

Our finding that long-term oral tamoxifen administration decreased BDNF expression in the hippocampus may point toward a putative mechanism underlying cognitive side effects that patients taking tamoxifen report. Considering the known association of estrogen receptor activation and BDNF transcription [20,26,27], it is possible that tamoxifen's action at estrogen receptors in the brain could disrupt BDNF transcription, altering plasticity and neuronal stability. Recent work in mice has shown that tamoxifen treatment induces widespread gene expression changes in the hypothalamus and preoptic area, and that these changes are dependent on estrogen receptor alpha (ER α) [49]. Similar changes in the hippocampus could impair cognitive function and lead to clinical symptoms, such as brain fog, memory deficits, and alterations in mood/anxiety. In support of this idea, Smith et al. (2022) found that short-term tamoxifen administration impacted hippocampal neurogenesis [42]. Specifically, tamoxifen injection is associated with decreased progenitor cell proliferation in the dentate gyrus, although tamoxifen ingestion is associated with increased neuronal differentiation in the dentate gyrus. Further, Klann et al. (2023) found that long-term intragastric administration of tamoxifen reduced BDNF expression in the hippocampus, along with reductions in downstream signaling via the ERK/Act/CREB cascade [41]. Thus, our finding that long-term oral tamoxifen administration decreased BDNF density in the current study is corroborated by studies using other administration methods and may be due to a decrease in downstream signaling and/or cell proliferation.

BDNF is difficult to visualize due to its relatively low expression in mature neurons. In the current study, we used an immunohistochemistry approach with a nickel-enhanced chromogen reaction to amplify visualization. This method produces robust BDNF staining, but can produce higher levels of background staining, necessitating a background-subtracted densitometry approach to quantification rather than individual cell counts. Further, BDNF staining patterns differ across published experiments, likely due to differences in antibodies. Here, we reported that BDNF expression in the granular cell

layer was reduced following long-term oral tamoxifen administration, but we found little BDNF expression in the mossy fiber layer. This matches the expression pattern previously shown with this antibody [35]. However, previous papers that used different antibodies reported BDNF staining in the mossy fiber layer, but only sparse staining in the granule cell layer [50,51]. It is possible that different antibodies label distinct pools of BDNF based on differences in the targeted epitope. The method of visualization and antibody choice are, therefore, important considerations when visualizing and quantifying BDNF in the brain.

Future studies using this model of long-term oral tamoxifen administration should include behavioral assays of cognition, mood, and anxiety. Indeed, recent work using sub-chronic intragastric administration of tamoxifen in gonad-intact Wistar rats produced deficits in behavioral measures of mood, anxiety, and recognition memory [41]. Our congruent finding that long-term tamoxifen administration decreased BDNF in the DG, CA1, and medial CA3 suggests that pattern separation, spatial memory, associative memory, and episodic memory processes could be particularly affected [52–54]. Disparate findings in CA3 subregions may further point toward tamoxifen’s effects on cognitive function [55,56]. A full behavioral profile of animals during long-term oral tamoxifen treatment, such as assays of cognition (e.g., object-in-place and attentional set shifting), anxiety-like behaviors (e.g., defensive burying and light–dark box), and learned helplessness or anhedonia (e.g., forced swim, tail suspension, splash test, and sucrose preference), would be useful to characterize tamoxifen’s effects on behavior in this model, and may suggest additional brain regions for exploration. Further, while this study focused on the hippocampus, it is likely that tamoxifen impacts other estrogen-sensitive brain regions that are associated with cognition, anxiety, and/or mood disorders, such as the nucleus accumbens and amygdala. Tamoxifen could disrupt BDNF transcription in these regions by interacting with estrogen receptors via the same putative mechanism that we have identified in the hippocampus. The relationship between tamoxifen, hippocampal BDNF levels, and body weight also requires further investigation, as BDNF is known to regulate energy balance via action in other parts of the brain (for a review, see [57]).

In addition to a novel administration paradigm, we also used a novel, sensitive, and reproducible method for the analysis of tamoxifen that is suitable for rat plasma. This will be useful to future researchers interested in the physiological effects of oral tamoxifen administration. These studies may also wish to investigate the active metabolites of tamoxifen, 4-OH-tamoxifen, and N-desmethyltamoxifen [38,58]. While not significant, we did observe a trend toward correlation between the plasma tamoxifen concentration and BDNF density in mCA3 and lCA3, supporting tamoxifen’s potential role in decreasing BDNF transcription in the hippocampus. It is worth noting that tamoxifen is also commonly used in neuroscience research as a tool to induce Cre mechanisms. While these research applications are markedly different, in that the doses are generally much higher and administration is acute (often a single injected dose) [59,60], our research suggests that tamoxifen administration affects BDNF expression, and researchers using tamoxifen in their work should consider its potential off-target effects on neurobiology.

5. Conclusions

Tamoxifen remains one of the gold-standard medications for preventing recurrence of estrogen-receptor-positive breast cancers. Its ongoing use as an adjuvant therapy will likely continue despite common affective and cognitive side effects, as tamoxifen treatments will enable breast cancer survivors to live longer and healthier lives. Further identifying and understanding the neural mechanisms underlying these side effects, however, could lead to promising interventions that would mitigate unwanted psychological changes without risking cancer recurrence. It is important that researchers and clinicians continue to explore ways to improve psychological health in at-risk and under-researched patient populations. Cancer survivors, women, and other gender minorities are particularly vulnerable to a range of affective, anxiety, and cognitive disorders [13,61,62]. It is imperative that we find ways to support all aspects of their health as they navigate treatment.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/cancers16071373/s1>, Figure S1: Body condition scoring [32].

Author Contributions: Conceptualization, L.E.B. and M.E.K.; methodology, L.E.B., A.R.H., S.M.B., A.G.B. and M.E.K.; formal analysis, A.R.H., S.M.B., E.M.B., G.E.R., K.I.D.R., P.E.A., L.M.B. and G.J.P.; investigation, A.R.H., S.M.B., E.M.B., G.E.R., K.I.D.R., K.B.P. and P.E.A.; resources, L.E.B. and M.E.K.; data curation, A.R.H., L.E.B. and M.E.K.; writing—original draft preparation, L.E.B., A.R.H. and M.E.K.; writing—review and editing, L.E.B., A.R.H. and M.E.K.; visualization, A.R.H.; supervision, L.E.B. and M.E.K.; funding acquisition, M.E.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by Haverford College Department of Psychology.

Institutional Review Board Statement: The animal study protocol was approved by the Institutional Animal Care and Use Committee of Haverford College (protocol #MEK101619, approved 16 October 2019).

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: The authors wish to thank Shanice Edwards, Christina Vedar, Abigail Cohen, Athena Zuppa, and Ganesh Moorthy from the Children’s Hospital of Philadelphia Research Institute Bioanalytical Core for developing and conducting the mass spectrometry assays. Some of the mass spectrometry data were previously presented as a poster at the American Society for Mass Spectrometry Conference on Mass Spectrometry and Allied Topics in Philadelphia, PA, in November of 2021. The authors also wish to thank Louise Charkoudian for her assistance interpreting the LC-MS data.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Jebahi, F.; Sharma, S.; Bloss, J.E.; Wright, H.H. Effects of tamoxifen on cognition and language in women with breast cancer: A systematic search and a scoping review. *Psycho-Oncol.* **2021**, *30*, 1262–1277. [[CrossRef](#)]
2. Kadakia, K.C.; Henry, N.L. Adjuvant Endocrine Therapy in Premenopausal Women with Breast Cancer. *Clin. Adv. Hematol. Oncol. H&O* **2015**, *13*, 663–672.
3. Novick, A.M.; Scott, A.T.; Epperson, C.N.; Schneck, C.D. Neuropsychiatric Effects of Tamoxifen: Challenges and Opportunities. *Front. Neuroendocrinol.* **2020**, *59*, 100869. [[CrossRef](#)] [[PubMed](#)]
4. Azizi-Malekabadi, H.; Pourganji, M.; Zabihi, H.; Saeedjalali, M.; Hosseini, M. Tamoxifen antagonizes the effects of ovarian hormones to induce anxiety and depression-like behavior in rats. *Arq. Neuro-Psiquiatr.* **2015**, *73*, 132–139. [[CrossRef](#)]
5. Lee, P.E.; Tierney, M.C.; Wu, W.; Pritchard, K.I.; Rochon, P.A. Endocrine treatment-associated cognitive impairment in breast cancer survivors: Evidence from published studies. *Breast Cancer Res. Treat.* **2016**, *158*, 407–420. [[CrossRef](#)] [[PubMed](#)]
6. Underwood, E.A.; Rochon, P.A.; Moineddin, R.; Lee, P.E.; Wu, W.; Pritchard, K.I.; Tierney, M.C. Cognitive sequelae of endocrine therapy in women treated for breast cancer: A meta-analysis. *Breast Cancer Res. Treat.* **2018**, *168*, 299–310. [[CrossRef](#)]
7. Boele, F.W.; Schilder CM, T.; de Roode, M.-L.; Deijen, J.B.; Schagen, S.B. Cognitive functioning during long-term tamoxifen treatment in postmenopausal women with breast cancer. *Menopause* **2015**, *22*, 17–25. [[CrossRef](#)]
8. Castellon, S.A.; Ganz, P.A.; Bower, J.E.; Petersen, L.; Abraham, L.; Greendale, G.A. Neurocognitive Performance in Breast Cancer Survivors Exposed to Adjuvant Chemotherapy and Tamoxifen. *J. Clin. Exp. Neuropsychol.* **2004**, *26*, 955–969. [[CrossRef](#)]
9. Lejbak, L.; Vrbancic, M.; Crossley, M. Endocrine therapy is associated with low performance on some estrogen-sensitive cognitive tasks in postmenopausal women with breast cancer. *J. Clin. Exp. Neuropsychol.* **2010**, *32*, 836–846. [[CrossRef](#)]
10. Chen, X.; Li, J.; Chen, J.; Li, D.; Ye, R.; Zhang, J.; Zhu, C.; Tian, Y.; Wang, K. Decision-making impairments in breast cancer patients treated with tamoxifen. *Horm. Behav.* **2014**, *66*, 449–456. [[CrossRef](#)]
11. Jenkins, V.; Shilling, V.; Fallowfield, L.; Howell, A.; Hutton, S. Does hormone therapy for the treatment of breast cancer have a detrimental effect on memory and cognition? A pilot study. *Psycho-Oncol.* **2004**, *13*, 61–66. [[CrossRef](#)] [[PubMed](#)]
12. Breckenridge, L.M.; Bruns, G.L.; Todd, B.L.; Feuerstein, M. Cognitive limitations associated with tamoxifen and aromatase inhibitors in employed breast cancer survivors. *Psycho-Oncol.* **2012**, *21*, 43–53. [[CrossRef](#)] [[PubMed](#)]
13. Ahles, T.A.; Root, J.C.; Ryan, E.L. Cancer- and Cancer Treatment-Associated Cognitive Change: An Update on the State of the Science. *J. Clin. Oncol.* **2012**, *30*, 3675–3686. [[CrossRef](#)]
14. Chen, D.; Wu, C.F.; Shi, B.; Xu, Y.M. Tamoxifen and toremifene cause impairment of learning and memory function in mice. *Pharmacol. Biochem. Behav.* **2002**, *71*, 269–276. [[CrossRef](#)] [[PubMed](#)]

15. Valvassori, S.S.; Borges, C.P.; Varela, R.B.; Bavaresco, D.V.; Bianchini, G.; Mariot, E.; Arent, C.O.; Resende, W.R.; Budni, J.; Quevedo, J. The different effects of lithium and tamoxifen on memory formation and the levels of neurotrophic factors in the brain of male and female rats. *Brain Res. Bull.* **2017**, *134*, 228–235. [CrossRef] [PubMed]
16. Velázquez-Zamora, D.A.; García-Segura, L.M.; González-Burgos, I. Effects of selective estrogen receptor modulators on allocentric working memory performance and on dendritic spines in medial prefrontal cortex pyramidal neurons of ovariectomized rats. *Horm. Behav.* **2012**, *61*, 512–517. [CrossRef] [PubMed]
17. Cechinel-Recco, K.; Valvassori, S.S.; Varela, R.B.; Resende, W.R.; Arent, C.O.; Vitto, M.F.; Luz, G.; de Souza, C.T.; Quevedo, J. Lithium and tamoxifen modulate cellular plasticity cascades in animal model of mania. *J. Psychopharmacol.* **2012**, *26*, 1594–1604. [CrossRef] [PubMed]
18. Kight, K.E.; McCarthy, M.M. Sex differences and estrogen regulation of BDNF gene expression, but not propeptide content, in the developing hippocampus. *J. Neurosci. Res.* **2017**, *95*, 345–354. [CrossRef] [PubMed]
19. Frick, K.M.; Kim, J.; Tuscher, J.J.; Fortress, A.M. Sex steroid hormones matter for learning and memory: Estrogenic regulation of hippocampal function in male and female rodents. *Learn. Mem.* **2015**, *22*, 472–493. [CrossRef]
20. Harte-Hargrove, L.C.; MacLusky, N.J.; Scharfman, H.E. Brain-derived neurotrophic factor–estrogen interactions in the hippocampal mossy fiber pathway: Implications for normal brain function and disease. *Neuroscience* **2013**, *239*, 46–66. [CrossRef]
21. Spencer, J.L.; Waters, E.M.; Romeo, R.D.; Wood, G.E.; Milner, T.A.; McEwen, B.S. Uncovering the Mechanisms of Estrogen Effects on Hippocampal Function. *Front. Neuroendocrinol.* **2008**, *29*, 219–237. [CrossRef] [PubMed]
22. Woolley, C.S. Estrogen-mediated structural and functional synaptic plasticity in the female rat hippocampus. *Horm. Behav.* **1998**, *34*, 140–148. [CrossRef] [PubMed]
23. Liu, F.; Day, M.; Muñiz, L.C.; Bitran, D.; Arias, R.; Revilla-Sánchez, R.; Grauer, S.; Zhang, G.; Kelley, C.; Pulito, V.; et al. Activation of estrogen receptor-β regulates hippocampal synaptic plasticity and improves memory. *Nat. Neurosci.* **2008**, *11*, 3. [CrossRef]
24. Green, A.D.; Galea LA, M. Adult hippocampal cell proliferation is suppressed with estrogen withdrawal after a hormone-simulated pregnancy. *Horm. Behav.* **2008**, *54*, 203–211. [CrossRef] [PubMed]
25. Walf, A.A.; Frye, C.A. A Review and Update of Mechanisms of Estrogen in the Hippocampus and Amygdala for Anxiety and Depression Behavior. *Neuropsychopharmacology* **2006**, *31*, 6. [CrossRef] [PubMed]
26. Scharfman, H.E.; MacLusky, N.J. Estrogen and brain-derived neurotrophic factor (BDNF) in hippocampus: Complexity of steroid hormone-growth factor interactions in the adult CNS. *Front. Neuroendocrinol.* **2006**, *27*, 415–435. [CrossRef] [PubMed]
27. Sohrabji, F.; Lewis, D.K. Estrogen–BDNF interactions: Implications for neurodegenerative diseases. *Front. Neuroendocrinol.* **2006**, *27*, 404–414. [CrossRef] [PubMed]
28. Luine, V.; Frankfurt, M. Interactions between estradiol, BDNF and dendritic spines in promoting memory. *Neuroscience* **2013**, *239*, 34–45. [CrossRef] [PubMed]
29. Scharfman, H.E.; MacLusky, N.J. Differential regulation of BDNF, synaptic plasticity and sprouting in the hippocampal mossy fiber pathway of male and female rats. *Neuropharmacology* **2014**, *76*, 696–708. [CrossRef]
30. Sato, K.; Akaishi, T.; Matsuki, N.; Ohno, Y.; Nakazawa, K. β-Estradiol induces synaptogenesis in the hippocampus by enhancing brain-derived neurotrophic factor release from dentate gyrus granule cells. *Brain Res.* **2007**, *1150*, 108–120. [CrossRef]
31. Farrar, M.C.; Jacobs, T.F. Tamoxifen. In *StatPearls*; StatPearls Publishing: St. Petersburg, FL, USA, 2022. Available online: <http://www.ncbi.nlm.nih.gov/books/NBK532905/> (accessed on 23 November 2023).
32. Hickman, D.; Swan, M. Use of a Body Condition Score Technique to Assess Health Status in a Rat Model of Polycystic Kidney Disease. *J. Am. Assoc. Lab. Anim. Sci.* **2010**, *49*, 155–159. [PubMed]
33. Bobin-Dubigeon, C.; Campone, M.; Rossignol, E.; Salaun, E.; Amiand, M.-B.; Bard, J.-M. New UPLC–MS/MS assay for the determination of tamoxifen and its metabolites in human plasma, application to patients. *Future Science OA* **2019**, *5*, FSO374. [CrossRef] [PubMed]
34. Rama Raju, K.S.; Taneja, I.; Singh, S.P.; Tripathi, A.; Mishra, D.P.; Hussain, K.M.; Gayen, J.R.; Singh, S.K.; Wahajuddin, M. Simultaneous determination of centchroman and tamoxifen along with their metabolites in rat plasma using LC-MS/MS. *Bioanalysis* **2015**, *7*, 967–979. [CrossRef] [PubMed]
35. Sun, C.; Krimm, R.; Hill, D.L. Maintenance of Mouse Gustatory Terminal Field Organization Is Dependent on BDNF at Adulthood. *J. Neurosci.* **2018**, *38*, 6873–6887. [CrossRef] [PubMed]
36. Taliazz, D.; Stall, N.; Dar, D.E.; Zangen, A. Knockdown of brain-derived neurotrophic factor in specific brain sites precipitates behaviors associated with depression and reduces neurogenesis. *Mol. Psychiatry* **2010**, *15*, 80–92. [CrossRef] [PubMed]
37. Paxinos, G.; Watson, C. *The Rat Brain in Stereotaxic Coordinates*, 7th ed.; Academic Press: Cambridge, MA, USA, 2013. Available online: <https://www.elsevier.com/books/the-rat-brain-in-stereotaxic-coordinates/paxinos/978-0-12-391949-6> (accessed on 1 February 2022).
38. Schindelin, J.; Arganda-Carreras, I.; Frise, E.; Kaynig, V.; Longair, M.; Pietzsch, T.; Preibisch, S.; Rueden, C.; Saalfeld, S.; Schmid, B.; et al. Fiji: An open-source platform for biological-image analysis. *Nature Methods* **2012**, *9*, 7. [CrossRef] [PubMed]
39. Lien, E.A.; Solheim, E.; Ueland, P.M. Distribution of tamoxifen and its metabolites in rat and human tissues during steady-state treatment. *Cancer Res.* **1991**, *51*, 4837–4844. [PubMed]
40. Pareto, D.; Alvarado, M.; Hanrahan, S.M.; Biegon, A. In vivo occupancy of female rat brain estrogen receptors by 2004, 17beta-estradiol and tamoxifen. *NeuroImage* **2004**, *23*, 1161–1167. [CrossRef]

41. Klann, I.P.; Fulco BC, W.; Nogueira, C.W. Subchronic exposure to tamoxifen modulates the hippocampal BDNF/ERK/Akt/CREB pathway and impairs memory in intact female rats. *Chem.-Biol. Interact.* **2023**, *382*, 110615. [[CrossRef](#)]
42. Smith, B.M.; Saulsberry, A.I.; Sarchet, P.; Devasthal, N.; Einstein, D.; Kirby, E.D. Oral and Injected Tamoxifen Alter Adult Hippocampal Neurogenesis in Female and Male Mice. *eNeuro* **2022**, *9*, ENEURO.0422-21.2022. [[CrossRef](#)]
43. Lampert, C.; Arcego, D.M.; Laureano, D.P.; Diehl, L.A.; Da Costa Lima, I.F.; Krolow, R.; Pettenuzzo, L.F.; Dalmaz, C.; Vendite, D. Effect of chronic administration of tamoxifen and/or estradiol on feeding behavior, palatable food and metabolic parameters in ovariectomized rats. *Physiol. Behav.* **2013**, *119*, 17–24. [[CrossRef](#)] [[PubMed](#)]
44. Gray, J.M.; Schrock, S.; Bishop, M. Estrogens and antiestrogens: Actions and interactions with fluphenazine on food intake and body weight in rats. *Am. J. Physiol. -Regul. Integr. Comp. Physiol.* **1993**, *264*, R1214–R1218. [[CrossRef](#)]
45. López, M.; Lelliott, C.J.; Tovar, S.; Kimber, W.; Gallego, R.; Virtue, S.; Blount, M.; Vázquez, M.J.; Finer, N.; Powles, T.J.; et al. Tamoxifen-Induced Anorexia Is Associated with Fatty Acid Synthase Inhibition in the Ventromedial Nucleus of the Hypothalamus and Accumulation of Malonyl-CoA. *Diabetes* **2006**, *55*, 1327–1336. [[CrossRef](#)] [[PubMed](#)]
46. Wade, G.N.; Heller, H.W. Tamoxifen mimics the effects of estradiol on food intake, body weight, and body composition in rats. *Am. J. Physiol.-Regul. Integr. Comp. Physiol.* **1993**, *264*, R1219–R1223. [[CrossRef](#)] [[PubMed](#)]
47. Walker, E.A.; Foley, J.J.; Clark-Vetri, R.; Raffa, R.B. Effects of repeated administration of chemotherapeutic agents tamoxifen, methotrexate, and 5-fluorouracil on the acquisition and retention of a learned response in mice. *Psychopharmacology* **2011**, *217*, 539–548. [[CrossRef](#)] [[PubMed](#)]
48. Fong, C.J.; Burgoon, L.D.; Williams, K.J.; Forgacs, A.L.; Zacharewski, T.R. Comparative temporal and dose-dependent morphological and transcriptional uterine effects elicited by tamoxifen and ethynodiol in immature, ovariectomized mice. *BMC Genom.* **2007**, *8*, 151. [[CrossRef](#)] [[PubMed](#)]
49. Zhang, Z.; Park, J.W.; Ahn, I.S.; Diamante, G.; Sivakumar, N.; Arneson, D.; Yang, X.; Veen, J.E.; Correa, S.M. Estrogen receptor alpha in the brain mediates tamoxifen-induced changes in physiology in mice. *eLife* **2021**, *10*, e63333. [[CrossRef](#)]
50. Conner, J.M.; Lauterborn, J.C.; Yan, Q.; Gall, C.M.; Varon, S. Distribution of Brain-Derived Neurotrophic Factor (BDNF) Protein and mRNA in the Normal Adult Rat CNS: Evidence for Anterograde Axonal Transport. *J. Neurosci.* **1997**, *17*, 2295–2313. [[CrossRef](#)] [[PubMed](#)]
51. Dieni, S.; Matsumoto, T.; Dekkers, M.; Rauskolb, S.; Ionescu, M.S.; Deogracias, R.; Gundelfinger, E.D.; Kojima, M.; Nestel, S.; Frotscher, M.; et al. BDNF and its pro-peptide are stored in presynaptic dense core vesicles in brain neurons. *J. Cell Biol.* **2012**, *196*, 775–788. [[CrossRef](#)]
52. Bartsch, T.; Döhring, J.; Rohr, A.; Jansen, O.; Deuschl, G. CA1 neurons in the human hippocampus are critical for autobiographical memory, mental time travel, and autonoetic consciousness. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 17562–17567. [[CrossRef](#)]
53. Cherubini, E.; Miles, R. The CA3 region of the hippocampus: How is it? what is it for? how does it do it? *Front. Cell. Neurosci.* **2015**, *9*, 19. [[CrossRef](#)]
54. Kesner, R.P. A behavioral analysis of dentate gyrus function. In *Progress in Brain Research*; Scharfman, H.E., Ed.; Elsevier: Amsterdam, The Netherlands, 2007; Volume 163, pp. 567–576. [[CrossRef](#)]
55. Langston, R.F.; Stevenson, C.H.; Wilson, C.L.; Saunders, I.; Wood, E.R. The role of hippocampal subregions in memory for stimulus associations. *Behav. Brain Res.* **2010**, *215*, 275–291. [[CrossRef](#)] [[PubMed](#)]
56. Fanselow, M.S.; Dong, H.-W. Are The Dorsal and Ventral Hippocampus functionally distinct structures? *Neuron* **2010**, *65*, 7. [[CrossRef](#)] [[PubMed](#)]
57. Xu, B.; Xie, X. Neurotrophic factor control of satiety and body weight. *Nat. Rev. Neurosci.* **2016**, *17*, 282–292. [[CrossRef](#)] [[PubMed](#)]
58. Robinson, S.P.; Langan-Fahey, S.M.; Johnson, D.A.; Jordan, V.C. Metabolites, pharmacodynamics, and pharmacokinetics of tamoxifen in rats and mice compared to the breast cancer patient. *Drug Metab. Dispos. Biol. Fate Chem.* **1991**, *19*, 36–43. [[PubMed](#)]
59. Donocoff, R.S.; Teteloshvili, N.; Chung, H.; Shoulson, R.; Creusot, R.J. Optimization of tamoxifen-induced Cre activity and its effect on immune cell populations. *Sci. Rep.* **2020**, *10*, 1. [[CrossRef](#)] [[PubMed](#)]
60. Heffner, C. *Intraperitoneal Injection of Tamoxifen for Inducible Cre-Driver Lines*; The Jackson Laboratory: Bar Harbor, ME, USA, 2011.
61. Di Giacomo, D.; Cannita, K.; Ranieri, J.; Coccilone, V.; Passafiume, D.; Ficarella, C. Breast cancer and psychological resilience among young women. *J. Psychopathology* **2016**, *3*, 191–195.
62. Fafouti, M.; Paparrigopoulos, T.; Zervas, Y.; Rabavilas, A.; Malamos, N.; Liappas, I.; Tzavara, C. Depression, Anxiety and General Psychopathology in Breast Cancer Patients: A Cross-sectional Control Study. *In Vivo* **2010**, *24*, 803–810.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.