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Biotransformation of Sildenafil in the Male Rat: Evaluation of Drug Interactions with Testosterone and Carbamazepine

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The biotransformation of sildenafil to its major circulating metabolite, UK-103,320, was studied in male rat liver microsomes. The conversion of sildenafil to UK-103,320 by rat microsomes followed Michaelis–Menten kinetics, for which the parameters were V_{max}=1.96 μM/minand K_m = 27.31 μM. Using substrates of CYP3A4 of testosterone and carbamazepine, the active sites on CYP3A4 responsible for metabolizing sildenafil were also evaluated. Sildenafil biotransformation was inhibited in the individual presence of testosterone and carbamazepine. The results showed drug interaction was observed in the sildenafil-testosterone and sildenafil-carbamazepine. Although testosterone and carbamazepine can inhibit sildenafil demethylation in concentration- and incubation time-dependent manners, sildenafil did not inhibit testosterone hydroxylation or carbamazepine epoxidation. These results may be explained by a model in which multiple substrates or ligands can concurrently bind to the active site of a single CYP3A4 molecule. However, the contribution of separate allosteric sites and conformational heterogeneity to the atypical kinetics of CYP3A4 cannot be ruled out in this study.

Keywords sildenafil; testosterone; carbamazepine; drug interaction; CYP3A4

INTRODUCTION

Sildenafil (Viagra), a selective inhibitor of cGMP phosphodiesterase type 5, is an orally active treatment for erectile dysfunction (ED) (Langtry & Markham, 1999). A study using human liver microsomes demonstrated that 79% of sildenafil's biotransformation to UK-103,320 (*N*-demethylsildenafil) is attributable to CYP3A. UK-103,320 has been identified as a metabolite of sildenafil in the mouse, rat, dog, and human (Walker et al., 1999). A small percentage of metabolite formation is due to CYP2C9 (20%), CYP2D6, and CYP2C19 (collectively <2%) activity (Hyland, Roe, Jones, & Smith, 2001). Current numbers indicate that approximately 30 million men in the U.S. are affected by ED, with half of all men aged >40 years experiencing some degree of ED. Because of the high frequency of ED in the U.S. as well as to the possible role of a variety of diseases or pharmacological agents in the pathogenesis of sexual dysfunction, sildenafil is likely to be co-administered with other drugs. In general, ED and depression frequently co-occur with other conditions, including diabetes, hypertension, cardiovascular disease, neurologic disorders (e.g., parkinsonism and multiple sclerosis), and endocrine disorders (e.g., adrenal thyroid and gonadal disorders) (Ashton & Bennett, 1999; Nurnberg, Lauriello, Hensley, Parker, & Keith, 1999). It can be expected that sildenafil will be co-administered with agents that either directly cause sexual dysfunction or are used to treat disease associated with sexual dysfunction. Thus, drug–drug interactions have become an important clinical issue because of the effects of one drug on the efficacy, toxicity, or disposition of another drug. The estimated incidence of clinically significant drug–drug interactions is as high as 20% in patients receiving multiple drugs. The majority of cases of drug–drug interactions are a result of pharmacokinetic or pharmacodynamic alterations. Although interacting agents can affect all aspects of drug disposition, including absorption, distribution, metabolism, and excretion through a variety of mechanisms, the most common drug interactions can be understood in terms of alterations in metabolism, which are associated primarily with changes in the activities of cytochrome P450. Co-administration of sildenafil and CYP3A4 inhibitors (ketoconazole and ritonavir) may lead to increased plasma concentrations of sildenafil (Warrington, Shader, von Moltke, & Greenblatt, 2000). This may, in turn, lead to an increase in adverse effects commonly associated with sildenafil such as headaches, flushing, dyspepsia, and visual changes. Therefore, it is important to understand the potential for drug interactions with sildenafil.

To better understand drug interactions with sildenafil, this study was conducted to investigate the effects of carbamazepine and testosterone on sildenafil metabolism and evaluate the possibility of drug–drug interactions with sildenafil. Carbamazepine is widely used for the treatment of epileptic seizures, trigeminal neuralgia, and psychiatric disorders. Carbamazepine is usually administered at daily oral doses ranging from 200 to 1200 mg or higher, which give rise to drug plasma levels of 4~12 μg/mL. The relationship between the carbamazepine dose and its plasma

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concentration is often unpredictable and depends on the patient's metabolic state and age and might be affected by cotherapy. The drug is principally metabolized by CYPs to 10,11-epoxy carbamazepine (Segelman, Kelton, Terzi, Kucharczy, & Sofia, 1985). At the same time, carbamazepine metabolism can be induced or inhibited by other drugs. The addition of felbamate to carbamazepine monotherapy results in a decrease in carbamazepine plasma concentrations. It is suggested that in vivo heteroactivation of CYP3A4 is a possible mechanism of clinically observed drug interactions between felbamate and carbamazepine (Egnell, Houston, & Boyer, 2003). In the human male, testosterone is the major circulating androgen. Testosterone is essential for the development and maintenance of specific reproductive tissues as well as for other characteristic male properties such as control of spermatogenesis, and many aspects of sexually dimorphic behavior. Indeed, in subsequent studies, Webb et al. demonstrated that an intracoronary infusion of physiological concentrations of testosterone increased coronary artery diameter and coronary blood flow in male patients with cardiovascular disease. Testosterone hydroxylation, yielding the 6ß-hydroxy metabolite, is considered to be a relatively specific index reaction for human CYP3A-mediated metabolism. In testosterone interaction studies, testosterone inhibited 1-OH-triazolam formation but significantly activated 4-OH-triazolam formation in human liver microsomes. The interaction patterns between compounds with CYP3A4 were found to be substrate-dependent. Mutual inhibition, partial inhibition, and activation were observed in testosterone–terfenadine, testosterone–midazolam, and terfenadine–midazolam interactions. As a result, drug–drug interactions associated with the modulation of CYP3A-mediated metabolism can be of substantial clinical importance (Wang, Newton, Liu, Atkins, & Lu, 2000).

Kinetic techniques that adequately describe the interaction between multiple drugs that bind simultaneously to a single enzyme active site are needed to aid in the understanding of clinically observed drug–drug interactions and in assessing their clinical significance. In many cases, CYP3A exhibits unusual kinetic characteristics that result from the metabolism of multiple substrates that coexist at the active site (Hosea, Miller, & Guengerich, 2000; Kenworthy, Clarke, Andrews, Houston, 2001; Korzekwa et al., 1998; Shou et al., 1994; Ueng, Kuwabara, Chun, & Guengerich, 1997;). It is hoped that application of kinetic characteristics can aid in our understanding of drug–drug interactions of sildenafil with carbamazepine and testosterone.

MATERIALS AND METHODS

Drugs and Chemicals

Standard sildenafil citrate was obtained from Trans American Chemical Co. (Upland, CA, USA). Nicotinamide adenine dinucleotide phosphate (NADPH)-CYP reductase, potassium dihydrogen phosphate, di-potassium hydrogen phosphate, trifluoroacetic acid, dimethyl sulfoxide, carbamazepine, 10,11-epoxide carbamazepine, and hydroxyl testosterone were purchased from Sigma Aldrich Chemical Co. (St. Louis, MO, USA). Testosterone was obtained from Fluka Chemical Co. (Buchs, Steinheim, Switzerland). Methanol and acetonitrile for liquid chromatography were high-performance liquid chromatograph (HPLC) grade and were obtained from Merck (Darmstadt, Germany). All other reagents used were of reagent grade or better.

Animals and Preparation of Liver Microsomes

Male adult Wistar rats (300 ± 50 g) were obtained from the Laboratory Animal Center of National Taiwan University (Taipei, Taiwan). All animal-use protocols were approved by the Laboratory Animal Research Committee of Taipei Medical University (Taipei, Taiwan). Rats were housed in stainless steel cages with five animals per cage in a temperature-controlled (24~26°C) room with a 12-h light/dark cycle. Rats were allowed free access to water and food for 1 week before the experiments. They were starved overnight before the experiments. Each animal was anesthetized with ether. Microsomes were prepared from pooled (6–8) fresh livers by homogenization and differential centrifugations, as previously described (Guengerich, 2001). All procedures were carried out at 4°C. The microsomes were stored at −80°C until use in 0.1 M phosphate buffer (pH 7.4) containing 20% (wt/vol) glycerol. Protein concentrations were determined using the Bio-Rad protein assay kit (Bio-Rad, Hercules, CA, USA) with BSA as the standard.

Sildenafil Kinetics in Rat Liver Microsomes

Varying quantities of sildenafil ranging from 2.5 to 10^3 μM were added to hepatic microsomes from rat preparations in the presence of NDPH and 0.1 M potassium phosphate buffer (pH 7.4). The mixtures were incubated for different times (5, 10, 20, and 40 min) at 37°C and terminated with the addition of methanol and exposure to ice. Furthermore, incubation mixtures were centrifuged at 14900 *g* for 10 min to remove the protein. The supernatants were transferred to autosampling vials for HPLC analysis. All samples were incubated in triplicate. Samples were chromatographed on a 25-cm Biosil Aqu-ODS-W column, with a mobile phase consisting of acetonitrile and water solution (containing 0.1% trifluoroacetic acid) at a 40:60 (vol/vol) ratio. The eluent was detected with a Jasco (Tokyo, Japan) UV-975 UV-VIS detector at 230 nm. The flow rate was set at 1.0 mL/min. This method was found to be selective, precise, and linear over a concentration range of 0.5–10^3 μM sildenafil (Sheu, Wu, Yeh, Hsia, & Ho, 2003). All mobile-phase solutions were filtered and degassed ultrasonically before use. The HPLC system was controlled by a PC workstation using Chromatography Data Station software (SISC, Taipei, Taiwan) installed on it.

Liquid Chromatography-Tandem Mass Spectrometry

Identification of UK-103,320 as the principal metabolite of sildenafil in incubation mixtures was performed by liquid chromatography-tandem mass spectrometry (LC-MS) (Hyland,

Roe, Jones, & Smith, 2000). For LC-MS studies, chromatography was conducted on a Hewlett-Packard HP 1100 gradient system. The system was controlled and data were processed using ChemStation Software revision A.06.01 (Hewlett Packard, Palo Alto, CA, USA). The MS system was operated using the API-ES mode in the positive ion mode. The gas used was nitrogen, the temperature was 325°C, and the fragment voltage was optimized. Separation was carried out on a 50×4.6-mm C8, 3.5-μm analytical column (Zorbax XDB, C8; Hewlett Packard). The mobile phase consisted of 0.1% trifluoroacetic acid in water (solvent A) and acetonitrile (solvent B). The following gradient was run: at time 0 min, 100% solvent A and at 8 min, 80% solvent B. The flow rate was 1.0 mL/min. The analytical column was also maintained at 40°C. One minute after sample injection, the mass-selective detector was activated.

Metabolic Interactions of Sildenafil with Carbamazepine and Testosterone in Rat Liver Microsomes

The effects of carbamazepine and testosterone on the metabolism of sildenafil (0.5–10^3 μM) by CYP enzymes were investigated in a pool of rat liver microsomes. The incubation mixture consisted of hepatic microsomes from rat preparations in the presence of NADPH, 0.1 M potassium phosphate buffer (pH 7.4), and carbamazepine or testosterone. The concentrations of carbamazepine and testosterone were varied from 20 to 600 and 10 to 200 μM, respectively. The incubation mixture was preincubated for 5 min at 37°C in a shaking water bath, and sildenafil (0.5 to 10^3 μM) was added to further incubation for different times (5, 10, 20, and 40 min) at 37°C. The reactions were terminated with the addition of methanol and exposure to ice. Furthermore, incubation mixtures were centrifuged at 14900 *g* for 10 min to remove the protein. The supernatants were analyzed immediately by HPLC. An HPLC system equipped with a pump (Jasco PU-980 Intelligent HPLC pump) and an autosampler (Jasco AS-950-10 Intelligent Sampler) were used. The supernatants of carbamazepine and testosterone were detected with a Jasco UV-975 UV-VIS detector at 236 and 254 nm, respectively. A 4.6 × 250-mm (I.D.) Biosil Aqu-ODS-W column (Biotic Chemical Co., Taipei, Taiwan) with a particle size of 5 μm and a mobile phase consisting of water, acetonitrile, and methanol (containing 0.1% trifluoroacetic acid) at 60:20:20 and 50:20:30 (vol/vol) ratios were used in separating the metabolites of carbamazepine and testosterone, respectively. The flow rate was set at 1.0 mL/min. These methods for analyzing testosterone and carbamazepine were found to be selective, precise, and linear over concentration ranges of 0.1~10 and 0.25~10 μM, respectively. All mobile-phase solutions were filtered and degassed ultrasonically before use. The HPLC system was controlled by a PC workstation using Chromatography Data Station software (SISC) installed on it.

Data Analysis

The formation of UK-103,320 by liver microsomes was consistent with Michaelis–Menten kinetics with single substrate enzymes reaction. The following equation was fitted to UK-103,320 data points:

$$V_0 = \frac{V_{max}[S]}{K_m + [S]};$$

in which V represents the velocity of UK-103,320 formation and S is the concentration of the substrate, sildenafil. V_{max} (representing the maximum reaction velocity) and K_m (indicating the substrate concentration corresponding to 50% V_{max}) were calculated by using non-linear regression analysis with SigmaPlot V8.02 (Systat Software, Inc., San Jose, CA, USA, 2002).

RESULTS

Identification of UK-103,320 (*N*-demethylsildenafil) and Metabolism of Sildenafil

Upon LC-MS analysis, a major metabolite (with a retention time of 5.7 min) of the CYP-catalyzed metabolism of sildenafil exhibited an MH^+ ion at *m/z* 461, suggestive of the demethylation of sildenafil. By comparing the HPLC profile and mass spectral information, the metabolite was identified as UK-103,320. Incubation of sildenafil with microsomes in the presence of NADPH led to the formation of the major metabolite, UK-103,320, which was identified by comparing the HPLC retentions and LC-MS spectra. Formation of UK-103,320 (μg/mL) in the metabolic reaction of various concentration of sildenafil incubated with rat microsomes for different incubation times is shown in Figure 1. Results indicate that the formation of UK-103,320 was proportionally enhanced by an increasing incubation time and concentration of sildenafil to 200 μM. Figure 2 shows UK-103,320 formation in rat liver microsomes was consistent with

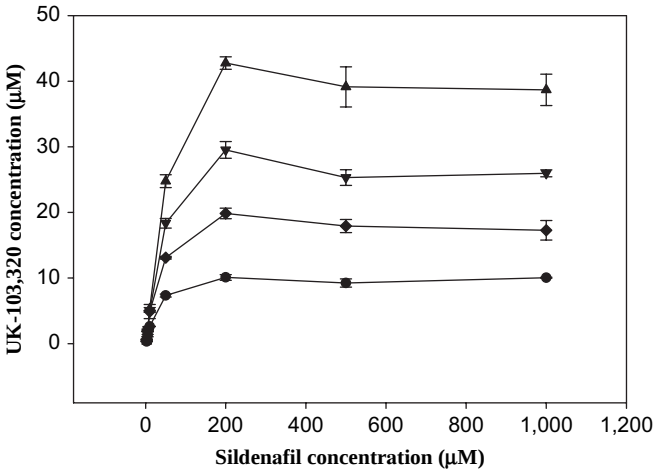

FIGURE 1. Formation of UK-103,320 (μg/mL) in the metabolic reaction of various concentrations of sildenafil incubated with rat microsomes for different incubation times (●, 5 min; ◆, 10 min; ▲, 20 min; ■, 40 min) (n = 3).

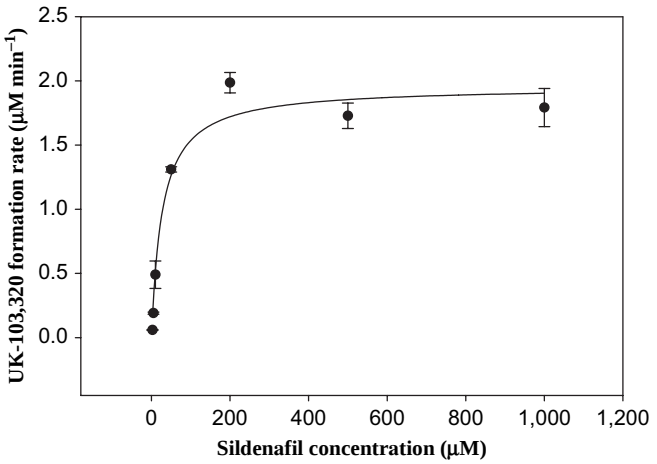

FIGURE 2. Michaelis–Menten plot of the conversion of sildenafil to UK-103,320.

single-enzyme Michaelis–Menten kinetics with uncompetitive substrate inhibition. The estimated K_m and V_{max} were 27.31 μM and 1.96 μM/min.

Metabolic Interaction of Sildenafil with Carbamazepine and Testosterone in Rat Liver Microsomes

Sildenafil was metabolized by CYP3A4 to UK-103,320, and we investigated the effects of testosterone and carbamazepine on the metabolic pathways of sildenafil. In the metabolism of sildenafil by microsomes, the presence of testosterone (10~200 μM) or carbamazepine (20˜600 μM) was found to inhibit the formation of UK-103,320. As shown in Figures 3 and 4, testosterone and carbamazepine inhibited the major sildenafil metabolic pathway. When the concentration of testosterone was increased from 10 to 200 μM, a similar extent of inhibition of the metabolism of sildenafil for different incubation times was noted. However, inhibition of sildenafil metabolism increased in parallel with an increase in the carbamazepine

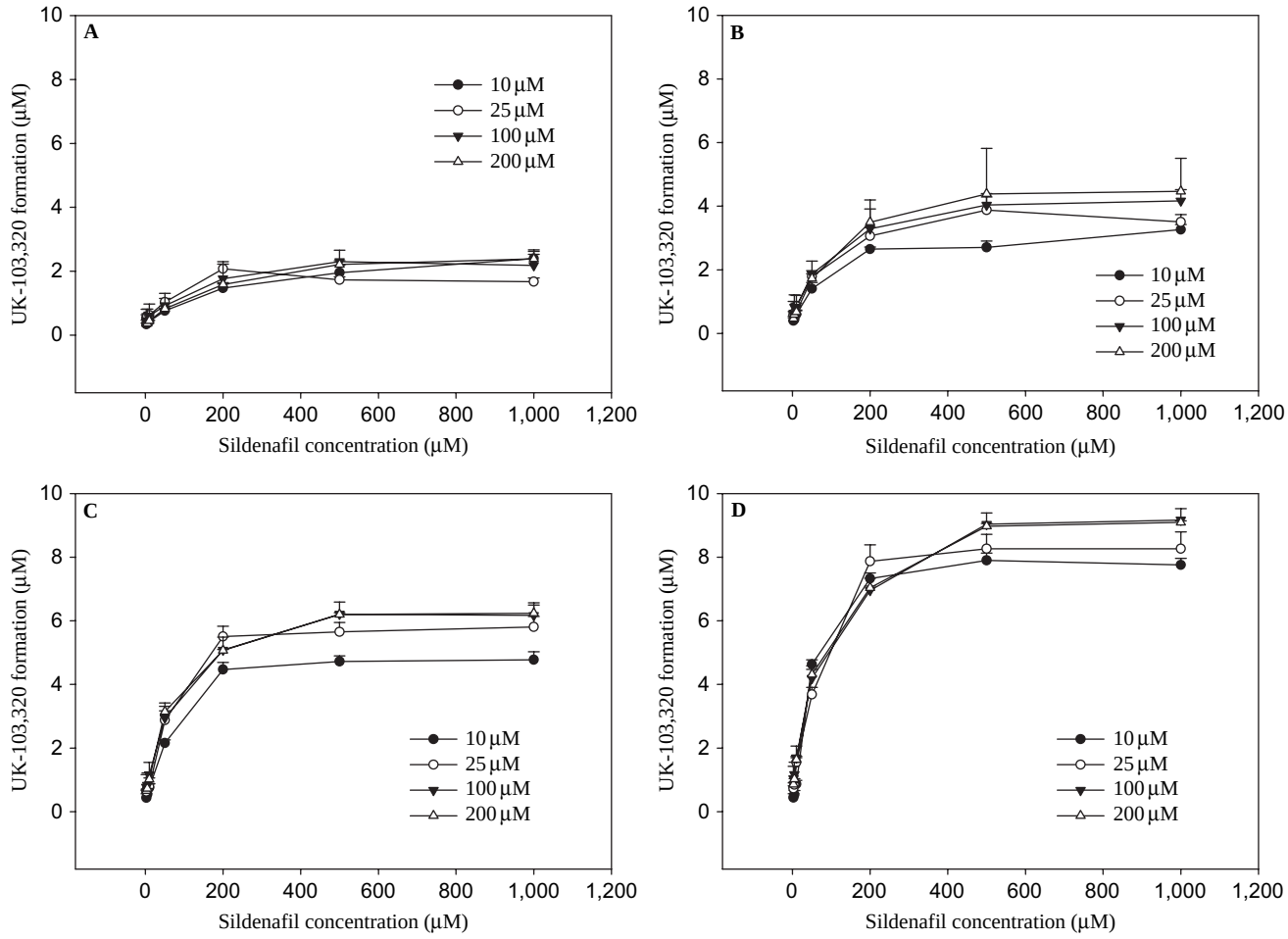

FIGURE 3. Formation of UK-103,320 (μg/mL), in the metabolism of sildenafil with the addition of different concentration of testosterone for different incubation times in rat microsomes (n = 3) (A, 5 min; B, 10 min; C, 20 min; D, 40 min).

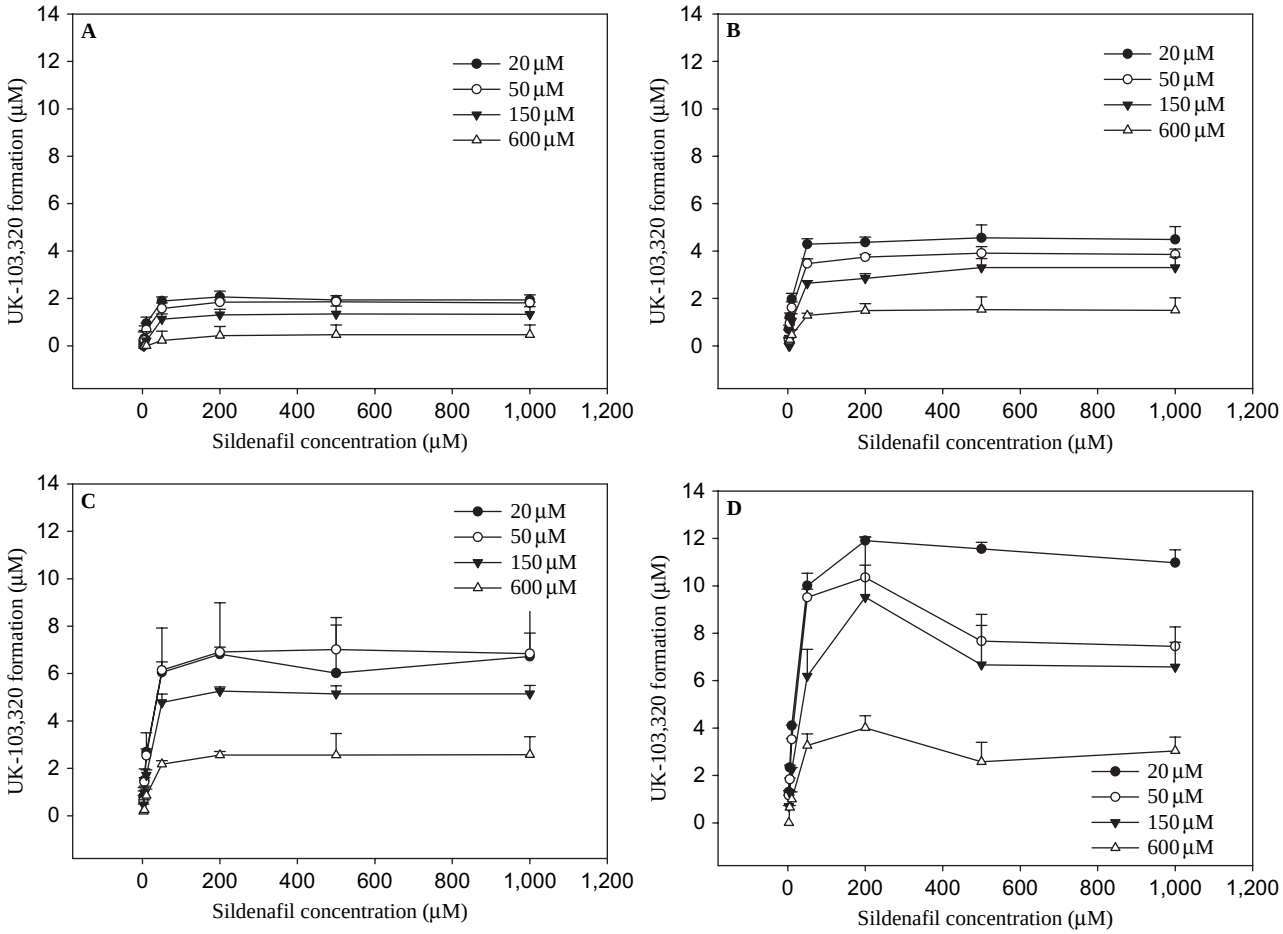

FIGURE 4. Formation of UK-103,320 (μg/mL), in the metabolism of sildenafil with the addition of different concentrations of carbamazepine for different incubation times in rat microsomes (n = 3) (A, 5 min; B, 10 min; C, 20 min; D, 40 min).

concentration and incubation time. At higher concentrations (150 and 600 μM), carbamazepine showed greater inhibition. Maximum inhibition was observed at approximately 600 μM carbamazepine with 40 min of incubation time. Both testosterone and carbamazepine produced almost complete inhibition of UK-103,320 formation at 200 μM sildenafil used. Effects of sildenafil on the formation of hydroxyl testosterone and 10,11-epoxide carbamazepine from biotransformation of testosterone and carbamazepine incubated with rat liver microsomes for different incubation times are listed in Tables 1 and 2, respectively. At fixed concentration of testosterone or carbamazepine, increasing concentrations of sildenafil produced insignificant differences in the formation of hydroxyl testosterone and 10,11-epoxide carbamazepine from the biotransformation of testosterone and carbamazepine incubated with rat liver microsomes for different incubation times. Thus, higher concentrations of sildenafil did not necessarily result in greater inhibition of testosterone 6β-hydroxylation and carbamazepine epoxidation. Instead, only partial inhibition was observed. These results showed that testosterone and carbamazepine can inhibit sildenafil demethylation, and that carbamazepine has an inhibitory effect in a concentration-dependant manner, but sildenafil did not inhibit testosterone hydroxylation or carbamazepine epoxidation.

DISCUSSION

Using rat liver microsomes, we demonstrated that sildenafil is *N*-demethylated to produce UK-103,320. The K_m for UK-103,320 formation in rat liver microsomes (27.31 μM) was similar to the K_m values for UK-103,320 formation by microsomes expressing CYP3A4 (23.1 μM) (Warrington, Shader, von Moltke, & Greenblatt, 2000). This further supports the role for CYP3A4 in UK-103,320 formation. The biotransformation of sildenafil in male rat liver microsomes is suitable as a model for sildenafil metabolism and evaluation of drug–drug interactions.

In general, substrates for CYP3A4 vary greatly in their physicochemical properties such as structure, molecular size and shape, lipophilicity, electronic characteristics, and kinetic

TABLE 1
Formation of Hydroxyl Testosterone (μg/mL) in the Metabolism of Different Concentrations of Testosterone with the Addition of Different Concentrations of Sildenafil for Different Incubation Times in Rat Liver Microsomes (n = 3)

	Time (min)															
	5				10				20				40			
Testosterone (μM)	10	25	100	200	10	25	100	200	10	25	100	200	10	25	100	200
2.5	0.31 ± 0.17	2.17 ± 0.37	7.04 ± 0.50	13.4 ± 0.21	0.18 ± 0.20	1.66 ± 0.45	7.64 ± 0.37	14.5 ± 0.36	0.33 ± 0.17	0.92 ± 0.60	11.03 ± 0.59	14.6 ± 0.22	0.34 ± 0.18	0.41 ± 0.72	9.78 ± 0.47	12.8 ± 0.25
5	0.25 ± 0.17	2.20 ± 0.40	9.21 ± 0.74	12.4 ± 0.18	0.31 ± 0.16	1.47 ± 0.53	7.51 ± 0.30	15.7 ± 0.42	0.17 ± 0.17	0.61 ± 0.64	10.67 ± 0.58	13.5 ± 0.31	0.34 ± 0.15	0.50 ± 0.70	10.86 ± 0.50	14.5 ± 0.42
10	0.31 ± 0.16	1.93 ± 0.47	7.40 ± 0.67	14.3 ± 0.45	0.33 ± 0.19	1.65 ± 0.41	8.08 ± 0.35	16.3 ± 0.22	0.29 ± 0.18	0.78 ± 0.57	9.86 ± 0.89	15.4 ± 0.44	0.32 ± 0.16	0.31 ± 0.80	9.44 ± 0.50	11.5 ± 0.26
50	0.26 ± 0.20	1.89 ± 0.45	6.82 ± 0.69	11.8 ± 0.46	0.21 ± 0.16	1.62 ± 0.45	7.02 ± 0.49	14.5 ± 0.14	0.29 ± 0.19	1.53 ± 0.34	6.85 ± 0.40	15.8 ± 0.29	0.35 ± 0.11	0.29 ± 0.71	7.53 ± 0.69	12.6 ± 0.27
200	0.32 ± 0.19	2.01 ± 0.38	6.32 ± 0.29	11.5 ± 0.25	0.31 ± 0.15	1.58 ± 0.41	6.10 ± 0.29	14.1 ± 0.33	0.29 ± 0.19	1.15 ± 0.59	7.42 ± 0.67	14.3 ± 0.39	0.29 ± 0.13	0.42 ± 0.65	6.43 ± 1.31	12.0 ± 0.31
500	0.32 ± 0.18	1.94 ± 0.42	6.11 ± 0.48	14.2 ± 0.24	0.21 ± 0.18	1.58 ± 0.43	6.10 ± 0.91	13.8 ± 0.30	0.27 ± 0.18	1.13 ± 0.49	7.44 ± 0.29	12.3 ± 0.17	0.23 ± 0.16	0.45 ± 0.66	6.86 ± 0.27	12.5 ± 0.12
1000	0.36 ± 0.14	1.85 ± 0.48	6.40 ± 0.38	12.9 ± 0.36	0.28 ± 0.12	2.16 ± 0.20	6.16 ± 0.28	14.6 ± 0.39	0.37 ± 0.19	1.08 ± 0.30	6.91 ± 1.05	15.6 ± 0.26	0.16 ± 0.18	0.48 ± 0.68	5.94 ± 0.61	11.5 ± 0.39

TABLE 2
Formation of 10–11 Epoxide Carbamazepine (μg/mL) in the Metabolism of Different Concentrations of Carbamazepine with the Addition of Different Concentrations of Carbamazepine for Different Incubation Times in Rat Liver Microsomes (n = 3)

	Time (min)															
	5				10				20				40			
Carbamazepine (μM)	20	50	150	600	20	50	150	600	20	50	150	600	20	50	150	600
2.5	0	0	0.40 ± 0.01	0.68 ± 0.01	0	0	0.42 ± 0.01	0.78 ± 0.03	0	0.49 ± 0.01	0.64 ± 0.01	0.66 ± 0.01	0.57 ± 0.02	0.71 ± 0.01	0.83 ± 0.01	1.11 ± 0.05
5	0	0	0.41 ± 0.01	0.68 ± 0.01	0	0	0.42 ± 0.01	0.70 ± 0.02	0	0.49 ± 0.01	0.63 ± 0.02	0.73 ± 0.00	0.57 ± 0.01	0.68 ± 0.06	0.81 ± 0.01	1.02 ± 0.04
10	0	0	0.40 ± 0.01	0.66 ± 0.01	0	0	0.43 ± 0.01	0.72 ± 0.03	0	0.49 ± 0.02	0.63 ± 0.02	1.02 ± 0.04	0.57 ± 0.02	0.68 ± 0.01	0.79 ± 0.01	1.04 ± 0.04
50	0	0	0.39 ± 0.01	0.67 ± 0.01	0	0	0.43 ± 0.01	0.72 ± 0.02	0	0.49 ± 0.01	0.63 ± 0.02	3.15 ± 0.17	0.58 ± 0.01	0.72 ± 0.02	0.80 ± 0.01	0.98 ± 0.04
200	0	0	0.40 ± 0.01	0.68 ± 0.02	0	0	0.42 ± 0.01	0.74 ± 0.04	0	0.48 ± 0.01	0.61 ± 0.01	5.07 ± 0.03	0.58 ± 0.03	0.68 ± 0.02	0.83 ± 0.01	1.03 ± 0.02
500	0	0	0.39 ± 0.02	0.65 ± 0.01	0	0	0.43 ± 0.01	0.72 ± 0.03	0	0.50 ± 0.01	0.64 ± 0.01	6.20 ± 0.06	0.59 ± 0.01	0.68 ± 0.02	0.81 ± 0.01	0.99 ± 0.02
1000	0	0	0.39 ± 0.01	0.65 ± 0.02	0	0	0.42 ± 0.01	0.71 ± 0.03	0	0.51 ± 0.02	0.60 ± 0.01	6.24 ± 0.26	0.60 ± 0.01	0.68 ± 0.02	0.79 ± 0.01	1.03 ± 0.04

interactions with enzyme proteins. The fact that CYP3A4 can accommodate substrates of a relatively large size, e.g., cyclosporine (MW=1201), suggests that multiple small or intermediate-sized molecules might be able to coexist at the active site of this enzyme. Indeed, some evidence has been obtained to support this hypothesis based on kinetic studies and NMR data (Shou et al., 1999, 2001). If an active site is capable of accommodating two substrates simultaneously, the resulting kinetic properties, e.g., binding affinity and catalytic ability, are likely to be affected differently from those observed with simple Michaelis–Menten inhibition and activation, both of which are derived from the one binding region at the active site (Domanski, He, Harlow, & Halpert, 2000; Schrag & Wienkers, 2001). Using substrates of CYP3A4 of testosterone and carbamazepine, active sites on CYP3A4 responsible for metabolizing sildenafil were evaluated in this study. Results demonstrated that the metabolism of sildenafil through *N*-demethylation by CYP3A4 in the presence of its substrate of either testosterone or carbamazepine was inhibited. These results suggest that the testosterone–CYP3A4–sildenafil and cabamazepine–CYP3A4–sildenafil complexes favor testosterone 6β-hydroxylation and carbamazepine epoxidation pathways rather than the sildenafil demethylation pathway. These observed kinetic changes with the interaction of two substrates with the enzyme cannot be explained by simple Michaelis–Menten kinetics. The interaction patterns between compounds with CYP were found to be substrate-dependent. A kinetic model for two substrates binding to two separate active sites was found to be optimal for describing the metabolism of sildenafil by CYP3A4 in the presence of either testosterone or carbamazepine. It was concluded that more than one site present on CYP3A4 is responsible for its metabolism.

The unusual kinetics associated with two or more substrate interactions have been documented in a number of reports. Several models have been proposed to explain the unusual kinetic characteristics with CYP3A4 involving two substrates. The atypical CYP3A4 kinetics, including activation, mutual inhibition, partial inhibition, and alteration of regiospecificity, observed in substrate oxidation and substrate–substrate interaction studies was explained by the two-substrate model (Korzekwa et al., 1998), the cooperative model (Ueng et al., 1997), and the multiple conformer model (Koley, Buters, Robinson, Markowitz, & Friedman, 1995). The two-site model proposes that two substrates can simultaneously bind to the CYP3A4 active site (Shou et al., 1994, Wang, Newton, Scheri, & Lu, 1997). Korzekwa et al. (1998) proposed a two-site (or multiple-site) model in which the enzyme can bind two molecules of one substrate or one molecule each of the two substrates, or one molecule each of the substrate and effector. The two-site model can describe many of the atypical CYP3A4 kinetics. The potential for binding to more than two sites on CYP3A4 was also alluded to by Shou et al. (1994) and more recently by Domanski, He, Harlow, and Halpert (2000) and Hosea et al. (2000). It has been proposed that the site for metabolism and activation by an effector may be distinct because two cooperative substrates have not been shown to cause mutual inhibition. Studies with site-directed mutants of CYP3A4 also support the hypothesis that both substrate and effector sites are closely linked and may be involved in substrate and/or effector binding, depending on the molecule of study (Domanski et al., 2000). Studies by Shou and co-workers (1994) on the cytochrome P450 active site also showed two different molecules can be simultaneously bound to the same P450 active site. In this study, we showed that testosterone and carbamazepine inhibited sildenafil demethylation, but less so for sildenafil inhibition of testosterone 6β-hydroxylation and carbamazepine epoxidation. As for the unusual sildenafil–testosterone and sildenafil–carbamazepine interactions, one can explain the results with a two-substrate model by postulating that testosterone and carbamazepine have freedom of movement and can bind to multiple sites, including the sildenafil-binding site of the CYP3A4 active site. Consequently, testosterone and carbamazepine can inhibit sildenafil demethylation, but inhibition of testosterone 6β-hydroxylation and carbamazepine epoxidation cannot be demonstrated kinetically. With the multiple conformer model, sildenafil–testosterone and sildenafil–carbamazepine interactions can be explained by assuming that testosterone and carbamazepine have high affinities for multiple CYP3A4 conformers (including the ones interacting with sildenafil), but sildenafil has only limited affinity for certain conformers. Perhaps one should consider a modified model that takes multiple binding sites, allosteric sites, and multiple conformations into account.

An unusual result was also found in the interaction between testosterone and nifedipine. Although nifedipine inhibited testosterone 6β-hydroxylation, testosterone did not inhibit nifedipine oxidation (Wang, 2000). One similar, but not identical, example was the report by Ueng et al. (1997), which stated the 7,8-benzoflavone activates the metabolism of aflatoxin B_1, but aflatoxin B_1 does not inhibit 7,8-benzoflavone metabolism. However, it is rare to find two substrates of the same enzyme that do not show mutual inhibition kinetics in the literature. These results may be explained by a model in which multiple substrates or ligands can bind concurrently to the active site of CYP molecules. However, the contribution of separate allosteric sites and conformational heterogeneity to the atypical kinetics of CYP cannot be ruled out in this model. Because of the unique properties of CYP3A4, substrate interactions involving this enzyme do not always follow typical competitive inhibition kinetics. Regardless of the mechanisms by which CYP3A4-dependent drug interactions occur, this study provides information that the co-administration of sildenafil and testosterone or carbamazepine may lead to increased plasma concentrations of sildenafil. This may, in turn, lead to an increase in the adverse effects commonly associated with sildenafil such as headaches, flushing, dyspepsia, and visual changes. Information on in vitro drug–drug interactions at the level of cytochrome P450 enzymes can be extremely useful in the evaluation of the potential of an agent to cause drug interactions in clinic use.

In conclusion, the effects of one substrate on the metabolism of another appeared to be dependent on the substrate of use. Clinicians should therefore be aware of the possibility of drug–drug interactions when prescribing sildenafil concomitantly with known substrates of CYP3A4.

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