

Clinical Pharmacogenetics Implementation Consortium (CPIC) Guideline for *CYP2B6* and Efavirenz-Containing Antiretroviral Therapy

Zeruesenay Desta¹, Roseann S. Gammal^{2,3}, Li Gong⁴, Michelle Whirl-Carrillo⁴, Aditya H. Gaur⁵, Chonlaphat Sukasem^{6,7}, Jennifer Hockings⁸, Alan Myers⁹, Marelize Swart¹, Rachel F. Tyndale¹⁰, Collen Masimirembwa¹¹, Otito F. Iwuchukwu¹², Sanika Chirwa¹³, Jeffrey Lennox¹⁴, Andrea Gaedigk¹⁵, Teri E. Klein⁴ and David W. Haas^{13,16,*}

The HIV type-1 nonnucleoside reverse transcriptase inhibitor, efavirenz, is widely used to treat HIV type-1 infection. Efavirenz is predominantly metabolized into inactive metabolites by cytochrome P450 (CYP)2B6, and patients with certain *CYP2B6* genetic variants may be at increased risk for adverse effects, particularly central nervous system toxicity and treatment discontinuation. We summarize the evidence from the literature and provide therapeutic recommendations for efavirenz prescribing based on *CYP2B6* genotypes.

Efavirenz is a potent inhibitor of HIV type-1 (HIV-1) replication, with a relatively narrow therapeutic index and large interindividual variability in pharmacokinetics, due in part to variants in the cytochrome P450 (CYP)2B6 gene (*CYP2B6*). The purpose of this guideline is to provide clinicians information that will allow the interpretation of clinical *CYP2B6* genotype tests so that the results can be used to guide efavirenz prescribing. Detailed guidelines for use of efavirenz as well as cost effectiveness of *CYP2B6* genotyping are beyond the scope of this document. Clinical Pharmacogenetics Implementation Consortium (CPIC) guidelines are periodically updated at www.cpicpgx.org/guidelines/.

FOCUSED LITERATURE REVIEW

A systematic literature review focused on *CYP2B6* genotype and efavirenz use was conducted (details in **Supplemental Material**).

Gene: *CYP2B6*

CYP2B6 is highly polymorphic with 38 known variant alleles and multiple suballeles (<https://www.pharmvar.org/gene/CYP2B6>; *CYP2B6* Allele Definition Table¹). Substantial differences in allele frequencies occur across ancestrally diverse groups (*CYP2B6* Frequency Table¹). Alleles are categorized into functional groups as follows: normal function (e.g., *CYP2B6**1), decreased function (e.g., *CYP2B6**6 and *9), no function (e.g., *CYP2B6**18), and increased function (e.g., *CYP2B6**4). Allele function assignments, as described in the *CYP2B6* Allele Functionality Table¹, have been made based on *in vitro* data with or without *in vivo* data. *CYP2B6**6 (p.Q172H, p.K262R) is the most frequently decreased function allele (15–60% minor allele frequency depending on ancestry) and has been studied most extensively. Although reduced protein expression due to aberrant splicing caused by the c.516G>T (rs3745274, p.Q172H) single-nucleotide polymorphism (SNP) contributes to reduced function of *CYP2B6**6,² *in vitro* studies also suggest complex substrate-dependent catalytic effects (reviewed in ref. 3). Therefore, it is somewhat challenging to assign function to *CYP2B6* alleles, as function may be substrate-specific.

The combination of inherited alleles determines a person's diplotype. **Table 1** defines each phenotype based on genotype and provides examples of diplotypes. Evidence based on few patients suggests that the *CYP2B6**4 and *22 alleles are associated with modestly reduced plasma efavirenz exposure. Thus, *CYP2B6**4 and *22 are categorized as increased function alleles. The phenotype categories of *CYP2B6* rapid metabolizer (RM; one normal function allele and one increased function allele) and *CYP2B6* ultrarapid metabolizer (UM; two increased function alleles) were

¹Department of Medicine, Division of Clinical Pharmacology, Indiana University School of Medicine, Indianapolis, Indiana, USA; ²Department of Pharmacy Practice, Massachusetts College of Pharmacy and Health Sciences University School of Pharmacy, Boston, Massachusetts, USA; ³Department of Pharmaceutical Sciences, St. Jude Children's Research Hospital, Memphis, Tennessee, USA; ⁴Department of Biomedical Data Science, Stanford University, Stanford, California, USA; ⁵Department of Infectious Diseases, St. Jude Children's Research Hospital, Memphis, Tennessee, USA; ⁶Division of Pharmacogenomics and Personalized Medicine, Faculty of Medicine Ramathibodi Hospital, Department of Pathology, Mahidol University, Bangkok, Thailand; ⁷Laboratory for Pharmacogenomics, Faculty of Medicine Ramathibodi Hospital, Somdech Phra Debaratana Medical Center, Bangkok, Thailand; ⁸Department of Pharmacy and Genomic Medicine Institute, Cleveland Clinic, Cleveland, Ohio, USA; ⁹Department of Diagnostic & Biomedical Sciences, The University of Texas Health Sciences Center School of Dentistry, Houston, Texas, USA; ¹⁰Centre for Addiction and Mental Health, University of Toronto, Toronto, Ontario, Canada; ¹¹African Institute of Biomedical Science & Technology, Wilkins Hospital, Harare, Zimbabwe; ¹²Division of Pharmaceutical Sciences, Fairleigh Dickinson University School of Pharmacy, Florham Park, New Jersey, USA; ¹³Department of Internal Medicine, Meharry Medical College School of Medicine, Nashville, Tennessee, USA; ¹⁴Division of Infectious Diseases, Emory University School of Medicine, Atlanta, Georgia, USA; ¹⁵Division of Clinical Pharmacology, Toxicology, & Therapeutic Innovation, Children's Mercy Kansas City, Kansas City, Missouri, USA; ¹⁶Departments of Medicine, Pharmacology, Pathology, Microbiology, & Immunology, Vanderbilt University School of Medicine, Nashville, Tennessee, USA. *Correspondence: David W. Haas (david.haas@vumc.org; contact@cpicpgx.org)

Received January 14, 2019; accepted April 12, 2019. doi:10.1002/cpt.1477

Table 1 Assignment of likely CYP2B6 phenotypes based on genotypes

| Likely phenotype | Genotypes | Examples of CYP2B6 diplotypes ^b |
|---------------------------------|--|---|
| CYP2B6 ultrarapid metabolizer | An individual carrying two increased function alleles | *4/*4, *22/*22, *4/*22 |
| CYP2B6 rapid metabolizer | An individual carrying one normal function allele and one increased function allele | *1/*4, *1/*22 |
| CYP2B6 normal metabolizer | An individual carrying two normal function alleles | *1/*1 |
| CYP2B6 intermediate metabolizer | An individual carrying one normal function allele and one decreased function allele OR one normal function allele and one no-function allele OR one increased function allele and one decreased function allele OR one increased function allele and one no-function allele ^a | *1/*6, *1/*18, *4/*6, *4/*18, *6/*22, *18/*22 |
| CYP2B6 poor metabolizer | An individual carrying two decreased function alleles OR two no-function alleles OR one decreased function allele and one no-function allele | *6/*6, *18/*18, *6/*18 |

CYP, cytochrome P450.

^aSee text for discussion regarding CYP2B6 rs4803419. ^bPlease refer to the diplotype to phenotype translation table online for a complete list.

created to allow for the possibility that these may be clinically relevant for efavirenz or other CYP2B6 substrates, such as bupropion and methadone. See the CYP2B6 Diplotype-Phenotype Table¹ for a complete list of possible diplotypes and phenotype assignments.

Genetic test interpretation

Many clinical laboratories report CYP2B6 genotype results using the star-allele (*) nomenclature. The (*)-allele nomenclature for CYP2B6 alleles is found at the Pharmacogene Variation (PharmVar) Consortium website (<https://www.pharmvar.org/gene/CYP2B6>). Some laboratories test and report only on specific SNPs that have been most extensively studied, such as c.516G>T and c.983T>C (rs28399499, p.I328T). These variants are the only defining SNPs for CYP2B6*9 and *18, respectively, but c.983T>C is also found in combination with another variant in *16, and c.516G>T is found in combination with other variants in 11 other CYP2B6 alleles (*6, *7, *13, *19, *20, *26, *29, *34, *36, *37, and *38). In cases where only these two SNPs are tested, it is not possible to distinguish between the (*) alleles that contain these variants. However, all alleles that carry c.516G>T or c.983T>C are considered decreased function or no function alleles, respectively, and result in the same CYP2B6 phenotypes based on diplotypes. Tables on the CPIC website contain a list of CYP2B6 alleles, the combinations of variants that define each allele, allele functional status, and allele frequency across major ancestral populations as reported in the literature.¹

The limitations of genetic testing, as described here, include: (i) known (*) alleles not tested for will not be reported, and instead, the allele will be reported as *1 by default; (ii) in cases where only c.516G>T and/or c.983T>C variants are genotyped, it will not be known if they exist in combination with other variants, and the alleles may be reported as *9 and *18, respectively, by default (although this limitation should not affect efavirenz plasma exposure); (iii) rare variants may not be genotyped; (iv) tests are not designed to detect unknown or *de novo* variants; and (v) CYP2B6 structural variations exist (hybrids, duplications), but little is known of their frequencies and clinical relevance.

Available genetic test options

See the Genetic Testing Registry (www.ncbi.nlm.nih.gov/gtr/) for more information on commercially available clinical testing options.

Incidental findings

No diseases or conditions have been consistently or strongly linked with genetic variations in CYP2B6 independent of drug metabolism and response.

Other considerations

In a genomewide association study, CYP2B6 rs4803419 (g.15582C>T) was independently associated with increased plasma efavirenz exposure.⁴ Patients who were homozygous for the minor allele (g.15582T/T) had plasma efavirenz concentrations comparable to CYP2B6 intermediate metabolizers (IMs; based on CYP2B6 c.516G>T and c.983T>C status). This SNP is not defining for any particular (*) allele but is part of the CYP2B6 *13 and *15 haplotypes, and the CYP2B6*1C suballele as defined in PharmVar (<https://www.pharmvar.org/gene/CYP2B6>).

Another CYP2B6 SNP, rs2279345 (g.18492T>C), has been associated with slightly decreased plasma efavirenz concentrations.^{5–9} This SNP is not part of any defined (*) alleles. The presence of this SNP together with coadministration of a strong CYP inducer may increase the likelihood of subtherapeutic plasma efavirenz concentrations.⁵

DRUG: EFAVIRENZ

Background

Efavirenz is a nonnucleoside HIV-1 reverse transcriptase inhibitor that suppresses HIV-1 replication. For treatment-naïve patients with HIV-positive disease, efavirenz in combination with tenofovir disoproxil fumarate and emtricitabine has been a cornerstone of treatment for >15 years based on its efficacy in randomized clinical trials, long half-life that allows for once-daily dosing, and availability of coformulation into a single tablet. It was part of the first “one pill, once a day” treatment

for HIV and largely supplanted the more cumbersome protease inhibitor-based regimens as first-line therapy. However, in 2015, the US Department of Health and Human Services re-assigned efavirenz-based regimens from the “recommended” to the “alternative” therapy category based on comparisons to HIV-1 integrase strand transfer inhibitor-based therapy in randomized clinical trials, which has better tolerability (efavirenz is notable for central nervous system (CNS) side effects) and

fewer drug–drug interactions than efavirenz-based regimens.¹⁰ Efavirenz is still extensively prescribed, especially in resource-limited countries worldwide, and is recommended as part of a first-line regimen for women who are pregnant or desiring pregnancy in World Health Organization guidelines.¹¹ Unlike some other antiretrovirals, efavirenz-containing regimens can be prescribed to patients who are receiving rifampicin-containing therapy for tuberculosis.

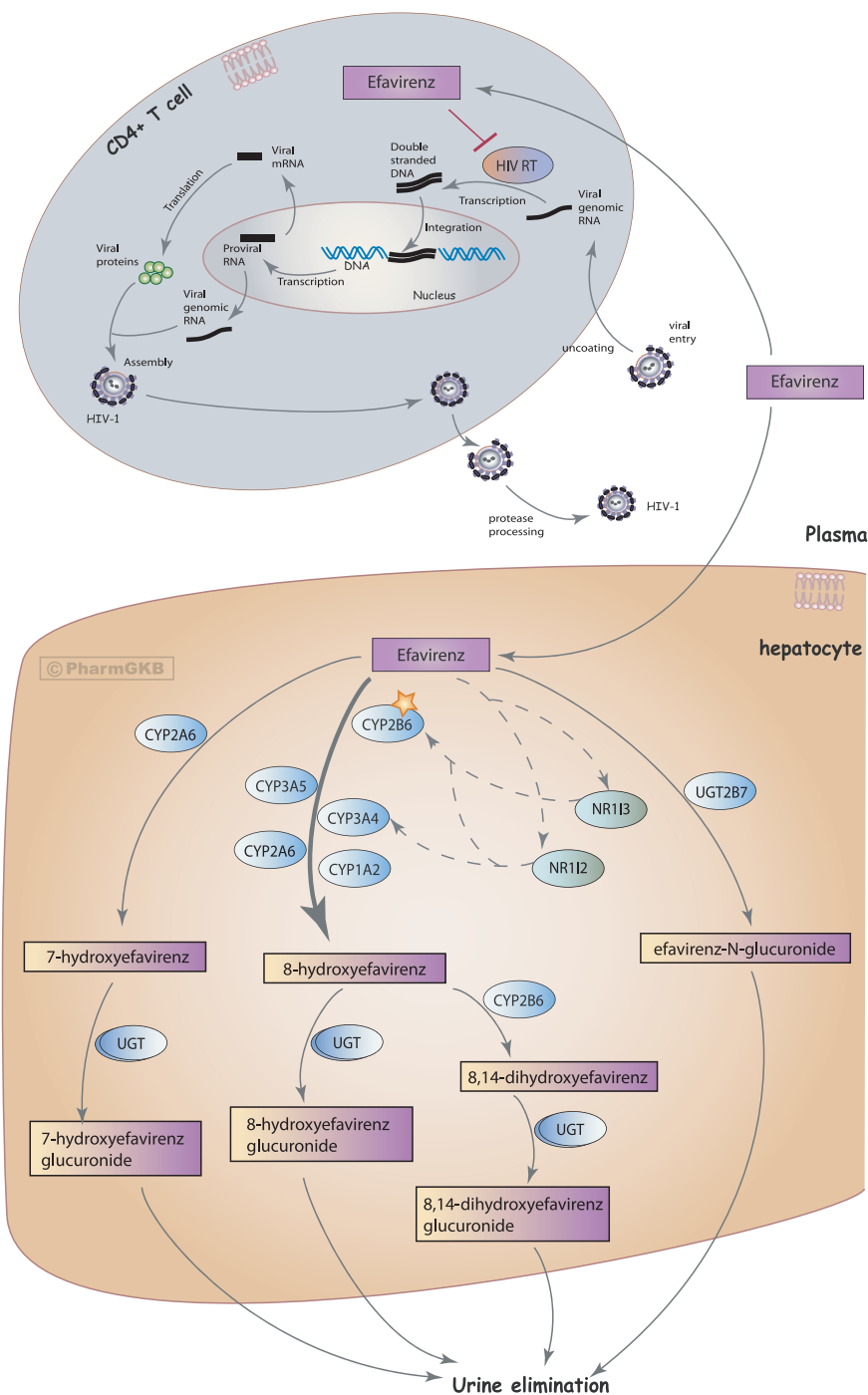


Figure 1 Schematic representation of efavirenz metabolism and mechanism of action against HIV.^{12,14} An interactive version of the pathway is available at <https://www.pharmgkb.org/pathway/PA166123135>. Image reproduced and is licensed under CC BY-SA 4.0 from PharmGKB. CYP, cytochrome P450; NR1, Transcription factors pregnane X receptor (PXR, NR1I2) and constitutive androstane receptor (CAR, NR1I3); RT, reverse transcriptase; UGT, UDP-glucuronosyltransferase.

Efavirenz is metabolized by CYP enzymes to form inactive hydroxylated metabolites¹² and by UDP-glucuronosyltransferases (UGT)-mediated direct N-glucuronidation.¹³ The major efavirenz metabolite is 8-hydroxy-efavirenz, which is generated primarily by CYP2B6 and lacks antiviral activity. Other CYP enzymes, including CYP2A6, CYP3A4, and CYP1A2, play minor roles in efavirenz 8-hydroxylation. CYP2A6-mediated hydroxylation to 7-hydroxy-efavirenz and UGT2B7-mediated glucuronidation to efavirenz N-glucuronide are minor metabolic pathways, although these enzymes may play a larger role in CYP2B6 poor metabolizers (PMs). The hydroxylated metabolites of efavirenz undergo conjugation via glucuronidation and/or sulfation and are subsequently excreted in urine. Details of efavirenz metabolic pathways are provided at the PharmGKB website and in **Figure 1**.^{12,14} The contribution of these pathways may differ following a single dose of efavirenz vs. chronic dosing. Efavirenz increases CYP2B6 expression via activation of the constitutive androstane receptor.¹⁵ As a result, chronic dosing of efavirenz enhances its own metabolism (“auto-induction”). The magnitude of efavirenz auto-induction varies among individuals and is, in part, affected by variations in the *CYP2B6* gene. For example, there is considerable CYP2B6 induction with the *CYP2B6**1/*1 and *1/*6 genotypes but little or no auto-induction with *CYP2B6**6/*6.¹⁶ Relationships between *CYP2B6* genotype and apparent oral clearance for efavirenz are shown in **Figure S1**.

Therapeutic drug monitoring may be used in some situations to ensure adequate plasma efavirenz concentrations. A therapeutic range for plasma efavirenz concentrations of 1–4 µg/mL has been suggested,¹⁷ although concentrations somewhat <1 µg/mL do not consistently predict treatment failure, and concentrations >4 µg/mL do not consistently predict toxicity. In one observational cohort study, virologic failure was observed in 50% of patients with plasma efavirenz concentrations <1 µg/mL (which may have reflected nonadherence in some patients) as compared to 22% and 18% of patients with concentrations between 1 and 4 µg/mL and >4 µg/mL, respectively. CNS side effects were observed in 24%, 9%, and 0% of patients with plasma efavirenz concentrations of >4 µg/mL, 1–4 µg/mL, and <1 µg/mL, respectively.¹⁷ CNS side effects may manifest as disordered sleep, impaired concentration, psychosis, suicidal ideation, and depression. Such effects typically manifest within the first few days of treatment initiation and largely resolve with continued dosing. However, symptoms may persist in some patients, impacting quality of life and resulting in treatment discontinuation. To minimize CNS adverse effects during waking hours, efavirenz is typically taken at bedtime.

Linking genetic variability to variability in drug-related phenotypes

Substantial evidence links *CYP2B6* genotype with variability in plasma efavirenz concentrations and with adverse effects. Most studies have examined the impact of *CYP2B6* c.516G>T and c.983T>C; therefore, these variants provide the basis for our clinical recommendations. As outlined in **Table S1**, the evidence associating these two variants with increased plasma

efavirenz concentrations was strong. Multiple studies have shown that the *CYP2B6* PM genotype, particularly defined by homozygosity or compound heterozygosity for *CYP2B6* c.516G>T and/or c.983T>C, is associated with decreased efavirenz clearance (**Figure S1**) and increased risk for efavirenz toxicity (particularly CNS toxicity, hepatic injury,¹⁸ and corrected QT prolongation¹⁹) and/or treatment discontinuation, although some studies have not shown such an association. Such associations seem to vary with race/ethnicity. For other *CYP2B6* alleles that are associated with interindividual variability in plasma efavirenz concentrations (e.g., *CYP2B6**4, *22, and g.15582C>T), associations have not been demonstrated with reduced efficacy, increased toxicity, or treatment discontinuation, perhaps because these alleles are either infrequent or have modest effects on plasma efavirenz exposure.

Therapeutic recommendations

CYP2B6-guided efavirenz dosing, particularly in the presence of *CYP2B6* c.516G>T, has been shown in clinical studies to be associated with therapeutic plasma efavirenz concentrations and decreased CNS toxicity, while maintaining virologic efficacy (see **Table S1**). **Table 2** summarizes therapeutic recommendations for efavirenz prescribing in adults based on *CYP2B6* phenotype. These recommendations also apply to children weighing >40 kg, as adult dosing applies to this group. Based on current evidence (**Table S1**), *CYP2B6* normal metabolizers (NMs) are expected to have normal efavirenz metabolism and achieve therapeutic efavirenz concentrations with standard dosing (600 mg/day). *CYP2B6* IMs may experience higher dose-adjusted trough concentrations compared with NMs, which may put these patients up to a 1.3-fold increased risk of adverse effects.^{20–25} For these patients, there is a “moderate” recommendation to consider initiating efavirenz with a decreased dose of 400 mg/day. *CYP2B6* PMs are at greatest risk for higher dose-adjusted trough concentrations compared with NMs and IMs, and greater overall plasma efavirenz exposure, which puts these patients up to a 4.8-fold increased risk for adverse effects and treatment discontinuation.^{20–31} For these patients, there is a “moderate” recommendation to consider initiating efavirenz with a decreased dose of either 400 or 200 mg/day. This “moderate” rather than “strong” recommendation reflects the fact that most *CYP2B6* PMs do not discontinue efavirenz 600 mg/day for adverse effects. Dose reduction to 400 mg/day may be feasible without increasing pill burden because, in 2018, the US Food and Drug Administration (FDA) approved a generic coformulated product consisting of efavirenz (400 mg), lamivudine, and tenofovir disoproxil fumarate. There is currently no coformulated tablet with 200 mg efavirenz, so decreasing the dose to 200 mg/day may be complicated by increased pill burden. If therapeutic drug monitoring is available and a decreased efavirenz dose is prescribed, steady-state plasma efavirenz concentrations may be obtained to ensure therapeutic concentrations (~1–4 µg/mL). Among *CYP2B6* IMs and PMs, prescribing efavirenz at 400 mg/day will almost certainly not reduce virologic efficacy, based on results of the ENCORE study in which treatment-naïve patients were randomized to initiate efavirenz-based regimens (combined with tenofovir and emtricitabine) at either 600 mg/day or

Table 2 Efavirenz dosing recommendations based on CYP2B6 phenotype in children ≥40 kg and adult patients

| CYP2B6 phenotype ^a | Implications for efavirenz pharmacologic measures | Therapeutic recommendations | Classification of recommendations ^b |
|---------------------------------|---|---|--|
| CYP2B6 ultrarapid metabolizer | Slightly lower dose-adjusted trough concentrations of efavirenz compared with normal metabolizers | Initiate efavirenz with standard dosing (600 mg/day) | Strong |
| CYP2B6 rapid metabolizer | Slightly lower dose-adjusted trough concentrations of efavirenz compared with normal metabolizers | Initiate efavirenz with standard dosing (600 mg/day) | Strong |
| CYP2B6 normal metabolizer | Normal efavirenz metabolism | Initiate efavirenz with standard dosing (600 mg/day) | Strong ^e |
| CYP2B6 intermediate metabolizer | Higher dose-adjusted trough concentrations of efavirenz compared with normal metabolizers; increased risk of CNS adverse events | Consider initiating efavirenz with decreased dose of 400 mg/day ^{c,d} | Moderate |
| CYP2B6 poor metabolizer | Higher dose-adjusted trough concentrations of efavirenz compared with normal metabolizers; significantly increased risk of CNS adverse events and treatment discontinuation | Consider initiating efavirenz with decreased dose of 400 or 200 mg/day ^{c,d} | Moderate |

CNS, central nervous system; CYP, cytochrome P450.

^aThe online CYP2B6 Frequency Table provides phenotype frequencies for major race/ethnic groups, and the online CYP2B6 Diplotype-Phenotype Table provides a complete list of possible diplotypes and phenotype assignments. ^bRating scheme described in the Supplementary Material online. ^cIf therapeutic drug monitoring is available and a decreased efavirenz dose is prescribed, consider obtaining steady-state plasma efavirenz concentrations to ensure concentrations are in the suggested therapeutic range (~ 1–4 µg/mL). ^dTo prescribe efavirenz at a decreased dose of 400 mg/day or 200 mg/day in a multidrug regimen may require prescribing more than one pill once daily. If so, the provider should weigh the potential benefit of reduced dose against the potential detrimental impact of increased pill number. ^eThe ENCORE study showed that in treatment-naïve patients randomized to initiate efavirenz-based regimens (combined with tenofovir and emtricitabine), 400 mg/day was noninferior to 600 mg/day regardless of CYP2B6 genotype.³²

400 mg/day regardless of CYP2B6 genotype and which showed that 400 mg/day was noninferior.³²

CYP2B6 RMs and UMs may experience slightly lower dose-adjusted trough concentrations of efavirenz compared with NMs, which may be clinically important for efavirenz. However, based on current evidence, the effect of the increased function alleles CYP2B6*4 and *22 seems to be modest.^{27,33–35} As such, current data are not sufficient to recommend a change from normal prescribing at this time, and patients with the RM or UM phenotype should receive standard efavirenz dosing. Of note, to define CYP2B6*4 requires documenting the absence of c.516G>T.

Pediatrics. Efavirenz is FDA-approved for use as part of antiretroviral therapy in children ≥3 months of age and weighing ≥3.5 kg. In the United States, efavirenz is available as capsules (50 or 200 mg); tablets (600 mg); a fixed-dose combination comprised of efavirenz 600 mg, emtricitabine 200 mg, and tenofovir disoproxil fumarate 300 mg and more recently a fixed dose combination called Symfi Lo (efavirenz 400 mg, lamivudine 300 mg, and tenofovir disoproxil fumarate 300 mg) for children weighing ≥35 kg. The US Department of Health and Human Services (DHHS) Guidelines for the Use of Antiretroviral Agents in Pediatric HIV Infection recommends efavirenz in combination with two-nucleoside reverse transcriptase inhibitors as an alternative nonnucleoside reverse transcriptase inhibitor regimen for initial treatment of HIV in children aged ≥ 3 years.³⁶

Children aged <3 years. Determining the optimal efavirenz dose for children <3 years of age or weighing <10 kg has been particularly challenging, as pharmacokinetic studies have shown a greater effect of genotype on efavirenz metabolism in young children due to high apparent clearance rates, especially among NMs.³⁷ In this population, as with adults (**Figure S1**), the apparent clearance was reduced by 19% and 57% with CYP2B6 c.516G/T and c.516T/T genotypes, respectively, compared to c.516G/G. With respect to CYP2B6 ontogeny, CYP2B6 mRNA expression levels and CYP2B6 activity are very low during fetal development and approach adult levels by 1 year of age.³⁸ Modeling based on data from a 24-week prospective cohort trial of efavirenz plus two nucleoside reverse transcriptase inhibitors in HIV-positive children 3 months to <36 months of age predicted that FDA-approved doses would produce subtherapeutic plasma concentrations in almost one third of children who are CYP2B6 NMs (c.516G/G) or IMs (c.516G/T) and supratherapeutic plasma concentrations in >50% of children who are CYP2B6 PMs (c.516T/T).³⁹ Subtherapeutic concentrations in this population may also be confounded by poor absorption. Given these data, similar to DHHS guidelines, we do not recommend use of efavirenz in infants and children aged 3 months to <3 years, except under special circumstances, such as tuberculosis coinfection. If a clinical situation requires use of efavirenz in this age group, CYP2B6 testing may be informative and dosing could be guided by the current DHHS guidelines, which were informed

by IMPAACT study P1070.³⁶ The guidelines recommended an efavirenz dose reduction based on weight groups for CYP2B6 PMs (c.516T/T): 5 kg to <7 kg: 50 mg; 7 kg to <14 kg: 100 mg; 14 kg to <17 kg: 150 mg; and ≥17 kg: 150 mg. Dosing for NMs (c.516G/G) and IMs (c.516G/T) is as follows: 5 kg to <7 kg: 300 mg; 7 kg to <14 kg: 400 mg; 14 kg to <17 kg: 500 mg; and ≥17 kg: 600 mg. Although current DHHS guidelines for efavirenz dosing in pediatrics do not consider c.983T>C, we recommend that dosing recommendations for c.516T/T also be applied to c.516T/c.983C and to c.983C/C. We also recommend measuring plasma efavirenz concentrations 2 weeks after initiation. The mid-dose plasma efavirenz concentration target of 1–4 mg/L derived from adult clinical monitoring data is typically also applied to trough concentrations in pediatric patients.

Children age > 3 years and weighing < 40 kg. Although the effect of *CYP2B6* genotype on efavirenz exposure has been demonstrated in children older than 3 years of age who weigh < 40 kg, specific clinical data supporting *CYP2B6* genotype-guided dosing are limited. Thus, although we cannot make a firm recommendation for dose adjustment based on *CYP2B6* genotype in this age and weight group, *CYP2B6* genotype almost certainly affects efavirenz exposure in these children such that efavirenz dose reduction in CYP2B6 PMs would also be reasonable. Therapeutic drug monitoring, where available and accessible, could help guide dosing adjustments in this age/weight group, especially in a setting of potential drug-related toxicity, virologic rebound, or lack of response in an adherent patient. For pediatric patients who weigh 40 kg or more, adult dosing applies (see **Table 2**).

Recommendations for incidental findings

Not applicable.

Other considerations

CYP2B6 rs4803419 (g.15582 C>T). In a study involving 856 participants from several prospective clinical trials, and after controlling for both *CYP2B6* c.516G>T and c.983T>C, increased plasma efavirenz concentrations were associated with *CYP2B6* g.15582C>T ($P = 4.4 \times 10^{-15}$).⁴ Other studies have not yet replicated this association for efavirenz, either because individual studies did not genotype this SNP or because this SNP was infrequent in small studies of primarily African cohorts.

Implementation of this guideline. The guideline supplement and CPIC website (<https://cpicpgx.org/guidelines/cpic-guideline-for-efavirenz-based-on-cyp2b6-genotype/>) contains resources that can be used within electronic health records to assist clinicians in applying genetic information to patient care for the purpose of drug therapy optimization (see Resources to incorporate pharmacogenetics into an electronic health record with clinical decision support in the **Supplemental Material**).

POTENTIAL BENEFITS AND RISKS FOR THE PATIENT

The potential benefit of using *CYP2B6* genotype data to guide efavirenz therapy is that patients with genotypes that predict higher

dose-adjusted plasma exposure and adverse effects may be identified and prescribed a decreased dose that will decrease the likelihood of toxicity and treatment discontinuation while still achieving therapeutic plasma efavirenz concentrations. Risks include the potential for subtherapeutic plasma efavirenz concentrations and treatment failure. As with any laboratory test, a possible risk to patients is an error in genotyping or phenotype prediction, which could have long-term adverse health implications for patients.

CAVEATS: APPROPRIATE USE AND/OR POTENTIAL MISUSE OF GENETIC TESTS

Rare *CYP2B6* variants may not be included in the genotype test used, and patients with rare variants may be assigned an NM phenotype (*CYP2B6**1/*1) by default. Thus, an assigned *1 allele could potentially harbor a decreased or no-function variant. Therefore, it is important that test reports include information on which variant alleles were genotyped.

As with any diagnostic test, *CYP2B6* genotype is just one factor that clinicians should consider when prescribing efavirenz. It is important to consider that efavirenz is typically coformulated in a fixed-dose combination tablet, which allows for one pill, once-daily dosing. If 400 mg or 200 mg doses of efavirenz are unavailable in a fixed-dose combination tablet, dose reduction may require prescribing two or three tablets daily, which not only increases pill burden but also risk for nonadherence and virologic failure with drug-resistant viruses. Another consideration is the impact of drug–drug interactions. For example, if coadministered with drugs that lower plasma efavirenz exposure (e.g., carbamazepine, phenytoin, and rifampin without isoniazid), it may be prudent to not further reduce efavirenz dose based on genotype. Although pregnancy does not substantially affect plasma efavirenz exposure,⁴⁰ clinical judgment should be exercised if genotype-informed dose reduction is considered during pregnancy.

SUPPORTING INFORMATION

Supplementary information accompanies this paper on the *Clinical Pharmacology & Therapeutics* website (www.cpt-journal.com).

Supplemental Material. CYP2B6 EFV Guidelines

ACKNOWLEDGMENTS

The authors acknowledge the critical input of Dr Mary Relling and members of the Clinical Pharmacogenetics Implementation Consortium (CPIC) of the Pharmacogenomics Research Network, funded by the National Institutes of Health. CPIC members are listed here: <https://cpicpgx.org/members/>.

FUNDING

This work was funded by the National Institutes of Health (NIH) for CPIC (R24GM115264 and U24HG010135), PharmGKB (R24GM61374) and PharmVar (R24 GM123930). Additional grant funding included R01 AI077505, UM1 AI069439, UM1 AI106701, P30 AI110527, TR 002243 (DWH); U01 HG007762, R01 GM121707, and R01 GM078501 (Z.D.); CAMH (R.F.T.), a Canada Research Chair in Pharmacogenomics (R.F.T.) and CIHR grant FDN-154294 (R.F.T.); a European and Developing Countries Clinical Trial Partnership (EDCTP) grant TMA 20016-1508 PRACE TMA2016SF, a SANBIO/Biofissall grant (C.M.).

CONFLICTS OF INTEREST

As an Associate Editor for *Clinical Pharmacology & Therapeutics*, Rachel F. Tyndale was not involved in the review or decision process for this paper. All other authors declared no competing interests for this work.

DISCLAIMER

Clinical Pharmacogenetics Implementation Consortium (CPIC) guidelines reflect expert consensus based on clinical evidence and peer-reviewed literature available at the time they are written and are intended only to assist clinicians in decision making, as well as to identify questions for further research. New evidence may have emerged since the time a guideline was submitted for publication. Guidelines are limited in scope and are not applicable to interventions or diseases not specifically identified. Guidelines do not account for all individual variation among patients and cannot be considered inclusive of all proper methods of care or exclusive of other treatments. It remains the responsibility of the health care provider to determine the best course of treatment for the patient. Adherence to any guideline is voluntary, with the ultimate determination regarding its application to be solely made by the clinician and the patient. CPIC assumes no responsibility for any injury to persons or damage to property related to any use of CPIC's guidelines or for any errors or omissions.

© 2019 The Authors *Clinical Pharmacology & Therapeutics* © 2019 American Society for Clinical Pharmacology and Therapeutics

- Clinical Pharmacogenetics Implementation Consortium (CPIC). CPIC Guideline for Efavirenz based on CYP2B6 genotype. <<https://cpicpgx.org/guidelines/cpic-guideline-for-efavirenz-based-on-cyp2b6-genotype>> (2018).
- Hofmann, M.H. et al. Aberrant splicing caused by single nucleotide polymorphism c.516G>T [Q172H], a marker of CYP2B6*6, is responsible for decreased expression and activity of CYP2B6 in liver. *J. Pharmacol. Exp. Ther.* **325**, 284–292 (2008).
- Zanger, U.M. & Klein, K. Pharmacogenetics of cytochrome P450 2B6 (CYP2B6): advances on polymorphisms, mechanisms, and clinical relevance. *Front. Genet.* **4**, 24 (2013).
- Holzinger, E.R. et al. Genome-wide association study of plasma efavirenz pharmacokinetics in AIDS Clinical Trials Group protocols implicates several CYP2B6 variants. *Pharmacogenet. Genom.* **22**, 858–867 (2012).
- Manosuthi, W., Sukasem, C., Thongyen, S., Nilkamhang, S., Manosuthi, S. & Sungkanuparph, S. CYP2B6 18492T>C polymorphism compromises efavirenz concentration in coinfecting HIV and tuberculosis patients carrying CYP2B6 haplotype *1/*1. *Antimicrob. Agents Chemother.* **58**, 2268–2273 (2014).
- Sukasem, C. et al. Pharmacogenetics and clinical biomarkers for subtherapeutic plasma efavirenz concentration in HIV-1 infected Thai adults. *Drug Metab. Pharmacokinet.* **29**, 289–295 (2014).
- Sukasem, C. et al. Low level of efavirenz in HIV-1-infected Thai adults is associated with the CYP2B6 polymorphism. *Infection* **42**, 469–474 (2014).
- Manosuthi, W. et al. Impact of pharmacogenetic markers of CYP2B6, clinical factors, and drug-drug interaction on efavirenz concentrations in HIV/tuberculosis-coinfecting patients. *Antimicrob. Agents Chemother.* **57**, 1019–1024 (2013).
- Sukasem, C. et al. Pharmacogenetic markers of CYP2B6 associated with efavirenz plasma concentrations in HIV-1 infected Thai adults. *Br. J. Clin. Pharmacol.* **74**, 1005–1012 (2012).
- Guidelines for the Use of Antiretroviral Agents in HIV-1-Infected Adults and Adolescents. <<https://aidsinfo.nih.gov/contentfiles/lvguidelines/adultandadolescentgl.pdf>> (2018). Accessed June 18, 2018.
- World Health Organization (WHO). Consolidated guidelines on the use of antiretroviral drugs for treating and preventing HIV infection. <http://apps.who.int/iris/bitstream/handle/10665/208825/9789241549684_eng.pdf?sequence=1> (2016). Accessed June 18, 2018.
- McDonagh, E.M., Lau, J.L., Alvarellos, M.L., Altman, R.B. & Klein, T.E. PharmGKB summary: efavirenz pathway, pharmacokinetics. *Pharmacogenet. Genom.* **25**, 363–376 (2015).
- Belanger, A.S., Caron, P., Harvey, M., Zimmerman, P.A., Mehlotra, R.K. & Guillemette, C. Glucuronidation of the antiretroviral drug efavirenz by UGT2B7 and an in vitro investigation of drug-drug interaction with zidovudine. *Drug Metab. Dispos.* **37**, 1793–1796 (2009).
- PharmGKB. Efavirenz pathway, pharmacokinetics. <<https://www.pharmgkb.org/pathway/PA166123135>>. Accessed July 25, 2018.
- Meyer zu Schwabedissen, H.E. et al. Compartment-specific gene regulation of the CAR inducer efavirenz in vivo. *Clin. Pharmacol. Ther.* **92**, 103–111 (2012).
- Ngaimisi, E. et al. Long-term efavirenz autoinduction and its effect on plasma exposure in HIV patients. *Clin. Pharmacol. Ther.* **88**, 676–684 (2010).
- Marzolini, C., Telenti, A., Decosterd, L.A., Greub, G., Biollaz, J. & Buclin, T. Efavirenz plasma levels can predict treatment failure and central nervous system side effects in HIV-1-infected patients. *AIDS* **15**, 71–75 (2001).
- Yimer, G. et al. High plasma efavirenz level and CYP2B6*6 are associated with efavirenz-based HAART-induced liver injury in the treatment of naive HIV patients from Ethiopia: a prospective cohort study. *Pharmacogenom. J.* **12**, 499–506 (2012).
- Abdelhady, A.M. et al. Efavirenz inhibits the human ether-A-go-go related current (hERG) and induces QT interval prolongation in CYP2B6*6*6 allele carriers. *J. Cardiovasc. Electrophysiol.* **27**, 1206–1213 (2016).
- Dooley, K.E. et al. Pharmacokinetics of efavirenz and treatment of HIV-1 among pregnant women with and without tuberculosis coinfection. *J. Infect. Dis.* **211**, 197–205 (2015).
- McIlleron, H.M. et al. Effects of rifampin-based antituberculosis therapy on plasma efavirenz concentrations in children vary by CYP2B6 genotype. *AIDS* **27**, 1933–1940 (2013).
- Dooley, K.E. et al. Safety, tolerability, and pharmacokinetic interactions of the antituberculous agent TMC207 (bedaquiline) with efavirenz in healthy volunteers: AIDS Clinical Trials Group Study A5267. *J. Acquir. Immune Defic. Syndr.* **59**, 455–462 (2012).
- Robarge, J.D. et al. Population pharmacokinetic modeling to estimate the contributions of genetic and nongenetic factors to efavirenz disposition. *Antimicrob. Agents Chemother.* **61** (2017). <https://doi.org/10.1128/AAC.01813-16>
- Mollan, K.R. et al. Race/ethnicity and the pharmacogenetics of reported suicidality with efavirenz among clinical trials participants. *J. Infect. Dis.* **216**, 554–564 (2017).
- Rotger, M. et al. Influence of CYP2B6 polymorphism on plasma and intracellular concentrations and toxicity of efavirenz and nevirapine in HIV-infected patients. *Pharmacogenet. Genom.* **15**, 1–5 (2005).
- Ribaudo, H.J. et al. Effect of CYP2B6, ABCB1, and CYP3A5 polymorphisms on efavirenz pharmacokinetics and treatment response: an AIDS Clinical Trials Group study. *J. Infect. Dis.* **202**, 717–722 (2010).
- Rotger, M. et al. Predictive value of known and novel alleles of CYP2B6 for efavirenz plasma concentrations in HIV-infected individuals. *Clin. Pharmacol. Ther.* **81**, 557–566 (2007).
- Gross, R. et al. CYP2B6 genotypes and early efavirenz-based HIV treatment outcomes in Botswana. *AIDS* **31**, 2107–2113 (2017).
- Cummins, N.W. et al. Investigation of efavirenz discontinuation in multi-ethnic populations of HIV-positive individuals by genetic analysis. *EBioMedicine* **2**, 706–712 (2015).
- Leger, P. et al. Pharmacogenetics of efavirenz discontinuation for reported central nervous system symptoms appears to differ by race. *Pharmacogenet. Genom.* **26**, 473–480 (2016).
- Johnson, D.H. et al. Neuropsychometric correlates of efavirenz pharmacokinetics and pharmacogenetics following a single oral dose. *Br. J. Clin. Pharmacol.* **75**, 997–1006 (2013).
- ENCORE1 Study Group. Efficacy of 400 mg efavirenz versus standard 600 mg dose in HIV-infected, antiretroviral-naïve adults (ENCORE1): a randomised, double-blind, placebo-controlled, non-inferiority trial. *Lancet* **383**, 1474–1482 (2014).
- Ariyoshi, N. et al. Q172H replacement overcomes effects on the metabolism of cyclophosphamide and efavirenz caused by CYP2B6 variant with Arg262. *Drug Metab. Dispos.* **39**, 2045–2048 (2011).
- Desta, Z. et al. Impact of CYP2B6 polymorphism on hepatic efavirenz metabolism in vitro. *Pharmacogenomics* **8**, 547–558 (2007).

35. Zukunft, J. *et al.* A natural CYP2B6 TATA box polymorphism (-82T→C) leading to enhanced transcription and relocation of the transcriptional start site. *Mol. Pharmacol.* **67**, 1772–1782 (2005).
36. National Institutes of Health (NIH). Guidelines for the Use of Antiretroviral Agents in Pediatric HIV Infection. <<https://aidsinfo.nih.gov/contentfiles/lvguidelines/pediatricguidelines.pdf>>. Accessed December 14, 2018.
37. Saitoh, A. *et al.* Efavirenz pharmacokinetics in HIV-1-infected children are associated with CYP2B6-G516T polymorphism. *J. Acquir. Immune Defic. Syndr.* **45**, 280–285 (2007).
38. Pearce, R.E. *et al.* Developmental expression of CYP2B6: a comprehensive analysis of mRNA Expression, protein content and bupropion hydroxylase activity and the impact of genetic variation. *Drug Metab. Dispos.* **44**, 948–958 (2016).
39. Bolton Moore, C. *et al.* CYP2B6 genotype-directed dosing is required for optimal efavirenz exposure in children 3–36 months with HIV infection. *AIDS* **31**, 1129–1136 (2017).
40. Hill, A., Ford, N., Boffito, M., Pozniak, A. & Cressey, T.R. Does pregnancy affect the pharmacokinetics of efavirenz? *AIDS* **28**, 1542–1543 (2014).