The Potential of *Sutherlandia frutescens* for Herb-Drug Interaction

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**ABSTRACT**

In Africa, *Sutherlandia frutescens* is a popular medicinal herb widely consumed by people living with human immunodeficiency virus/AIDS. Concomitant use with antiretroviral drugs has generated concerns of herb-drug interaction (HDI). This study investigated the inhibitory effects of the crude extracts of *S. frutescens* on the major cytochrome P450 isozymes with the use of pooled human liver microsomes. Its effect on the metabolite clearance of midazolam using cryopreserved hepatocytes was also monitored. The potential of *S. frutescens* to inhibit human ATP-binding cassette transporters (P-gp and BCRP) and the human organic anion transporting polypeptide (OATP1B1 and OATP1B3) activity was assessed using cell lines overexpressing the transporter proteins. *S. frutescens* showed inhibitory potency for CYP1A2 (*IC₅₀ = 41.0 μg/ml*), CYP2A6 (*IC₅₀ = 160 μg/ml*), CYP2B6 (*IC₅₀ = 20.0 μg/ml*), CYP2C8 (*IC₅₀ = 22.4 μg/ml*), CYP2C9 (*IC₅₀ = 23.0 μg/ml*), CYP2C19 (*IC₅₀ = 35.9 μg/ml*), and CYP3A4/5 (*IC₅₀ = 17.5 μg/ml [with midazolam1'-hydroxylation]*; *IC₅₀ = 28.3 μg/ml [with testosterone 6β-hydroxylation]*). Time-dependent (irreversible) inhibition by *S. frutescens* was observed for CYP3A4/5 (*Kᵢ = 296 μg/ml, kₚreact = 0.063 min⁻¹*) under the conditions of this study. *S. frutescens* also delays the production of midazolam metabolites in the hepatocytes, decreasing its clearance by 40%. Furthermore, *S. frutescens* inhibited P-gp (*IC₅₀ = 324.8 μg/ml*), OATP1B1 (*IC₅₀ = 10.4 μg/ml*), and OATP1B3 (*IC₅₀ = 6.6 μg/ml*). The result indicates the potential for HDI between *S. frutescens* and the substrates of the affected enzymes, if sufficient in vivo concentration of the extract is attained.

**Introduction**

Although the use of medicinal herbs, a principal component of traditional medicine, predates the emergence of human immunodeficiency virus (HIV)/AIDS, herbal products as immune boosters and symptomatic management of AIDS have been popularized in Africa (Namuddu et al., 2011). The high burden of HIV/AIDS has attracted various policy designs to accommodate a holistic approach to management. Although the use of traditional herbal medicines by persons living with HIV/AIDS in South Africa, despite the availability and/or consumption of ARVs (Morris, 2002; Mills et al., 2005; Malangu, 2007). As a popular and culturally attached practice, an estimated 80–85% of Africans consult traditional health practitioners (THP) for the management of various physical ailments and social disharmony (UNAIDS, 2006). For the majority of this group of individuals, THPs are the first point of call for health services.

Studies have shown that the majority of South Africans consult THPs, especially for the treatment of sexually transmitted infections, such as gonorrhea, syphilis, and assumed HIV/AIDS (Peltzer, 2001, 2003). Although some patients with HIV/AIDS consume medicinal herbs ab initio, it has been reported that a number of them resort to herbal medicine in response to perceived adverse reactions to ARVs (Peltzer and Mngqundaniso, 2008). The number of patients with HIV/AIDS who consume herbal medicine alone or concomitantly with ARVs is often underestimated. In a cross-sectional study performed by Peltzer and colleagues (2008), up to 90% of respondents who were taking herbal therapies for HIV infection did not disclose this to their health care providers. This, therefore, calls for more research to establish the therapeutic benefit and safety of such practices.

Widely known as cancer bush because of its traditional use in the management of cancer, *Sutherlandia frutescens* (Sutherlandia) is one of the most reputable herbal remedies consumed among persons living with HIV/AIDS in South Africa, to boost immunity and enhance general well-being (Gerickc, 2001). It is referred to variously in local languages as insiswa, kankerbos, kankerbossie, lerumo-lamadi, mukakana, phetola, and unwele (Gerickc et al., 2001). Its decoction is used in the treatment of open wounds, fever, chicken pox, gonorrhea, syphilis, and assumed HIV/AIDS (Peltzer, 2001, 2003). Although some patients with HIV/AIDS consume medicinal herbs ab initio, it has been reported that a number of them resort to herbal medicine in response to perceived adverse reactions to ARVs (Peltzer and Mngqundaniso, 2008). The number of patients with HIV/AIDS who consume herbal medicine alone or concomitantly with ARVs is often underestimated. In a cross-sectional study performed by Peltzer and colleagues (2008), up to 90% of respondents who were taking herbal therapies for HIV infection did not disclose this to their health care providers. This, therefore, calls for more research to establish the therapeutic benefit and safety of such practices.
Influence of Sutherlandia on Drug Metabolism

Table 1: Probe substrates, microsomal protein concentrations, and incubation times

<table>
<thead>
<tr>
<th>Enzyme</th>
<th>Probe Substrate</th>
<th>Microsome Concentration</th>
<th>Probe Substrate Concentration</th>
<th>Literature Km Value</th>
<th>Internal Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>CYP1A2</td>
<td>Phenacetin</td>
<td>0.2</td>
<td>10</td>
<td>9.0±1, 14±2, 31±1, 54±4</td>
<td>[1H]Acetaminophen</td>
</tr>
<tr>
<td>CYP2A6</td>
<td>Coumarin</td>
<td>0.2</td>
<td>2.5</td>
<td>0.5</td>
<td>[13C6]7-Hydroxy coumarin</td>
</tr>
<tr>
<td>CYP2B6</td>
<td>Bupropion</td>
<td>0.1</td>
<td>25</td>
<td>76±1, 89±5,76±6</td>
<td>[1H]Hydroxybupropion</td>
</tr>
<tr>
<td>CYP2C8</td>
<td>Paclitaxel</td>
<td>0.2</td>
<td>10</td>
<td>4.0±2, 15±8</td>
<td>Warfarin</td>
</tr>
<tr>
<td>CYP2C9</td>
<td>Diclofenac</td>
<td>0.1</td>
<td>5</td>
<td>3.4±1, 9.0±20</td>
<td>[13C6]4'-Hydroxy diclofenac</td>
</tr>
<tr>
<td>CYP2C19</td>
<td>S-Mephenytoin</td>
<td>0.5</td>
<td>30</td>
<td>51±1, 42±1, 31±14</td>
<td>[1H]3'-Hydroxy mephenytoin</td>
</tr>
<tr>
<td>CYP2D6</td>
<td>Bufuralol</td>
<td>0.2</td>
<td>5</td>
<td>15±1, 44±10</td>
<td>[1H]1'-Hydroxybufuralol</td>
</tr>
<tr>
<td>CYP2E1</td>
<td>Chloroxazone</td>
<td>0.5</td>
<td>10</td>
<td>22±9±17</td>
<td>[1H]3'-Hydroxy mephenytoin</td>
</tr>
<tr>
<td>CYP3A4/5</td>
<td>Midazolam</td>
<td>0.1</td>
<td>1</td>
<td>3.3, 2.5±5.6±18</td>
<td>[1H]1'-Hydroxymidazolam</td>
</tr>
<tr>
<td>CYP3A4/5</td>
<td>Testosterone</td>
<td>0.2</td>
<td>30</td>
<td>50-60±9, 51±20</td>
<td>[1H]6β-Hydroxy testosterone</td>
</tr>
</tbody>
</table>


Gastrointestinal cramps, rheumatism, heartburn, hemorrhoids, diabetes, inflammation, and eye infections among indigenous South Africans (Van Wyk and Albrecht, 2008). It has been investigated for many of the anecdotal claims. Many of such studies have suggested its potential for beneficial effects in HIV/AIDS (Harnett et al., 2005), cancer (Stander et al., 2007, 2009; Skerman et al., 2011), diabetes (Chadwick et al., 2007; Mackenzie et al., 2012), inflammation (Ojewole, 2004), microbial infection (Katerere and Elloff, 2005), stress (Prevoo et al., 2004), and convulsion (Ojewole, 2008). Commercial twice-daily Sutherlandia capsules containing 300 mg of powdered dried leaves are also available in the herbal medicines shops in South Africa (Van Wyk and Albrecht, 2008).

Studies have identified various phytochemical constituents of Sutherlandia to include L-canavanine, GABA, and D-pinitol. A recent study by the South Africa Medical Research Council has suggested that Sutherlandia is free of obvious toxicities (Seier et al., 2002).

The influence of Sutherlandia on drug metabolism is not been demonstrated. This is necessary to ascertain the presence or absence of the potential for herb drug interaction (HDI). HDI may be deleterious in persons living with HIV/AIDS because of the high number of medications used in ARV therapy and other comorbidities. There is no information available in the literature to address this concern. A recent study on the in vitro effects of Sutherlandia on Caco-2 cell line suggests its potential to influence the absorption of atanavir (Müller et al., 2012). Therefore, the aim of the current study was to investigate the potential of the crude extracts of Sutherlandia to inhibit nine major cytochrome P450 (P450) isoforms with use of human liver microsomes (HLMs), two efflux and two uptake proteins using cell lines expressing the transporter proteins, and CYP3A4-mediated midazolam clearance in human hepatocytes.

Materials and Methods

Plant Materials

Fresh leaves of Sutherlandia were sourced from two South African THPs who identified the plant as unweld in local Xhosa language. The collected samples were identified with the help of experts in the Compton Herbarium, South African National Biodiversity Institute, Cape Town, and Voucher specimens were prepared and housed at the Division of Pharmacology, University of Stellenbosch. Information on the mode of use, dose, and specific HIV/AIDS-related indications were obtained and documented through semi-structured interview.

Ethical approval was obtained from the University of Stellenbosch Health Research Ethics Committee.

Chemical Compounds

The necessary chemical compounds were obtained as indicated: 1'-hydroxybufuralol maleate, 1'-hydroxymidazolam, 4'-hydroxyphenytoin, 6-hydroxytestosterone, bufuralol hydrochloride, and midazolam from Ultrafine Chemicals (Pty) Ltd (Manchester, UK); 6-hydroxychloroxazone, 7-hydroxycoenarin, acetaminophen, bupropion, chloroxazone, coumarin, furalfiline, NADPH, estradiol-17β-α-glucuronide (sodium salt), paclitaxel, tranylcypromine, troglitazomycin (TAO), warfarin, rifamycin, thioconazole, digoxin, cyclosporine A, and testosterone from Sigma-Aldrich (Pty) Ltd. (St. Louis, MO); dimethyl sulfoxide (DMSO), di-potassium hydrogen phosphate (K2HPO4), acetonitrile, formic acid, testosterone from Sigma-Aldrich (Pty) Ltd. (St. Louis, MO); dimethyl sulfoxide (DMSO), di-potassium hydrogen phosphate (K2HPO4), acetonitrile, formic acid and methanol from Merck Chemicals (Pty) Ltd (Darmstadt, Germany); [13C6]4'-hydroxydiclofenac, [13C6]7-hydroxycoenarin, [1H]3'-Hydroxyphenytoin, [1H]6β-Hydroxytestosterone.
diclofenac, and paroxetine from Novartis Pharma AG (Basel, Switzerland); hydroxybuproprion, [2H6]hydroxybuproprion, and [19H]1'-hydroxybufuralol from BD Biosciences (Pty) Ltd (San Jose, CA); 6α-hydroxypaclitaxel from Gentest BD Biosciences (Woburn, MA); [2H3]6b-hydroxytestosterone, [19H]1'-hydroxymidazolam from Cerilliant Chemicals (Pty) Ltd (Texas); phenacetin, magnesium chloride hexahydrate, ticlopidine hydrochloride, and potassium dihydrogen phosphate (KH2PO4) from Fluka Chemicals (Pty) Ltd (Buchs, Switzerland); 9'-hydroxydiclofenac from Calbiochem (Pty) Ltd (La Jolla, CA); (3S,6S,12aS)-1,2,3,4,6,7,12a-octahydro-9-methoxy-6-(2-methyl-propyl)-1,4-dioxopyrazino[1’:2’;1,6]pyrido[3,4-b]indole-3-propanoic acid 1,1-dimethyl ester (Ko143) from Tocris Bioscience (Pty) Ltd (Ellisville, MO); 2-amino-1-methyl-6-phenylimidazo[4,5-b]pyridine-2 (PhIP) and its radio-labeled from (1.85 MBq/nmol, radiochemical purity > 99%) from Toronto Research Chemicals (Pty) Ltd (North York, Toronto, ON, Canada); radio-labeled [3H]digoxin (1.103 MBq/nmol, radiochemical purity > 97%) and [3H]estradiol-17β-glucuronide (1.172 MBq/nmol, radiochemical purity > 97%); from PerkinElmer Radiochemicals (Pty) Ltd (Waltham, MA); and zosuquidar trihydrochloride from Chembiotek (Pty) Ltd (Kolkata, India).

Assay Enzymes and Cells
Pooled mixed-gender HLMs prepared from 50 individual donors with total P450 and cytochrome b5 content of 290 and 790 pmol/mg protein, respectively, was obtained from Gentest BD Biosciences (Woburn, MA). The Catalytic activities of enzymes were provided by the manufacturer. Pooled, mixed-gender cryopreserved hepatocytes prepared from 20 donors were obtained from Celsis In Vitro Technologies (Pty) Ltd (Baltimore, MD).


**Influence of Sutherlandia on Drug Metabolism**

The potency of inhibitory effects of Sutherlandia on P450 expressed in IC50 Values

<table>
<thead>
<tr>
<th>P450 Enzyme</th>
<th>Probe Reaction</th>
<th>IC50 Value µg/ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>CYP1A2</td>
<td>Phenacetin O-deethylation</td>
<td>41.0 ± 1.2</td>
</tr>
<tr>
<td>CYP2A6</td>
<td>Coumarin 7-hydroxylation</td>
<td>160 ± 2.1</td>
</tr>
<tr>
<td>CYP2B6</td>
<td>Bupropion hydroxylation</td>
<td>20.1 ± 1.7</td>
</tr>
<tr>
<td>CYP2C8</td>
<td>Paclitaxel 6a-hydroxylation</td>
<td>22.4 ± 1.3</td>
</tr>
<tr>
<td>CYP2C9</td>
<td>Diclofenac 4'-hydroxylation</td>
<td>23.0 ± 1.5</td>
</tr>
<tr>
<td>CYP2C19</td>
<td>S-Mephenytoin 4'-hydroxylation</td>
<td>35.9 ± 1.0</td>
</tr>
<tr>
<td>CYP2D6</td>
<td>Bufuralol 1’-hydroxylation</td>
<td>n.i.o.</td>
</tr>
<tr>
<td>CYP2E1</td>
<td>Chlorozaxone 6-hydroxylation</td>
<td>n.i.o.</td>
</tr>
<tr>
<td>CYP3A4/5</td>
<td>Midazolam 1’-hydroxylation</td>
<td>17.5 ± 1.3</td>
</tr>
<tr>
<td>CYP3A4/5</td>
<td>Testosterone 6p-hydroxylation</td>
<td>28.3 ± 1.3</td>
</tr>
</tbody>
</table>

n.i.o., no inhibition observed.

The cryopreserved hepatocytes were thawed and the cells were suspended in HepatoZYME buffer. The viability of the suspended hepatocytes was determined at the beginning and end of incubation (in the presence and absence of Sutherlandia) with use of a Guava EasyCyte Mini system using the ViaCount assay according to the instructions of the supplier (Guava Technologies, Hayward, CA). After cell counting, the cell density was adjusted with HepatoZYME to 1 × 10^6 viable cells/ml. The incubation procedure involved the coincubation of 1 µM midazolam and 100 µg/ml Sutherlandia in 1 ml of hepatocyte mixture at 37°C under a humidified atmosphere of 95% air and 5% CO2 in a Heraeus incubator/Cytoperm. Aliquots of the incubation mixtures were taken for LC-MS analysis at 0, 1, 2, 4, and 6 hours of incubation. The metabolic reactions were stopped by the addition of 2 volumes of acetonitrile containing 0.3 µM d4-hydroxymidazolam as internal standard. Samples were kept at −20°C until analysis. Control incubation to monitor appropriate internal standard (Table 1). Total separation and elution of the analytes were achieved within 10 minutes retention time, using the Luna Phenyl-Hexyl (3 µm, inner dimensions 50 × 1 mm; Phenomenex, Torrance, CA) column (30°C), in a dual mobile phase of water and acetoniitrile (each containing 1% v/v formic acid), with a gradient (group A) and isocratic (group B and C; 70:30) flow set at 60 µl/min.

Before chromatographic analysis, samples were pooled according to the groups and subjected to solid-phase extraction using an Oasis HLB 96-well plate (30 µm (30 mg) Elution plate (Waters, Milford, CT). This was performed by sequential washing with 1 ml each of water and water-methanol (95/5; v/v), followed by two-time elution with 1 ml of methanol. The elutes were dried using the 96-well Micro-DS96 evaporator (Porvair Sciences Ltd., Shepperton, UK) at 37°C and reconstituted in 100 µl of 10% acetonitrile containing 0.1% formic acid for LC-MS analysis. Enzyme activity was measured in terms of the production of the P450-specific metabolite. Relative activity (100%) was defined in terms of metabolite production in the absence of inhibitor. The enzyme inhibition parameter (IC50) was calculated by using the kinetic equation for sigmoid curves (Eq. 1), where x = concentration, y = relative enzyme activity, and s = slope factor.

\[
y = \frac{100\% - y}{1 + \left( \frac{x}{IC_{50}} \right)} = 100\% - \frac{y}{1 + \left( \frac{x}{IC_{50}} \right)}
\]

Calculation of Kinetic Parameters for Time-Dependent Inhibition

The enzyme activity in the presence of each inhibitor concentration was determined relative to activity at time, t = 0. The resulting data pairs of relative enzyme activities and preincubation times were fitted with an Excel template in a least square approach to the exponential function (Eq. 2), where y = relative activity, x = preincubation time, a = optimal starting value for relative activity, and b = optimal negative rate of inactivation for a given inhibitor concentration.

\[
y = a \cdot e^{-b \cdot x}
\]

The rate of CYP3A4 inactivation in the absence of test substance was subtracted from all other inactivation rates. The resulting values, along with the corresponding inhibitor concentrations, were used in a second least square fit to calculate kinetic parameters by linear regression to the Michaelis–Menten-like equation (Eq. 3), where y = inactivation rate constant, x = inhibitor concentration, KI = inhibitor concentration that produces half-maximal inhibition; and k_{inact} = maximal inactivation rate constant using the Enzyme Kinetic SigmaPlot, version 12.1.

\[
y \cdot K_I + x
\]

The Effects of Sutherlandia on the Clearance of Midazolam in Human Hepatocytes

**Incubation Procedure.** The cryopreserved hepatocytes were thawed, and the cells were suspended in HepatoZYME buffer. The viability of the suspended hepatocytes was determined at the beginning and end of incubation (in the presence and absence of Sutherlandia) with use of a Guava EasyCyte Mini system using the ViaCount assay according to the instructions of the supplier (Guava Technologies, Hayward, CA). After cell counting, the cell density was adjusted with HepatoZYME to ~1.3 million viable cells/ml. The incubation procedure involved the coincubation of 1 µM midazolam and 100 µg/ml Sutherlandia in 1 ml of hepatocyte mixture at 37°C under a humidified atmosphere of 95% air and 5% CO2 in a Heraeus incubator/Cytoperm. Aliquots of the incubation mixtures were taken for LC-MS analysis at 0, 1, 2, 4, and 6 hours of incubation. The metabolic reactions were stopped by the addition of 2 volumes of acetonitrile containing 0.3 µM d4-hydroxymidazolam as internal standard. Samples were kept at −20°C until analysis. Control incubation to monitor
the stability of midazolam in cell-free HepatoZYME was performed. The rate of metabolism of midazolam in the presence and absence of Sutherlandia was compared.

Clearance calculations. Initial half-life ($t_{1/2}$) and elimination rate constants ($\lambda = \ln2/t_{1/2}$) of MDZ in hepatocyte incubates were calculated by log-linear regression of MDZ concentrations profiled against time with use of data from the sampling points of the 1 mM MDZ incubates.

The intrinsic clearance in vitro ($CL_{i\text{nt,in vitro}}$) was calculated from lambda and the cell density in the respective incubation (number of viable hepatocytes per milliliter at time zero) and scaled up to the intrinsic clearance in vivo ($CL_{i\text{nt,in vivo}}$) with use of the human liver mass (25.7 g/kg body mass) and the hepatocellularity (number of hepatocytes per gram of liver = 99 million cells/g liver):

$$CL_{i\text{nt,in vitro}} = \frac{\lambda}{\text{cell density}}$$

$$CL_{i\text{nt,in vivo}} = CL_{i\text{nt,in vitro}} \times \text{ liver mass } \times \text{ hepatocellularity}$$

From $CL_{i\text{nt}}$ in vivo and the hepatic blood flow [$Q$ (20.7 ml/min/kg body mass)], the hepatic metabolic blood clearance ($CL_{h,b}$) was predicted using the well-stirred model as follows:

$$CL_{h,b} = \frac{(CL_{i\text{nt,in vivo}} \times Q)}{(CL_{i\text{nt,in vivo}} + Q)}$$

No corrections were made for the free fractions in vitro or in vivo (i.e., they were assumed to be identical) (Davies and Morris, 1993).

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**Fig. 2.** Effect of Sutherlandia on CYP2C9-mediated diclofenac 4'-hydroxylation (A), CYP2C19-mediated S-mephentoin 4'-hydroxylation (B), CYP3A4/5-mediated midazolam 1'-hydroxylation (C), and CYP3A4/5-mediated testosterone 6β-hydroxylation in pooled human liver microsomes (D).
Determination of the Effects of Sutherlandia on P-gp and BCRP

Sutherlandia was soluble up to a final concentration of 700 μg/ml in P-gp uptake buffer and 200 μg/ml in BCRP uptake buffer. LLC-PK1 cells stably transfected with human P-gp were grown and maintained in Medium 199 supplemented with 10% fetal-bovine serum (FBS), 50 ng/ml gentamycin, and 100 ng/ml hygromycin B at 37°C under an atmosphere of 5% CO2. MDCKII cells stably transfected with human BCRP were grown and maintained in DMEM supplemented with 10% FBS, 1% l-glutamine, and 1% penicillin/streptomycin at 37°C under an atmosphere of 5% CO2. Cells (~0.6 x 10^5 cells per well for LLC-PK1-P-gp and MDCKII-BCRP transfectants) were seeded into Falcon clear-bottom 96-well plates (Becton Dickinson) with 200 μl of culture medium, and the assay was performed after 24 hours. Graded concentrations of Sutherlandia were prepared in HBSS containing 12.5 mM HEPES adjusted with HCl to pH of 7.4 (for P-gp) and OPTI-MEM containing 12.5 mM HEPES adjusted to pH of 7.8 (for BCRP). The assay procedure was begun by the aspiration and replacing the culture medium with preincubation uptake buffer system containing Sutherlandia or the specific inhibitors as positive control (10 μM cyclosporine A for P-gp and 1 μM Ko143 for BCRP). Plates were subsequently incubated at 37°C for 10 minutes. Transporter-mediated uptake was initiated by the addition of the radiolabeled probe substrates (1 μM digoxin for P-gp and 1 μM PhIP for BCRP). The uptake reaction was terminated after 40 minutes by removing the incubation solution. The cells were then washed twice with ice-cold phosphate-buffered saline buffer, and monolayer integrity was assessed optically. This was followed by the dissolution of the cells by the addition on 0.2 N NaOH (200 μl per well) and incubation for 20 minutes at 37°C. Dissolved cells were then transferred to scintillation vials containing scintillation cocktail, and uptake substrates were measured using a scintillation counter. All uptake studies were performed in triplicate in an incubator without shaking.

Determination of the Effects of Sutherlandia on OATP1B1 and 1B3

Human embryonic kidney 293 cells stably transfected with human OATP1B1 were grown and maintained in DMEM supplemented with 10% FBS, 1% l-glutamine, 1% penicillin/streptomycin, and 50 ng/μl hygromycin B at 37°C under an atmosphere of 5% CO2. Human embryonic kidney 293 cells stably transfected with human OATP1B3 were grown and maintained in DMEM supplemented with 10% FBS, 1% l-glutamine, 1% penicillin/streptomycin, and 0.8 mg/ml G418 at 37°C under an atmosphere of 5% CO2. Cells (~0.2 x 10^6 cells per well) for overexpressing OATP1B1 and OATP1B3 were seeded in precoated (poly-L-lysine, poly-L-ornithine, 0.1 mg/ml) clear-bottom 96-well plates (Corning Product No. 734-1795; Corning Incorporated Life Sciences (Pty) Ltd, Tewksbury, MA) with 200 μl of culture medium. Graded concentrations of Sutherlandia were prepared in HBSS containing 12.5 mM HEPES adjusted with HCl to pH of 7.8. Uptake studies, performed 72 hours after seeding, was started by aspirating and replacing the culture medium with the final incubation buffer system containing Sutherlandia or the positive control inhibitor (20 μM rifamycin and 10 μM atorvastatin) The uptake reactions were terminated after 5 minutes by removing the incubation solution. Subsequently, the wells were washed twice with ice-cold phosphate-buffered saline buffer, and monolayer integrity was assessed optically. Radioactive samples were analyzed using liquid scintillation counting in a similar procedure as described above. All uptake studies were performed in triplicate in an incubator without shaking.

Drug Uptake Clearance Calculations

Probe substrate uptake clearance (nl/min/mg protein) by the stably transfected cells expressing the transporter proteins was determined from the specific amount of radiolabeled probe substrate inside the cells divided by the concentration in the incubation medium and normalized to the incubation time and the mean protein concentration measured in test wells.
Absolute transporter uptake data were converted into relative inhibition values by defining membrane permeability of the probe substrate in the absence of inhibitor as 0% inhibition while the positive control exerted 100% transporter inhibition. Relative inhibition (%) was profiled against inhibitor concentration, and the IC\textsubscript{50} was calculated using the nonlinear-regression method using the Enzyme Kinetic SigmaPlot, version 12.1.

The IC\textsubscript{50} values were calculated using the following equation:

\[ y = y_0 + \frac{a \cdot I^n}{IC_{50}^n + I^n} \]

where, \( n \) is the slope factor (Hill coefficient), \( y_0 \) is the relative baseline inhibition, and \( a \) is the maximal transporter inhibition (%).

Results

Influence of Sutherlandia on P450s

Sutherlandia showed a concentration-dependent inhibition of CYP1A2, CYP2A6, CYP2B6, CYP2C8, CYP2C9, CYP2C19, and CYP3A4/5. The extract concentration profiled against relative enzyme activity is shown in Fig. 1, and Table 2 shows the IC\textsubscript{50} values. Little or no competitive inhibition of CYP2D6 and CYP2E1 was observed at Sutherlandia concentrations up to 100 µg/ml.

Sutherlandia-Induced Time-Dependent Inhibition of CYP3A4

Time-dependent (irreversible) inhibition of CYP3A4/5 by graded concentration of Sutherlandia was observed with a \( K_I = 296 \) µg/ml and \( k_{inact} = 0.063 \) min\(^{-1}\) under the conditions of this study. The influence of preincubation time, Sutherlandia concentration, and the positive control troleandomycin on the enzymatic activity of CYP3A4/5 is shown in Figs. 2 and 3.

Influence of Sutherlandia on Midazolam Clearance in Human Hepatocytes

During the incubation with MDZ, the viability of the hepatocytes (percentage viable cells relative to total cells) decreased from 78.3% at time zero to 42.7% without test inhibitor and 45.6% with Sutherlandia. Midazolam was also found to be stable in the HepatoZYME media and the absence of hepatocytes as determined after 6 hours of incubation.

TABLE 3

The intrinsic clearance of midazolam in hepatocytes in the presence and absence of Sutherlandia

<table>
<thead>
<tr>
<th>Hepatocytes</th>
<th>MDZ</th>
<th>MDZ + Sutherlandia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-life (h)\textsuperscript{a}</td>
<td>0.72</td>
<td>1.18</td>
</tr>
<tr>
<td>CL\textsubscript{int} (µl/min/million cells)\textsuperscript{b}</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>CL\textsubscript{int-scaled} (ml/min/kg)\textsuperscript{c}</td>
<td>40.98</td>
<td>24.98</td>
</tr>
<tr>
<td>CL\textsubscript{h,b} (hepatic blood clearance) (ml/min/kg body weight)\textsuperscript{d,e}</td>
<td>14</td>
<td>11</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Half-lives were evaluated by linear extrapolation.

\textsuperscript{b} \((\ln(2)/T_{1/2})/\text{mio viable cells} \times 1000\).

\textsuperscript{c} \((\text{CL}_{\text{int}}/1000) \times (\text{cells/g liver}) \times (\text{gliver/kg body weight})\).

\textsuperscript{d} \(\text{CL}_b = (Q_h \times CL_{\text{int-scaled}}) + CL_{\text{int-scaled}}\), where \(Q_h\) is hepatic blood flow (well-stirred liver model).

\textsuperscript{e} \(Q_h\) (ml/min/kg body weight): 55 (rat); 30.9 (dog); 43.6 (monkey); and 20.7 (human).
Thus, degradation in the presence of hepatocytes is attributable to the cellular activities.

**Influence of Sutherlandia on the Formation of Midazolam Metabolites**

After the analysis of an aliquot of human hepatocyte incubate with midazolam ($t = 6$ hours) by LC-MS/MS, four metabolites were detected and were assigned as M1, M2, M3, and M4. With use of a combination of accurate mass measurement, elemental composition, and MS/MS analysis, the four metabolites were identified as a combination of oxygenation and glucuronidation (M1), direct glucuronidation (M2), and a single oxygenation of MDZ (M3 and M4). These metabolites are consistent with previously published data on the metabolism of midazolam (Kronbach et al., 1989). The influence of Sutherlandia on the formation of the metabolites is shown in Figs. 4 and 5.

**Intrinsic Metabolic Clearance from Hepatocytes**

The intrinsic metabolic clearance of midazolam in the presence and absence of Sutherlandia was measured in human hepatocytes (Table 3). Extrapolation to hepatic blood clearance was performed using the well-stirred liver model. Sutherlandia reduced the clearance of midazolam by 40%.

**TABLE 4**

<table>
<thead>
<tr>
<th>Transporter</th>
<th>Probe Substrate</th>
<th>IC$_{50}$ Value$^a$</th>
<th>$K_i^c$</th>
<th>Maximum Inhibition$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μg/ml</td>
<td></td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>P-gp</td>
<td>Digoxin</td>
<td>324.8</td>
<td>324.3</td>
<td>69.5 ± 7.7</td>
</tr>
<tr>
<td>BCRP</td>
<td>PhIP</td>
<td>Not observed$^c$</td>
<td>Not applicable</td>
<td>Not observed$^c$</td>
</tr>
<tr>
<td>OATP1B1</td>
<td>Estradiol-17β-α-glucuronide</td>
<td>10.4 ± 0.6</td>
<td>8.2</td>
<td>101.4 ± 0.6</td>
</tr>
<tr>
<td>OATP1B3</td>
<td>Estradiol-17β-α-glucuronide</td>
<td>6.6 ± 0.9</td>
<td>5.6</td>
<td>85.3 ± 5.4</td>
</tr>
</tbody>
</table>

$^a$ Sutherlandia concentration estimated to inhibit transporter activity by 50%.
$^b$ Data used for curve fitting are mean ± S.D. ($n = 3$).
$^c$ Calculated with $K_i = IC_{50}/(1 + S/K_m)$, where $S$ is the substrate concentration of the probe substrate and $K_m$ is the transporter affinity of the probe substrate according to Michaelis-Menten.
$^d$ Maximal observed inhibition with respect to positive control.

$^e$ No inhibition of BCRP was observed up to the maximum Sutherlandia concentration of 200 μg/ml.
This inhibitory influence will be more pronounced on repeated Sutherlandia consumption, as shown with the time-dependent inhibition of P450. In reality, herbal remedies are consumed repetitively over a long period. As shown from this study, a continuous suppression of enzymatic activity may occur. This may precipitate drug accumulation and toxicity.

There is no information on the extent of absorption after Sutherlandia administration. However, with claims of its systemic activity on immune boosting, cancer treatment among others, its phytochemicals are expected to be absorbed for efficacy. Because OATP1B1 and OATP1B3 are located at the sinusoidal membrane of the liver, the inhibitory effects on the OAT1B1 and OTP1B3 will be important if there is absorption. In addition to this, absorbed phytoconstituents of Sutherlandia may inhibit the activity of P450s and transport proteins in the liver and other organs, with consequent alteration of the pharmacokinetic profile of coadministered drugs.

In comparison with a control, with the microbodies used in vitro studies, the results of in vitro use of cryopreserved hepatocytes are closer to in vivo conditions because of the complete expression of the cell matrix and the presence of other enzymes (Fasinu et al., 2012). Thus, the reduction of midazolam clearance by 40% by Sutherlandia, as shown with the in vitro–in vivo correlation is significant and may reflect a stronger likelihood in vivo. With the ongoing policy making focusing on the integration of traditional and orthodox medicine in Africa, it is important to understand the potential for HDI and the necessary caution required in concomitant herb-drug administration.

However, a few factors may limit the conclusions derivable from this study. Sutherlandia was obtained from traditional healers, just as their clients do. The phytochemical composition of herbs is known to vary depending on the place and time of harvesting. In addition, methanol and water will extract most phytochemicals. This may not be the same with intestinal fluids. The extracts that may be systemically available in significant quantities are also not known. Although in vitro HDI studies provide the indication for in vivo relevance, in vivo human studies are the ultimate proof of clinically significant HDI.

In conclusion, Sutherlandia may inhibit the metabolic clearance of comedication metabolized by CYP1A2, CYP2A6, CYP2B6, CYP2C8, CYP2C9, CYP2C19, CYP3A4/5, P-gp, OATP1B1, and OATP1B3 if sufficient in vivo concentration is achieved. CYP3A4/5 inhibition may be amplified by administration of multiple doses. Sutherlandia is not expected to inhibit human CYP2D6, CYP2E1, or BCRP. Thus, there is the potential for pharmacokinetic interaction if Sutherlandia is coadministered with the substrates of these enzymes and transport proteins. Extreme caution should therefore be taken, especially in using Sutherlandia in HIV-infected patients treated with ARVs.

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**Authorship Contributions**

- **Participated in research design:** Fasinu, Gutmann, Schiller, James, Bouic, Rosenkranz.
- **Conducted experiments:** Fasinu.
- **Contributed new reagents or analytical tools:** Gutmann, Schiller, James, Rosenkranz.
- **Performed data analysis:** Fasinu, Gutmann, Schiller, James.
- **Wrote or contributed to the writing of the manuscript:** Fasinu, Gutmann, Schiller, James, Bouic, Rosenkranz.