



**HAL**  
open science

## Major pitfalls of protein kinase inhibitors prescription: a review of their clinical pharmacology for daily use

Paul Gougis, Lola-Jade Palmieri, Christian Funck-Brentano, Angelo Paci, Ronan Flippot, Olivier Mir, Romain Coriat

### ► To cite this version:

Paul Gougis, Lola-Jade Palmieri, Christian Funck-Brentano, Angelo Paci, Ronan Flippot, et al.. Major pitfalls of protein kinase inhibitors prescription: a review of their clinical pharmacology for daily use. *Critical Reviews in Oncology/Hematology*, 2019, 141, pp.112-124. 10.1016/j.critrevonc.2019.06.006 . hal-02289357

**HAL Id: hal-02289357**

**<https://hal.sorbonne-universite.fr/hal-02289357>**

Submitted on 16 Sep 2019

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## Review

# Major pitfalls of protein kinase inhibitors prescription: a review of their clinical pharmacology for daily use.

Paul Gougis<sup>1-2</sup>, MD, Lola-Jade Palmieri<sup>3</sup>, MD, MSc, Christian Funck-Brentano<sup>1,4</sup>, MD, PhD, Angelo Paci<sup>5</sup>, PharmD, PhD, Ronan Flippot<sup>6</sup>, MD, Olivier Mir<sup>6,7\*</sup>, MD, PhD and Romain Coriat<sup>3\*</sup>, MD, PhD.

\* Equal contribution

1: Sorbonne Université, Faculty of Medicine, AP-HP, Pitié-Salpêtrière Hospital, Department of Pharmacology and Clinical Investigation Center, F-75013 Paris, France.

2: CLIP<sup>2</sup> Galilée, Pitié-Salpêtrière Hospital, F-75013 Paris, France.

3: AP-HP, Cochin Hospital, Department of gastroenterology and gastrointestinal oncology, Université Paris Descartes, Paris, France.

4: INSERM, CIC-1421 and UMR ICAN 1166, Institute of Cardiometabolism and Nutrition (ICAN), F-75013 Paris, France.

5: Service de Pharmacologie, Département de Biologie et Pathologie Médicales, Gustave Roussy et Université Paris Saclay, Villejuif, France.

6: Department of Medical Oncology, Gustave Roussy, 114 rue Edouard Vaillant, 94800, Villejuif, France.

7: Department of Ambulatory Care, Gustave Roussy Cancer Campus, Villejuif, France.

### Corresponding author:

Paul Gougis, MD

Email: [Paul.gougis@aphp.fr](mailto:Paul.gougis@aphp.fr)

Postal address: Centre d'Investigation Clinique Paris-Est, Hôpital Pitié-Salpêtrière, 47-83 Boulevard de l'Hôpital, 75013 Paris, FRANCE

## **Abstract**

Protein kinase inhibitors (PKI) are a growing class of anticancer agents. They are prescribed with flat doses, and their oral administration is associated with interindividual variability in exposure. Patients can be over- or underexposed, due to numerous factors. We reviewed key pharmacokinetic concepts and mechanisms by which PKIs prescription could be altered. Challenging situations that could lead to increased toxicity or to therapeutic failure are described and recommendation for clinicians are proposed. Finally, the interest of therapeutic drug monitoring and indications for its use in daily practice is discussed.

**Keywords:** protein kinase inhibitors, cancer treatment, pharmacology, therapeutic drug monitoring

## Table of content

|   |    |
|---|----|
| Introduction  | 4  |
| Basic pharmacokinetics concepts                                     | 4  |
| 1- AUC, dose and therapeutic index                                  | 4  |
| 2- Volume of distribution and Clearance                             | 4  |
| General phenomenon involved in PKI's pharmacokinetics               | 5  |
| 1- Absorption   | 5  |
| Pharmacokinetic principles of bioavailability                       | 5  |
| Saturable absorption  | 5  |
| Gastric surgery   | 5  |
| Role of proton pump inhibitors and anti-acids                       | 6  |
| Food  | 6  |
| Role of transporters  | 7  |
| Time of the day   | 7  |
| Adherence   | 7  |
| Other sources of variation  | 8  |
| 2- Distribution   | 8  |
| PK principles   | 8  |
| Protein Binding   | 8  |
| Role of sarcopenia  | 8  |
| Role of obesity   | 9  |
| Blood-brain barrier, leptomenigeal and brain metastases             | 9  |
| 3- Metabolism / Elimination   | 10 |
| PK principles   | 10 |
| Cytochromes mediated drug-drug interaction (DDI)                    | 11 |
| Food and herb-drug interactions                                     | 11 |
| Glucuronidation, UGT  | 12 |
| ABC transporters  | 12 |
| Role of genetic polymorphism  | 12 |
| Role of Tobacco   | 12 |
| Hepatic failure   | 13 |
| Renal failure   | 13 |
| PK/PD relationships and Impact of Therapeutic Drug Monitoring (TDM) | 14 |
| 1- Therapeutic index  | 14 |
| 2- Interests of therapeutic drug monitoring                         | 14 |
| Conclusion  | 15 |

## Introduction

Protein kinase inhibitors (PKIs), including tyrosine kinase inhibitors, are small molecules (as compared to monoclonal antibodies) that inhibit the phosphorylation of tyrosine kinases or serine/threonine kinases. The physiological role of kinases is to transduce the signal of the binding of a ligand to an external tyrosine kinase receptor into a nuclear signal of proliferation or survival. For example, epidermal growth factor (EGF) physiologically binds to EGF receptor (EGFR), which in turn activates a series of phosphorylations that lead to the activation of transcription programs that promote cell proliferation.

Each PKI has a very variable spectrum of actions on the kinome which is composed of over 500 human proteins that have a phosphorylation activity (Manning et al., 2002).

PKIs can be divided into 2 categories: narrow spectrum or large spectrum:

- PKIs with a narrow spectrum are targeting oncogenic addiction (Weinstein and Joe, 2008). Erlotinib for EGFR-mutated lung adenocarcinoma or imatinib for c-KIT mutated gastro-intestinal stromal tumour are examples of such PKIs. They usually have a good tolerance profile.
- PKIs with very large spectrum of inhibition, like sunitinib or sorafenib, have a less favourable tolerance profile.

Many of these PKIs have been approved as anticancer drugs in the last fifteen years. Understanding the pharmacological properties of these drugs is critical for patient care since small variations in their blood concentrations might compromise the efficacy of the treatment or expose a patient to threatening adverse events. In this review, we present a summary of pharmacokinetics of PKIs, and discuss some pitfalls of their prescription. Finally we discuss the interest of Therapeutic Drug Monitoring (TDM) in clinical practice.

## Basic pharmacokinetics concepts

### *1- AUC, dose and therapeutic index*

PKIs' activity and toxicity are proportional to the Area Under the Curve (AUC, Figure 1). Many of these molecules have a narrow therapeutic index, and are often toxic at therapeutic dose. AUC should be in the right range: if the AUC is too low, the drug might not be effective, and if the AUC is too high, the drug could be more toxic. Modifications of bioavailability, volume of distribution or clearance have a direct impact on AUC (Figure 2).

### *2- Volume of distribution and Clearance*

Two important pharmacokinetic variables are the volume of distribution and the clearance of the active substance. The volume of distribution (Vd) reflects the volume in which the drug is "virtually" diluted. It is not a physiological variable and might be higher than the body volume itself, if the drug has a high affinity for tissues. A drug which is very hydrophilic and stays in the plasma will have a Vd close to the intravascular total volume (5 to 8 L), whereas a drug which is very lipophilic will not stay in the plasma (which contains mostly water) and will have a much larger Vd. Sunitinib for example has a Vd which has been evaluated to 2230 L. Hydrophilicity or lipophilicity of a drug is its ability to be attracted by water or lipids respectively and depends on the polarity of the drug. It could be measured by the partition coefficient log P, which is the ratio of the amount of drug attracted by octanol (lipid phase) or water.

Clearance reflects the volume of plasma cleared of the substance by amount of time. The half-life is the time needed to eliminate half of the drug from plasma. It depends on both clearance and Vd.

Precisely assessing AUC for each patient is not feasible in daily routine. Population pharmacokinetics through parametric or non-parametric modelling (Bayesian models) (Darwich et al., 2017) helps extrapolate the

pharmacokinetic parameters from 2 measures, using probabilities to assess steady state AUC (Figure 3).

## General phenomenon involved in PKI's pharmacokinetics

### 1- Absorption

#### *Pharmacokinetic principles of bioavailability*

Most PKIs have a highly variable bioavailability (F). The bioavailability reflects the fraction of the parent substance that reaches the systemic blood compartment unchanged. Bioavailability differs among individuals because a drug which is taken orally has to go through several barriers. First in the intestine by passive or active re-uptake and then through the liver which might metabolise it before it gets into the main circulation in a process called hepatic first-pass effect.

The reference is always the intravenous injection. The absolute bioavailability is defined by the formula:

$$F = \frac{AUC_{(oral)}}{AUC_{(IV)}}$$

By definition, a drug given by the intravenous route will have an absolute bioavailability of 100%.

Bioavailability is a major source of interindividual pharmacokinetic variation (Hellriegel et al., 1996). Although there is no absolute threshold to define low or good bioavailability, a bioavailability under 30% is low, 30 to 70% moderate and over 70% considered good. When the average bioavailability of an active substance is high and close to 100%, there are very few interindividual variations. There is more AUC variability for drugs with low than with high bioavailability because low bioavailability implies several transport and/or metabolism steps preventing the parent compound from reaching the systemic circulation. Each of these transport and/or metabolism steps can have variable expressions, sometime genetically-determined, among subjects. Drugs with high bioavailability have little transport or metabolism after oral administration and therefore have less variable AUCs. Most PKIs have a low bioavailability: less than 30 % (Klümper et al., 2011).

Absorption also depends on the liposolubility of a drug. A liposoluble drug crosses different membranes with passive diffusion, whereas hydrophilic drugs, which are polarised, have a lower absorption rate through the epithelium of the gastro-intestinal tract. We summarised key pharmacological parameters in table 1.

#### *Saturable absorption*

Absorption can happen through 2 different mechanisms: passive diffusion or active transport. Active transporters are saturable. When the given dosage is too high, the transporters cannot re-uptake all the drug, resulting in a decreased global bioavailability. For example, the AUC of sorafenib is almost the same with a dose of 800 mg per intake or with a dose of 1600 mg per intake, because of saturable absorption (Hornecker et al., 2012). As a consequence, 400 mg 3 times a day gives a higher AUC than 800 mg twice a day. Pazopanib also has a saturable absorption. According to Yu & colleagues (Yu et al., 2016), switching from 800 once daily to 400mg twice daily could increase AUC by 59% (model-based simulations)

Splitting the dose of a drug could increase more efficiently the AUC than increasing a single dose per day.

#### *Gastric surgery*

Weak acids are absorbed in the acidic stomach. Gastrectomy could decrease the absorption of weak acids, when pKa, which is the negative base-10 logarithm of the acid dissociation constant (Ka) of a solution, is between 2 and 6.

Major gastric surgery decreases the bioavailability of nilotinib in the treatment of GastroIntestinal Stromal Tumours (GIST) (Kim et al., 2011). Nilotinib, which has 2 acid groups, has two pKa: one at 2.1 and one at 5.4. Thus, nilotinib

might exist in 3 forms in the gastro-intestinal tract. In its acid form, nilotinib has no charge, and is therefore lipophilic and able to go through membranes by passive diffusion. However, the basic form of nilotinib is charged. When the pH increases above 5.4, nilotinib molecules are becoming more hydrophilic and have a lower ability to cross cell membranes. This can be extrapolated to other PKIs with a PKa between 2 and 6: pH can affect PKI's absorption, which explains why patients with major gastrectomy might not be able to absorb some PKIs.

This has also been shown in 2 case reports of obese patients treated with 400mg OD imatinib who underwent a sleeve gastrectomy (Liu and Artz, 2011; Pavlovsky et al., 2009). One had a 2 fold decrease of imatinib plasma concentration after sleeve gastrectomy (1558 ng/mL before and 629 to 836 ng/mL after) and the other 6 fold (965 ng/mL before and 166ng/mL after).

Gastrectomised patients might have a very different bioavailability, and whenever relevant, these patients could be followed by therapeutic drug monitoring.

#### *Role of proton pump inhibitors and anti-acids*

Anti-acids and particularly proton pump inhibitors (PPI) are widely used in the cancer population, with a prevalence of 20% - 55 % depending on the cancer type (Budha et al., 2012). Esomeprazole and other PPI increase average gastric pH affecting PKI's absorption.

Pazopanib for example, has shown a very low bioavailability in patients receiving concomitant esomeprazole, for similar reasons than nilotinib (cf. supra). Pazopanib is highly liposoluble at pH 1.0 and is showing a very low liposolubility and bioavailability above a pH of 4.0 (Tan et al., 2013). Patients treated by sunitinib for metastatic renal Clear Cell Carcinoma (mRCC) have a significant decrease in overall survival when treated with PPI or ranitidine (Ha et al., 2015). Nilotinib has a 34% decrease in AUC with concomitant use of omeprazole (Yin et al., 2010). Kletz & al (Kletzl et al., 2015) estimated that erlotinib AUC is divided by 2 with concomitant omeprazole. Staggered ranitidine, i.e. 150 mg twice daily of ranitidine with erlotinib given 10 h after the previous evening dose and 2 h before the next ranitidine morning dose, resulted in an erlotinib exposure decrease of approximately 15%.

Van Leeuwen & al (van Leeuwen et al., 2014) reviewed some of these interactions and recommend that crizotinib, dasatinib, erlotinib, gefitinib and lapatinib should not be associated with PPI and crizotinib, dasatinib and gefitinib should not be associated with anti-H2.

Acidic beverage could replace gastric acidity: patients treated with erlotinib and concomitant proton pump inhibitors had their bioavailability significantly increased (+39%, P = .004) by taking the treatment with cola when compared to erlotinib taken with water.

Whenever a drug's absorption relies on gastric acidity (cf. supra) direct anti-acid should be given at least 4 hours before or 2 hours after the drug intake. PPI and anti-H2 should be avoided whenever possible and PPI and anti-H2 should always be taken at least 2 hours after the PKI or 10 hours before, in order to have a normal gastric pH whenever the drug is taken. When PPI could not be avoided, concomitant dosing of the drug with cola could be considered.

#### *Food*

The pH of the stomach is around 1.2 during sleep, while it is around 3.5 after a meal. A meal also alters gastric emptying, which is delayed by the secretion of cholecystokinin in the duodenum when lipids and proteins leave the stomach. Bioavailability of a drug taken fed raises a problem of intra-individual variation, because patients have very diverse diets, especially regarding the amount of fat. Fat intakes notably slow digestion speed, and could increase the absorption of lipophilic drugs Therefore, pazopanib administered with food shows a twofold higher exposure compared to fasted (fed/fasted ratio which is the ratio of the AUC fed under the AUC fasted) (Verheijen et al., 2016). Lapatinib presents a fed/fasted ratio of around 4.1 (Kang and Ratain, 2010).

Some PKIs have been developed fed and some other fasted. The modality of administration should be explained to the patient before initiation of the oral treatment. Patients are considered fasting for oral drugs when the drug intake is at least one hour before or two hours after the ingestion of food. Patients with unexpected toxicity or no side effects should be asked their schedule of drug and food intakes.

#### *Role of transporters*

Permeability-glycoprotein (P-gp), also known as multidrug resistance protein 1 (MDR1) or ATP-binding cassette sub-family B member 1 (ABCB1), is an efflux pump with a very large spectrum of activity, present in various endothelium: liver, jejunum, or in brain capillary endothelial cell among others. P-gp notably plays a role in the blood brain barrier to protect the neurones from xenobiotics. ABCG2 (ATP Binding Cassette subfamily G member 2), also known as BCRP (Breast Cancer Resistant Protein) has a similar role. As a mechanism of resistance, P-gp can be overexpressed by cancer cells, pumping out of the cell the drug that is active intracellularly.

Some PKIs are known as substrates, activators or inhibitors of P-gp activity, impacting their own absorption. Imatinib for example, is an ABCG2 substrate and activator. Imatinib exposure decreases when given chronically with the same dosage: imatinib increases the expression of intestinal efflux pump, decreasing its absorption over time (Judson et al., 2005). In vitro, Caco-2 cells (model of gut wall cells) exposed to imatinib increase the expression of ABCG2 and, to a lesser extent, P-gp (Burger et al., 2005). A similar phenomenon has been demonstrated for sorafenib when chronic drug intake reduces drug exposure (Arrondeau et al., 2012) in patients treated for a metastatic hepatocellular carcinoma.

As a consequence, chronic exposure to a PKI could change its own bioavailability (and clearance). Clinicians should be aware that better tolerance and decreased efficacy of a treatment by PKI on the long term could be due to lower exposure, and could be therefore an indication of PKI dose increase or drug monitoring.

#### *Time of the day*

Enzymes and transporters involved in the pharmacokinetics of drugs, such as CYP3A4 and ABCB1, have time-dependent variations in expression which may have profound effect on the exposure to several drugs. Kloth & al (Kloth et al., 2015) found that sunitinib trough plasma concentrations were significantly lower when patients were administered sunitinib in the morning, than at noon or in the evening. However, AUC was not significantly different when sunitinib was administered at different time of the day. The difference in sunitinib trough concentrations may be attributed to daily changes in elimination. A study conducted in rabbit showed that sunitinib C<sub>max</sub> more than doubled and AUC increased by 64 % in rabbits that were given the drug at 20:00 instead of 8:00 (Szalek et al., 2014).

Although the chronobiology of PKI's pharmacokinetics remains poorly explored, patients should be advised to take their PKIs at the same clock time of the day.

#### *Adherence*

Jabbour & al (Jabbour et al., 2012) classified the causes of non-adherence into 3 categories:

- Treatment: side effects, cost, complexity of treatment regimen, concomitant medication, lack of immediate benefit.
- Patient: lack of understanding of the treatment and the disease, psychological factors, poor literacy, lack of support system, religious/cultural belief, physical difficulties, age under 40 or older than 75 yrs.
- Health care provider: lack of relationship or poor communication with the prescriber, fragmented health care system, failure to select patient for oral therapy

This might result in either a loss of drug efficacy or increased toxicity (if the patient tries to compensate a missed intake by taking several doses of the drug in one intake) (McCue et al., 2014).



Several interventions might improve adherence. A good communication and therapeutic education of the patient, including the explanation of the expected or possible adverse events and their management is essential. It is also important to simplify prescriptions as much as possible. Other healthcare professionals might also help: pharmacists play an important role detecting important adverse effects, providing therapeutic education and giving practical recommendations especially regarding drug administration. The DRug Adherence Work-up (DRAW) (Doucette et al., 2012) tool might help them. Other professionals, such as nurses, might also help improve treatment adherence. Particular attention should be paid to patients after 75 years (Marcum et al., 2017), and the use of mind reminder tools, like smartphone apps (Dayer et al., 2013), might help this category of patients.

It should never be assumed that patient comply to the treatment. A patient with no side effects should be questioned on treatment observance. TDM could help in the diagnosis of poor compliance.

#### *Other sources of variation*

Gut motility might also be a factor of variability. Using parasympatholytics or mimetics can change drug absorption. Metoclopramide for example, increases gastric emptying, and could be a source of pharmacokinetic change (Greiff and Rowbotham, 1994). There is no clinical proof yet that such an effect could increase the toxicity of PKIs, but this should be borne in mind. The available surface of the gut also plays a role. A normal intestine has a surface of absorption of around 200m<sup>2</sup>. Therefore, patients having important digestive surgeries should be closely monitored.

## *2- Distribution*

### *PK principles*

Depending on their affinity for tissues, proteins or lipids, different drugs have different distributions into the body as reflected by the volume of distribution. For example sunitinib has a Vd of approximately 2500L.

### *Protein Binding*

PKIs are extensively protein-bound to albumin (about 95%) and, to a lesser extent, to  $\alpha_1$ -acid glycoprotein. Only the free part of the drug is active, and the equilibrium between bound and free drug is reversible and follows the law of mass action. Although only unbound drug is active, albumin concentration rarely influences drug exposure. Lower albumin concentrations decrease the bonded fraction of the drug, which makes the effective concentration higher, but this effect is balanced by a higher clearance of the drug (if the drug elimination processes are not saturable).

Sorafenib is a highly bound kinase inhibitor, with >99.5% bound to plasma proteins, mainly albumin. Although the clearance is increased when albumin is low (Tod et al., 2011), there is no evidence that it affects directly the exposure to the drug. However, albuminemia also reflects sarcopenia (Visser et al., 2005) which is a known factor of poor tolerance to PKIs (see below). For similar reasons  $\alpha_1$ -acid glycoprotein, whose concentration increase during inflammation, is unlikely to change drug exposure significantly (Israili and Dayton, 2001).

### *Role of sarcopenia*

Sarcopenic patients, who have a low muscle mass, have a higher risk of toxicity when treated with sunitinib for mRCC or sorafenib for HCC and mRCC (Antoun et al., 2010; Huillard et al., 2013) . Patients with sarcopenia would have high intra-tissular exposure to unbound PKI. They have an increased propensity for nosocomial infections and other complications, which possibly reflects a global frailty and a vulnerability to PKI adverse events.

Sarcopenia is not necessarily correlated to body mass index (BMI), and obese patients can be sarcopenic, which makes clinical diagnosis difficult. Standardised techniques have been developed to assess sarcopenia which can for example be appraised by measuring area of muscle of the cross section of the third lumbar vertebra (Antoun et al.,

2010). This method is reproducible and might be automatized. The combination of sarcopenia as assessed below and a BMI < 25 is a good predictor of a PKI's toxicity.

Sarcopenic patients are more sensitive to PKIs toxicity and should be clinically monitored more thoroughly.

#### *Role of obesity*

The proportion of fat tissue might have a big impact on the volume of distribution. Fat proportion might range from 10% in malnutrition to 50 % for obese patients. Lipophilic substances then have a larger volume of distribution and consequently a lower clearance. Bioavailability is also increased (Brill et al., 2014), possibly due to obesity-induced suppression of CYP3A activity (Brill et al., 2015; van Rongen et al., 2018).

Very few cases have been reported of PKI treatments among obese patients.

Desar & al [27] reported the case of a patient treated with sunitinib for a GIST having a BMI of 47 kg/m<sup>2</sup> treated with 50 mg of sunitinib per day. The steady-state concentrations reported were 20 to 25 ng/mL, which is roughly 70% less than the average exposure reported in the literature. Pavlovsky & al (Pavlovsky et al., 2009) reported the case of an obese patient treated by 400 mg of imatinib per day for a CML, who had normal plasma exposure (1558 ng/mL, higher than the mean exposure concentration i.e. 1000 ng/mL). Liu et al described a patient who had a sleeve surgery and (Liu and Artz, 2011) a BMI of 50. She was initially treated with 400 mg of imatinib per day, and showed partial response with 35 % of Chromosome Philadelphia in bone marrow (95 % of chromosome Phi + at diagnosis). After doubling the dosage, the patient had a complete response (0 % of chromosome Phi + in bone marrow sample), but had important adverse effects. This example illustrates the risk of underdosing an obese patient.

Obese patients are a category of patients who need a closer attention. Whenever no adverse effects are seen, dose could be increased and TDM could help to reach an efficient dose.

#### *Blood-brain barrier, leptomeningeal and brain metastases*

##### **The blood-brain barrier**

The brain is protected from xenobiotics by the blood-brain barrier (BBB). The efflux pumps P-gp (ABCB1) and ABCG2 (BCRP), reject substrate drugs into the plasma when they reach the cytoplasm of BBB endothelial cells. Drugs with high liposolubility, allowing passive diffusion, and with a low molecular mass can cross the BBB if they are not substrates of P-gp or ABCG2.

##### **Brain metastases**

The ability to cross BBB could play an important role for anti-cancer drugs. Crizotinib, a selective inhibitor of the anaplastic lymphoma kinase (ALK), is highly active in EML4/ALK translocated lung adenocarcinoma. Crizotinib has a low diffusion into healthy brain, with a cerebrospinal fluid (CSF)-to-plasma ratio of 0.0026 (Costa et al., 2011). New therapies i.e. ALK inhibitors of third generation, have a better ability to cross the BBB, allowing the treatment of brain metastasis resistant to crizotinib. Alectinib and brigatinib, two third generation ALK inhibitors, are associated with better response rates of central nervous system (CNS) lesions compared to crizotinib (78% with brigatinib, 81% with alectinib, compared to 29-50% with crizotinib (Camidge et al., 2018; Peters et al., 2017)). Similar results have been reported with osimertinib in EGFR-mutated lung cancer (Reungwetwattana et al., 2018) (objective CNS response rate of 91% with osimertinib vs. 68% with standard anti-EGFR therapy).

The vascularization of brain metastases, and its permeability, could differ from the healthy vessels which protects the CNS (Wang et al., 2017). Most PKIs are substrates of both P-gp and BCRP and have a poor diffusion into the cerebrospinal fluid (CSF) [38–44]. A drug which is not able to cross the BBB could nevertheless have an activity if the permeability of the tumour vessels is high enough. Carbon-11 radiolabeled lapatinib could penetrate into brain

metastasis, although it does not diffuse into normal brain (Saleem et al., 2012). However, 2 phase II studies of lapatinib in HER2+ breast cancer with brain metastases had poor CNS lesion response (~5%) (Lin et al., 2009, 2008).

Concomitant radiotherapy is a way to create a breach (Zhang et al., 2014) in the BBB, thus allowing a better diffusion in the CSF and brain metastasis. A meta-analysis conducted by Zheng et al. (Zheng et al., 2016) reviewed the association of whole brain radiotherapy (WBRT) alone or with erlotinib/gefitinib in brain metastatic lung cancer with a wild type or a mutated EGFR profile. WBRT combined with gefitinib/erlotinib significantly increased CNS response rate (OR = 2.16, 95% CI: 1.35–3.47;  $P = 0.001$ ) and prolonged 1-year survival rate compared to WBRT alone (OR = 2.43, 95% CI: 1.51–3.91;  $P = 0.0002$ ). EGFR status was unknown for most analysed studies.

Most PKIs have a low CSF concentration, due to the fact that most of them are substrate of both P-gp and BCRP. Although the ratio of CSF/plasma concentration is not an absolute surrogate to predict PKIs activity against a brain metastasis, PKIs BBB diffusion should always be considered for the treatment of any cancer with a brain lesion.

### **Leptomeningeal carcinomatosis (LMC)**

Small leptomeningeal lesions are poorly connected to the systemic vasculature, and the cancer cell exposure to treatment relies only on the ability of the drug to diffuse through the BBB. The concentration in the CSF and penetration rate of gefitinib in the CSF of patients are 8.2 nM ( $\pm 4.3$  nM) and 1.1% while the concentration and penetration rate of erlotinib in the CSF are 66.9 nM ( $\pm 39.0$  nM) and 2.8% (Togashi et al., 2012). Erlotinib thus exhibits a better brain diffusion than gefitinib. Lee & al, confirmed this effect clinically [31]: in a retrospective analysis, 9 of 14 patients treated with erlotinib converted to negative cytology compared to 1 of 11 treated with gefitinib, (64% vs 9%,  $p=0.012$ ).

Reinwald & al (Reinwald et al., 2014) studied nilotinib CSF concentration and measured a ratio of CSF/plasma concentration of 0.0053. However, nilotinib in the treatment of BCR-ABL leukaemia with CNS lesions was shown to be effective in the brain. An explanation would be the high protein binding affinity of this drug and the absence of albumin in CSF allowing the unbound concentration of the drug in the CNS to be high enough to be effective.

Efflux pump polymorphism also has an impact on CSF diffusion. Patients with the deficient ABCG2 421C>A allele have a significantly higher erlotinib CSF penetration (Fukudo et al., 2013).

High doses could theoretically allow saturating P-gp and BCRP efflux pump and increase CSF diffusion. Pulsatile methods, i.e. weekly administration of large intakes, have been proposed for patients with leptomeningeal disease of EGFR-mutated lung adenocarcinoma. Case reports of 1000 to 1500 mg in one intake per week, in addition to radiotherapy led to manageable toxicities and disease stabilisation (Clarke et al., 2010). A phase 1 study of erlotinib at 2000 mg weekly showed similar results (Milton et al., 2006).

New generation EGFR inhibitors such as osimertinib which has a good brain diffusion profile should be preferred whenever possible in EGFR-mutated NSCLC (Nanjo et al., 2018; Planchard, 2017; Sakai et al., 2017; Yang et al., 2017).

### *3- Metabolism / Elimination*

#### *PK principles*

Most PKIs are too hydrophobic in their active form to be eliminated through the glomeruli and excreted in urine: they require prior metabolisation before hepatic or renal elimination.

There are 2 types of metabolisations which transform lipophilic drugs into more hydrophilic metabolite(s):

- Phase I metabolism via cytochromes (CYP450). There are more than 50 cytochrome P450 enzymes, but six of them metabolise 90 percent of drugs, with the two most significant enzymes being CYP3A4 and CYP2C. This process

includes oxidation, but not only. Reduction and hydrolysis or cyclisation might also occur.

- Phase II metabolism via conjugation reactions. Glucuronidation, the transfer of a glucide, is an important mechanism and occurs via Uridine 5'-diphospho-glucuronosyltransferase (UDP-glucuronyl-transferase). Other mechanisms include: glutathione conjugation, methylation, acetylation or sulfonation.

Cytochromes are found in many organs (skin, kidney, gut wall, lungs) but most of CYP-dependent metabolism occurs in the liver.

#### *Cytochromes mediated drug-drug interaction (DDI)*

Cytochrome P450 enzymes can be inhibited or induced by drugs, resulting in clinically significant drug-drug interactions that can cause unanticipated adverse reactions or therapeutic failures. Antiepileptic or antiretroviral treatments are known to interact with CYP3A4 which is the main metabolic pathway of most PKIs (table 1).

Other interactions are less expected : glucocorticoids are widely used and they induce the expression of CYP3A4 (El-Sankary et al., 2002). Similarly, inflammation, via interleukine-6 (Robertson et al., 2008a), inhibits the expression of CYP3A4, and could lead to excessive drug toxicity caused by reduced CYP3A4-mediated metabolism (Robertson et al., 2008b). Although there is no proof of an increased toxicity in patients treated by PKIs, patients having CRP >10mg/L or  $\alpha_1$ -acid glycoprotein level >1.5 g/L have 3 times more non-haematological complications, when treated by docetaxel, which is mainly eliminated by CYP3A4 (Charles et al., 2006).

Fenofibrate, which is a widely prescribed drug for triglyceride reduction, is also a potent CYP3A4 inducer. Mir&al (Mir et al., 2011) showed that the progression of a patient treated by erlotinib for a lung adenocarcinoma with an EGFR mutation and treated with concomitant fenofibrate, exhibited a serum plasma concentration half of the lower normal limit. Doubling erlotinib intakes restored plasma concentration of erlotinib and drug efficacy with a partial response. Approximately 50 % of patients treated with everolimus exhibit hypertriglyceridemia which is often treated with fenofibrate, a CYP3A4 inducer. Mir & al (Mir et al., 2015) reported a case of a patient treated by everolimus who developed grade 2 stomatitis and grade 2 hypertriglyceridemia. When fenofibrate was started, everolimus concentration dropped from 10.1 ng/mL to 4.2ng/mL, and both adverse events disappeared. Fenofibrate was discontinued and the plasma concentration of everolimus later normalised.

Mitotane, a drug used in adrenocortical carcinoma, is one of the most powerful CYP 3A4 inducer known. It also has a very high lipophilicity and thus a very long half-life (18-159 days) (van Erp et al., 2011). Sunitinib has been used for the treatment of adrenocortical carcinoma (Kroiss et al., 2012). Patients primarily treated with mitotane had worse outcomes and their sunitinib plasma concentrations were almost 10 fold lower than mitotane-naïve patients. This effect on CYP 3A4, due to mitotane's very long half-life, might last more than 3 months, compromising most second line treatment in this disease.

More generally, any drug that alters CYP3A4 activity should be suspected of causing drug interactions when a concomitant treatment with a PKI is started.

#### *Food and herb-drug interactions*

Grapefruit and Saint-John's Wort are well known to respectively inhibit and induce CYP3A4. We summarized in table 2 other clinically relevant her or food CYP3A4 inhibitors or inducers (no in vitro or animal model was considered) which should be avoided concomitantly to PKIs.

Food habits and phytotherapy intakes should always be investigated before the initiation of a PKI and when high grade toxicity or no adverse event is seen. Most interactions between phytotherapy and CYP3A4 have poorly been explored and phytotherapy-induced interaction should always be considered.

### *Glucuronidation, UGT*

5'-diphospho-glucuronosyltransferase (UDP-glucuronyl-transferase) also called UGT, has a well-known importance for the metabolism of SN-38, the active metabolite of irinotecan, a camptothecin derivative. UGT1A1 polymorphism predicts severe toxicity (deficiency is known as Gilbert' syndrome). UGT is an enzyme which transfers a glucose derivative on xenobiotics, making them more hydrophilic.

Like cytochromes, there are different families of UGT. UGT1A9 has a demonstrated role in sorafenib metabolism. However, no major role of UGT1A9 polymorphism on sorafenib exposure has been clearly demonstrated so far (Boudou-Rouquette et al., 2012). Similarly, no drug-drug interactions from glucuronidation mechanism have been clearly identified with PKIs.

### *ABC transporters*

ABC transporters (ATP-Binding Cassette), play an important role in the bioavailability, the BBB, and the detoxification of drugs. Both P-gp (ABCG1) and ABCG2 (BCRP) were originally discovered as being responsible for some Multi-Drug Resistance cancer cell phenotype. Durmus & al (Durmus et al., 2015) reviewed the role of these transporters in multi-kinase inhibitors: most of them are substrate of both P-gp and ABCG2.

Interestingly, some multi-kinase inhibitors also inhibit ABC transporters. Imatinib, for example, is a potent ABCG2 inhibitors (He and Wei, 2012), and reverses some in vitro MDR phenotypes.

A role of proton pump inhibitors on P-gp and PKI drug-drug interaction should also be expected (cf. supra). Afatinib, which is mainly eliminated without transformation via P-gp (Wind et al., 2017). However, rifampicin, a known powerful P-gp modulator, had no clinically relevant effect on afatinib exposure (Wind et al., 2014). Clinically significant transporter mediated interactions with PKIs are unlikely.

### *Role of genetic polymorphism*

Some cytochromes, such as CYP2D6, are highly polymorphic, dividing patients between poor metaboliser, intermediate metaboliser, extensive metaboliser, or ultra-extensive metaboliser. These polymorphisms can have a direct impact on therapeutic response as was shown with tamoxifen (Borges et al., 2006). Same variations could occur through ABC transporters protein and the UGT. The impact of pharmacogenetics on cytotoxic treatment is now well established (Deenen et al., 2011). Similarly, forty-nine single nucleotide polymorphisms (SNPs) involved in the pharmacokinetic and pharmacodynamic pathway of sunitinib were associated with progression-free survival (PFS) and overall survival (OS) in 127 patients with advanced GIST treated with sunitinib (Kloth et al., 2018, p. 201). Similar results were found for genetic polymorphisms related to angiogenesis which modified outcomes of patients with GIST treated with imatinib (Verboom et al., 2017).

However, no study has demonstrated the role of pharmacogenomics to improve efficiency and safety of PKIs in daily routine.

### *Role of Tobacco*

Tobacco's polycyclic aromatic hydrocarbons can induce CYP 1A2, CYP 1A1 and CYP 2E1 (Zevin and Benowitz, 1999). EGFR-mutated lung cancers are more common in the "never smoker population". However, some of them smoke. The pharmacokinetics of erlotinib, a PKI specific of EGFR mutation, is influenced by smoking. Erlotinib is mainly eliminated by CYP 1A2 and CYP 3A4 and shows an approximately 2 fold decreased exposure in the plasma of smoking patients (Hamilton et al., 2006). Hughes &al (Hughes et al., 2009) proposed to double the dosage from 150 to 300 mg per day for patients smoking more than 10 cigarettes per day, restoring erlotinib activity.

Imatinib is partially metabolised by CYP1A2. Although smoking has not proved to significantly change the pharmacokinetics of imatinib (van Erp et al., 2008), non-smoking patients treated with imatinib for a GIST have a trend

to respond better (PFS) than smokers ( $p=0.052$ ).

Patients treated with erlotinib should be encouraged to quit smoking. When it is not possible, alternative treatments (gefitinib, afatinib or even osimertinib) should be preferred, or erlotinib doses can be doubled and plasma concentrations monitored.

#### *Hepatic failure*

PKIs mainly have biliary elimination. Sorafenib, mostly metabolised by CYP3A4 and UGT1A9, has first been approved for the treatment of hepatocellular carcinoma (Bruix et al., 2017; Llovet et al., 2008). Most patients with hepatocellular carcinoma have cirrhosis, and thus an impaired hepatic function. Non-cancerous hepatic tissue of patients having a HCC has a 4 to 10-fold lowered cytochrome P-450 activity per gram of liver (Ye et al., 2014). Nevertheless, the recommended starting dose of sorafenib was found to be the same in hepatocellular carcinoma than in clear renal cell carcinoma or other solid cancer i.e. 400mg b.i.d. (Strumberg et al., 2007), with no substantial PK difference between Child-Pugh A and Child-Pugh B patients in a phase 2 study (Abou-Alfa et al., 2006). Similarly, imatinib pharmacokinetic properties were not altered in a phase I study in patients with HCC (Treiber et al., 2008). Two case reports did not show an increased toxicity with imatinib in GIST patients with cholestasis and impaired hepatic function (Bauer et al., 2002). A phase 1 study was conducted with sorafenib in patients with altered hepatic function (Miller et al., 2009). The authors recommended to lower sorafenib initial doses when bilirubinemia is  $> 3x$  ULN or if albuminemia is  $< 25g/L$ , which reflects the severity of liver dysfunction. Another phase 1 study conducted in patients receiving erlotinib (Miller et al., 2007) showed that patients with  $AST > 3xULN$  or bilirubin  $> 1mg/dL$  or albuminemia  $< 25 g/L$  should be treated with half-dose, due to a 2 to 3-fold lower clearance in this population.

Pazopanib was also evaluated in a phase 1 study among patients having a liver dysfunction (Shibata et al., 2013) and treated for a solid cancer. Patients having a mild hepatic impairment (total bilirubin  $>$  upper limit normal (ULN) to 1.5 x ULN or  $AST > ULN$ , according to the National Cancer Institute Organ Dysfunction Working Group) exhibited normal toxicity and pharmacokinetics and should be treated like other patients. Patients having a moderate or severe dysfunction according to the same criteria had both a MTD of 200 mg per day, although having a much lower plasma concentration of Pazopanib.

All these authors recommend that in case of moderate or severe dysfunction (Child-Pugh B or C), the drug should be started at lower dose and an early drug monitoring should be performed.

#### *Renal failure*

PKIs are too hydrophobic to be directly eliminated in the urine. Only hydrophilic metabolites, often inactive, are excreted by renal route. Thus, renal impairment has a very low impact on kinase inhibitors toxicity. As an example, erlotinib and sorafenib clearance do not differ in patients with renal dysfunction (studies limited to  $GFR > 20mL/min/1.73m^2$ ) and patients with normal renal function [70].

Sunitinib is not dialyzable (Izzedine et al., 2009; Janus et al., 2012). Yet, a phase 1 study (Khosravan et al., 2010) showed a lower maximum plasma concentration of sunitinib among hemodialysed patients, possibly due to a diminution of the bioavailability of the drug (unknown mechanism). Severe renal impairment ( $GFR < 30mL/min$ ) did not influence the pharmacokinetics of sunitinib administered as a single 50 mg dose. Sunitinib, temsirolimus, everolimus and pazopanib, in small cohorts of patients treated for mRCC and hemodialysed seemed to have a similar toxicity profile. However, severe adverse events due to cardio-vascular complications were also reported (Kennoki et al., 2011; Masini et al., 2012; Shetty et al., 2014). Sorafenib AUC increased in hemodialysed patients (Hilger et al., 2009) and initial drug dose should be decreased and plasma concentrations monitored.

Erlotinib gefitinib, afatinib, nilotinib and imatinib display a safe profile of use among hemodialysed patients in case

series (Bersanelli et al., 2014; Janus et al., 2012; Onaka et al., 2012; Togashi et al., 2010).

Anti-angiogenics PKIs can cause serious cardio-vascular side effects and patients with renal failure or requiring hemodialysis should be treated with more caution (start with lower dose) and closely monitored clinically. Janus et al. reviewed the use of PKIs (Janus et al., 2012) and recommend that they should be administered post dialysis, since the dialysability of these drugs is most of the time unknown.

## **PK/PD relationships and Impact of Therapeutic Drug Monitoring (TDM)**

### *1- Therapeutic index*

Correct exposure to a PKI with adequate AUC is required for the treatment to be efficient and not too toxic. Most PKIs are prescribed at a flat dose, despite a high inter-patient variability and a narrow therapeutic index. Many patients fail to reach an appropriate exposure, and thus might experience treatment failure. In its recommendation for prescription, only axitinib proposes an increase of its dosage in case of good tolerance (which was originally proposed in the phase 3 study), lowering the chances of underdosing the patient. Drug monitoring is suitable for drugs satisfying certain criteria (Ghiculescu, 2008) such as a narrow therapeutic index, significant pharmacokinetic variability, a significant relationship between plasma concentration and clinical effects, and an available cost-effective drug assay.

Most antiangiogenic PKIs prescribed in oncology have a wide kinase spectrum activity and inhibit kinase that could be responsible for off-target effects (Gougis et al., 2017). Therefore the efficacy dose is close to the toxic dose and they have a narrow therapeutic index. For sunitinib, among others, toxicity could also be a surrogate of efficacy. In clear cell renal cell carcinoma patients treated with sunitinib, hypertension (Izzedine et al., 2015) or hypothyroidism (Schmidinger et al., 2011) correlate with better outcome. For these PKIs, exposure is correlated to efficacy (Hayato et al., 2018; Houk et al., 2010; Lacy et al., 2018; Solms et al., 2017; Sternberg et al., 2018) as well as adverse effects.

On the other hand, EGFR targeting PKIs such as erlotinib, gefitinib or osimertinib have a limited action on the kinome and are more specific than antiangiogenic PKIs. Multiple studies failed to prove a relationship between exposure and efficacy (Brown et al., 2017; Hirose et al., 2016; Kobayashi et al., 2015; Xin et al., 2015), but a linear relationship between exposure and adverse effects remains. Therefore, the first category of PKIs is a better candidate for TDM.

### *2- Interests of therapeutic drug monitoring*

Drug monitoring allows correcting the systemic exposure of a patient. Rousselot et al. randomised patients treated with imatinib for chronic myeloid leukaemia when the trough plasma concentration was too low, between a dose-increase strategy aiming to reach the threshold of 1000 ng/ml versus classic clinical imatinib management. Two-thirds of the patients were underexposed, and the rate of major molecular response was higher at one year with TDM (63% vs. 37%,  $p=0,031$ ). For sunitinib, patients AUC is predictive of time to tumour progression and overall survival (Houk et al., 2010) and one-third of the patients seem to have a too low dosage (Lankheet et al., 2014). Sunitinib, sorafenib or everolimus among other PKIs (Gao et al., 2012) are good candidates for TDM although no randomised trial has proven better clinical outcome with TDM yet. The intra-patient variability could also make it challenging. In a small cohort (13 patients), de Wit et al. (de Wit et al., 2015) evaluated if a PK-guided strategy could increase the percentage of patients within the target window of AUC. The study was terminated early due to high intra-patient plasma concentration variations.

Although the usefulness of generalised PK-guided dosing strategies remains to be proven in randomised trials, TDM could help with the management of patients with predictive factors of pharmacological failure. We summarised in table 3 situations where TDM could be useful.

## **Conclusion**

With the approval of more and more of these molecules in oncology, it is difficult to know everything about the pharmacology of PKIs. However, basic knowledge of the pharmacology of PKIs is needed for the safe use of this class of drugs. We reviewed and synthesized relevant information in order for clinicians to avoid major pitfalls.

The bioavailability of a PKI could be compromised when gastric acidity is modified by either gastrectomy, proton pump inhibitors or food. Adherence is an important cause of treatment failure and should be explored when no toxicity is seen for a patient. Sarcopenia is an independent marker of toxicity and the tolerance to PKIs of sarcopenic patients should be closely monitored. Most PKIs are metabolised by CYP3A4. Drug-drug interaction and herb-drug interaction through CYP3A4 should be anticipated and concomitant CYP3A4 modifiers prescription changed whenever possible. Hepatic failure could compromise PKI treatment. Renal failure and haemodialysis have no major effect on PKIs but could be associated with an increase of cardio-vascular events for patients treated with PKIs, in this fragile population.

Whenever there is a predictive risk of underdosing a patient, for obese patients for example, therapeutic drug monitoring can help to reach a target window of AUC.

**Funding:** This review has not been funded

**Conflict of Interest:** The authors declare that there is no conflict of interest regarding the publication of this article

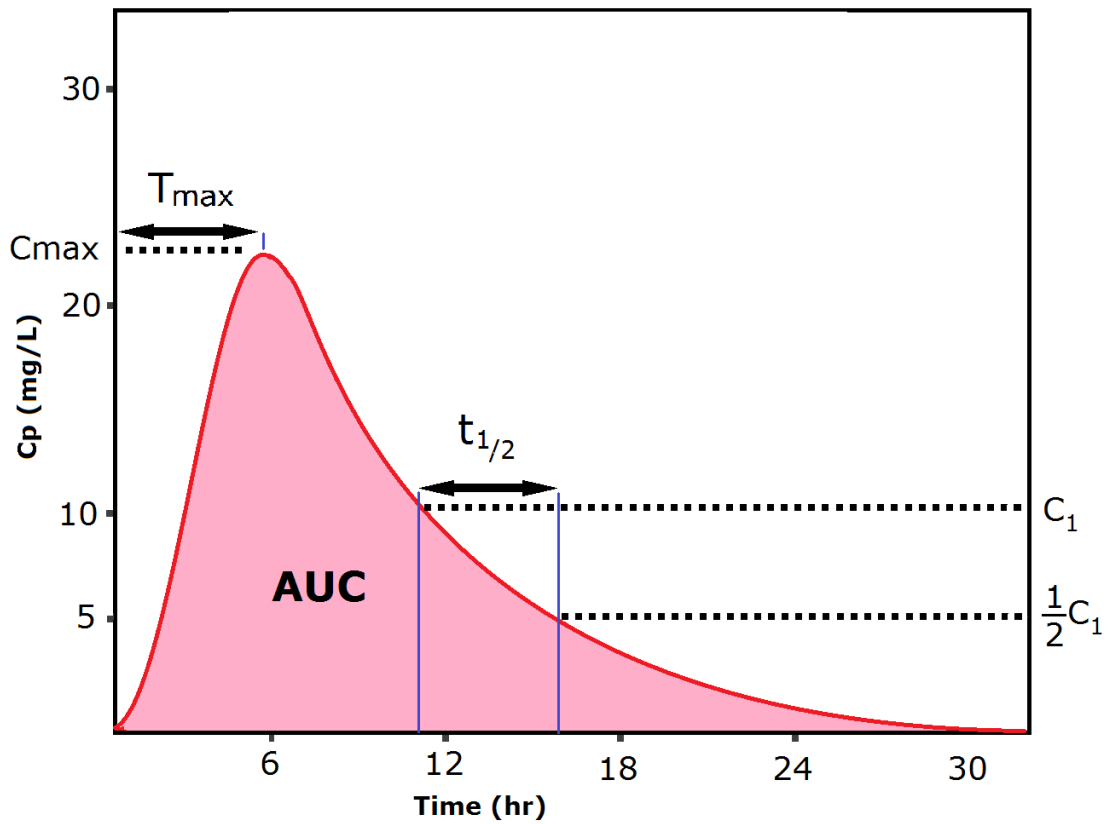
**Acknowledgements:** The authors thank the Van 1 association for their advice and moral support.



## Figures and tables

**Figure 1: Plasma concentration vs. time profile of a single oral drug administration.**

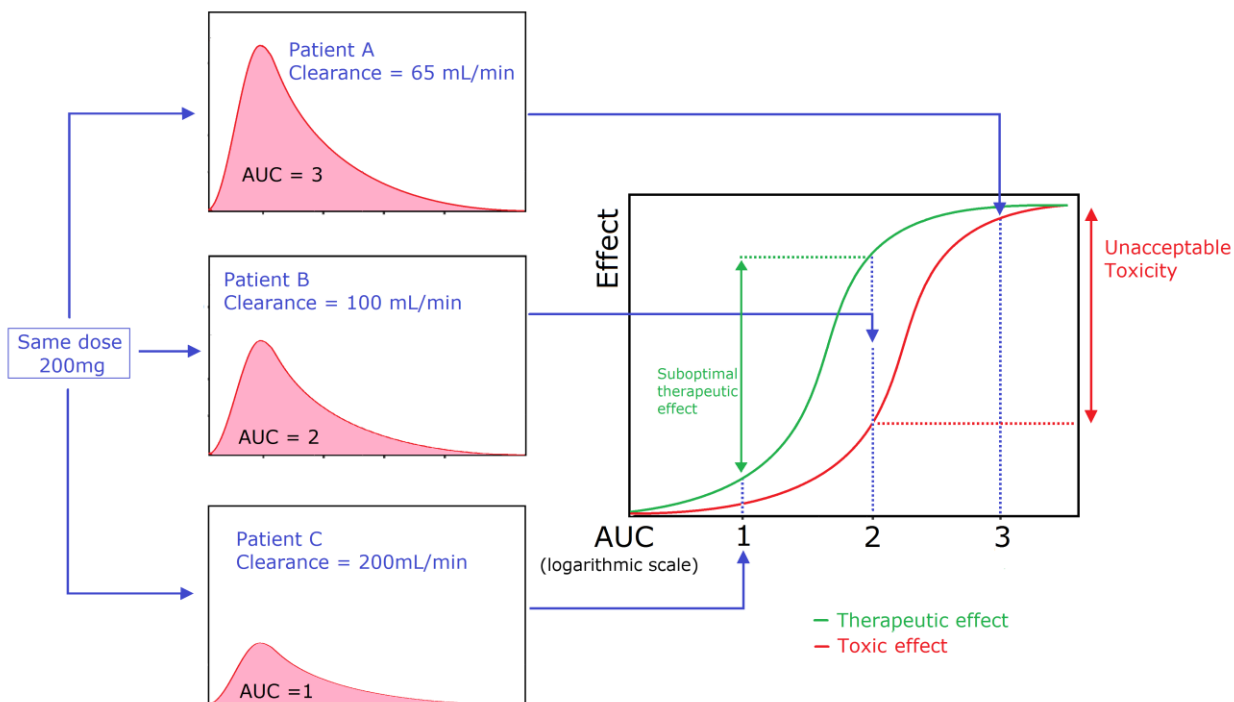
Area under curve of a single dose of a drug administered orally. In the elimination phase (when the drug is fully absorbed), the concentration  $C_1$  is divided by 2 after 1 half-life  $t_{1/2}$



AUC: area under curve;  $C_p$ : plasma concentration of the drug;  $C_{max}$ : maximum plasma concentration;  $T_{max}$ : time to reach maximum concentration;  $t_{1/2}$ : terminal half-life

**Figure 2: Inter-individual variation of Area Under Curve (AUC) exposure with the same dose due to variation of the clearance**

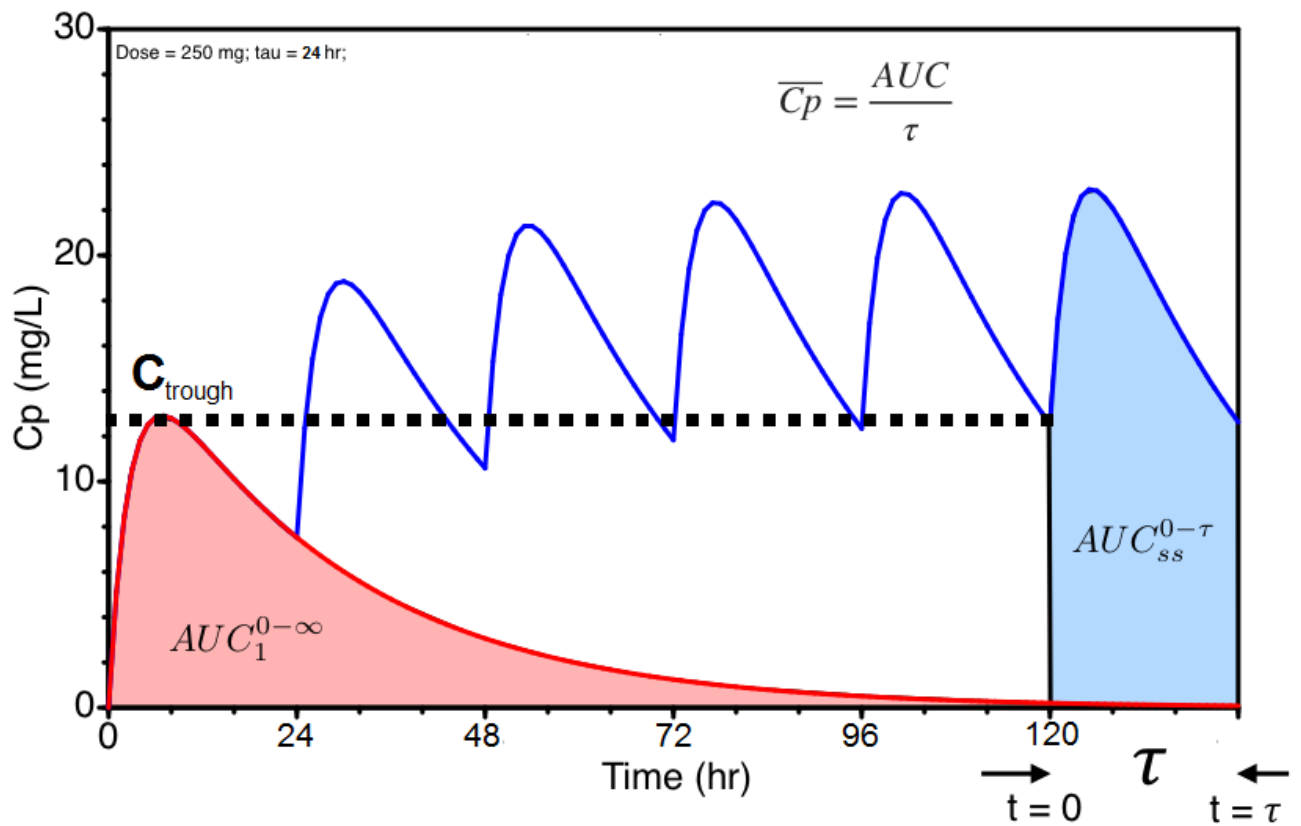
Patient A will experience drug induced adverse event due to an increased exposure to the drug. Patient C could have a treatment failure due to low exposition.



AUC: area under curve;  $C_p$ : plasma concentration of the drug;  $C_{max}$ : maximum plasma concentration;  $T_{max}$ : time to reach maximum concentration;  $t_{1/2}$ : terminal half-life

**Figure 3: Plasma concentration of a hypothetical drug given every tau hours**

$C_{\text{trough}}$  at steady state (SS) can be used to estimate the  $AUC(0-\tau)$  at steady state which reflects drug's exposure. Tau is 24 hours in this example.



AUC: area under curve;  $C_p$ : plasma concentration of the drug;  $C_{\text{max}}$ : maximum plasma concentration;  $T_{\text{max}}$ : time to reach maximum concentration;  $t_{1/2}$ : terminal half-life

**Table 1: Pharmacokinetic properties of approved protein kinase inhibitors in oncology**

| TKI                 | Targets                                  | Indication                                      | Absorption  |          | Distribution |                 | Metabolism                 | Excretion           | T <sub>1/2</sub> |
|---------------------|--|---|-------------|----------|--------------|-----------------|----------------------------|---------------------|------------------|
|                     |  |   | F           | Pic      | Vd           | Protein binding |                            |                     |                  |
| <b>Afatinib</b>     | EGFR                                     | EGFR+ NSCLC                                     | NA<br>↓     | 2-5h     | 4500L        | 95%             | -                          | Biliary             | 37h              |
| <b>Alectinib</b>    | ALK                                      | ALK+ NSCLC                                      | 37%<br>↗    | 4-6h     | 475L         | >99%            | Hepatic (CYP3A4)           | Biliary             | 32h              |
| <b>Axitinib</b>     | VEGFR                                    | RCC   | 58%         | 4h       | 160L         | >99%            | Hepatic (CYP3A4)           | Biliary/<br>Urinary | 2,5-<br>6h       |
| <b>Bosutinib</b>    | SRC, ABL                                 | Ph+ CML   | NA<br>↗     | 6h       | 10 000L      | 96%             | Hepatic (CYP3A4)           | Biliary             | 34h              |
| <b>Cabozantinib</b> | MET, VEGFR-2, RET                        | RCC, MTC  | NA<br>↗     | 3-4h     | 319L         | >99%            | Hepatic (CYP3A4)           | Biliary/<br>Urinary | 99h              |
| <b>Ceritinib</b>    | ALK                                      | ALK+ NSCLC                                      | 25%<br>↗    | 4-6h     | NA           | 97%             | Hepatic (CYP3A4)           | Biliary/<br>Urinary | 31-<br>41h       |
| <b>Cobimetinib</b>  | MEK                                      | BRAF V600 melanoma                              | 46%         | 2,4h     | 800L         | 95%             | Hepatic (CYP3A4 & UGT2 B7) | Biliary             | 44h              |
| <b>Crizotinib</b>   | ALK, MET, ROS1                           | ALK+ NSCLC                                      | 43%         | 4-6h     | 1700L        | 91%             | Hepatic (CYP3A4)           | Biliary/<br>Urinary | 42h              |
| <b>Dabrafenib</b>   | BRAF                                     | BRAF V600 melanoma                              | 95%<br>↓    | 2h       | 46L          | 99,7%           | Hepatic (CYP3A4 & CUP2C8)  | Biliary/<br>Urinary | 8-10h            |
| <b>Dasatinib</b>    | BCR-ABL, c-KIT, PDFR-β, SRC              | Ph+ CML, Ph+ ALL                                | 80%         | 0,5 – 3h | 2500L        | 96%             | Hepatic (CYP3A4)           | Biliary/<br>Urinary | 3-6h             |
| <b>Erlotinib</b>    | EGFR                                     | EGFR+ NSCLC, PC                                 | 59%<br>↗    | 4h       | 232L         | 95%             | Hepatic (CYP3A4 & CYP 1A2) | Biliary             | 36h              |
| <b>Gefitinib</b>    | EGFR                                     | EGFR+ NSCLC                                     | 59%         | 3-7h     | 1400L        | 90%             | Hepatic (CYP3A4 & CYP2D6)  | Biliary             | 42h              |
| <b>Imatinib</b>     | BCR-ABL, c-KIT, PDGFR-α                  | GIST, CML, ALL, dermatofibrosarcoma protuberans | 98%         | 2-4h     | 295-590L     | 95%             | Hepatic (CYP3A4/5)         | Biliary/<br>Urinary | 18-<br>22h       |
| <b>Lapatinib</b>    | HER2, EGFR                               | HER2+ breast cancer                             | NA<br>↗     | 4h       | 2200L        | 99%             | Hepatic (CYP3A4)           | Biliary             | 24h              |
| <b>Lenvatinib</b>   | VEGFR, FGFR,                             | Iodine refractory thyroid carcinoma             | 70-85%      | 1-4h     | 43-121L      | 98,5%           | Hepatic (CYP3A4)           | Biliary/<br>Urinary | 28h              |
| <b>Nilotinib</b>    | BCR-ABL, c-KIT                           | Ph+ CML   | 30%<br>↗    | 2-4h     | 579-800L     | 98%             | Hepatic (CYP3A4)           | Biliary             | 17h              |
| <b>Osimertinib</b>  | EGFR T790M                               | EGFR T790M NSCLC                                | NA          | 6h       | 986L         | High            | Hepatic (CYP3A4)           | Biliary/<br>Urinary | 48h              |
| <b>Palbociclib</b>  | CDK 4/6                                  | RH+ breast cancer                               | 46%         | 6-12h    | NA           | 85%             | Hepatic (CYP3A4 & SULT2A1) | Biliary/<br>Urinary | 28h              |
| <b>Pazopanib</b>    | VEGFR, c-KIT                             | RCC, GIST                                       | 14-39%<br>↗ | 2-4h     | 9-13L        | 99%             | Hepatic (CYP3A4)           | Biliary             | 30h              |
| <b>Regorafenib</b>  | VEGFR, PDGFR-β, RAF, FLT-3, c-Kit, Ang-2 | CRC, HCC, (Ewing sarcoma)                       | <70%<br>↗   | 4h       | 76L          | 99,5%           | Hepatic (CYP3A4 & UGT1A9)  | Biliary/<br>Urinary | 20-<br>30h       |
| <b>Sorafenib</b>    | VEGFR, RAF, FLT-3, c-Kit                 | RCC, HCC, non-medullary thyroid carcinoma       | 39-49%<br>↓ | 2-6h     | 213-400L     | 99,5%           | Hepatic (CYP3A4 & UGT1A9)  | Biliary/<br>Urinary | 25-<br>48h       |
| <b>Sunitinib</b>    | VEGFR, c-KIT                             | RCC, GIST, p-NET                                | NA          | 6-12h    | 2230L        | 95%             | Hepatic (CYP3A4)           | Biliary/<br>Urinary | 40-<br>60h       |
| <b>Trametinib</b>   | MEK                                      | BRAF V600                                       | 72%         | 1,5h     | 1200L        | 97%             | Carboxylest                | Biliary/            | 5,3d             |

|                    |                    |                    |         |       |       |     |                  |                 |     |
|--------------------|--------------------|--------------------|---------|-------|-------|-----|------------------|-----------------|-----|
|                    |                    | melanoma           | ↘       |       |       |     | erases           | Urinary         |     |
| <b>Vandetanib</b>  | EGFR, VEGFR-2, RET | MTC                | NA      | 4-10h | 7500L | 94% | Hepatic (CYP3A4) | Biliary/Urinary | 19d |
| <b>Vemurafenib</b> | BRAF               | BRAF V600 melanoma | NA<br>↗ | 4h    | 90L   | 99% | Hepatic (CYP3A4) | Biliary         | 50h |

↗: Absorption increased with meals; ↘: absorption decreased with meals

CRC: ColoRectal Cancer; F: biodisponibilité; GIST: Gastro-Intestinal Stromal Tumor; HCC: Hepato-cellular Carcinoma; HR: hormone receptor MTC: Medullary Thyroid Cancer; NSCLC: Non-Small Cell Lung Cancer; PC: Pancreatic Cancer; p-NET: pancreatic NeuroEndocrine Tumor; RCC: Renal Cell carcinoma; T ½: half-life; Vd: distribution volume

**Table 2: Herbs or food with clinically relevant known interactions with CYP3A4 probes (either induction or inhibition).** Concomitant use of these complementary alternative medicine or diet can lead to increased toxicity (CYP3A4 inhibition) or decreased efficiency (CYP3A4 induction) and is strongly discouraged for most PKIs.

| CYP3A4 Inhibitor  | CYP3A4 Inductors   |
|---|--|
| Cranberry ( <i>Vaccinium Macrocarpon</i> ) (Ngo et al., 2009)                             | Echinacea ( <i>Echinacea Purpurea</i> ) (Gorski et al., 2004; Penzak et al., 2010) |
| Green tea ( <i>Camellia Sinensis</i> ) (Chow et al., 2006)                                | Ginseng ( <i>Panax Ginseng</i> ) (Malati et al., 2012)                             |
| Goldenseal ( <i>Hydrastis Canadensis</i> ) (Gurley et al., 2008, 2005; Xin et al., 2006)  | Licorice ( <i>Glycyrrhiza Glabra</i> ) (Tu et al., 2010)                           |
| Lime ( <i>Citrus Arantifolia</i> ) (Bailey et al., 2003)                                  | Ginkgo ( <i>Ginkgo Biloba</i> ) (Markowitz et al., 2003; Uchida et al., 2006)      |
| Pomelo ( <i>Citrus Maxima</i> ) (Grenier et al., 2006)                                    | Saint-John's wort ( <i>Hypericum Perforatum</i> ) (Markowitz et al., 2000)         |
| Grapefruit ( <i>Citrus Paradisi</i> ) (Edgar et al., 1992)                                | Soy extracts ( <i>Glycine max</i> )/ genistein (Xiao et al., 2012)                 |
| Sevilla orange ( <i>Citrus Aurantium</i> ) (Di Marco et al., 2002; Lemahieu et al., 2003) |  |
| Peppermint ( <i>Mentha Piperita</i> ) (Dresser et al., 2002; Gelal et al., 2005)          |  |
| Black seed ( <i>Nigella Sativa</i> ) (Al-Jenoobi et al., 2010)                            |  |
| Wuzhi ( <i>Schisandra Sphenanthera</i> ) (Jiang et al., 2010; Xin et al., 2009)           |  |
| Broccoli sprouts extracts /kale/sulforaphane (Poulton et al., 2013)                       |  |
| Quercetin (Duan et al., 2012)   |  |
| Vitamin E (Bárány et al., 2001)   |  |
| Resveratrol (Bedada and Nearati, 2015; Chow et al., 2010)                                 |  |
| Piperin / pepper extracts ( <i>Piper Nigrum</i> ) (Rezaee et al., 2014)                   |  |

**Table 3: Phenomenon involved in PKI's pharmacokinetics and recommendations for clinical practice**

| <b>ADME</b>                     | <b>Pitfall</b>                             | <b>Potential consequences</b>   | <b>Clinical recommendations</b>  |
|---------------------------------|--|---|--|
| <b>Absorption</b>               | Gastric surgery                            | Increase of gastric pH decreases PKI's bioavailability  | Chose PKI with no influence of gastric acidity whenever possible. TDM can help when no alternatives are possible   |
|                                 | Proton pump inhibitors and anti-acids      | Increase of gastric pH decreases PKI's bioavailability  | PPI should be avoid whenever possible, anti-H2 should always be taken 2 hours after the PKI, direct anti-acid should be taken 2 hours after the PKI  |
|                                 | Food                                       | Meals alter the gastric emptying and increase gastric pH, increasing or decreasing PKI's exposure.  | Respect the fed or fasted recommendation for the drug  |
|                                 | Time of the day                            | Enzymes and transporters involved in the pharmacokinetics of PKIs have time-dependent variations in expression  | Limited evidence of influence on the efficiency / toxicity   |
|                                 | Adherence                                  | PKI's oral drug prescription is particularly at risk of non-adherence   | Consider using adherence scales. TDM could be used in case of doubts   |
|                                 | Other sources of variation                 | Use of parasympatholytics or mimetics can change PKI's absorption   | No evidence of influence on the efficiency or toxicity   |
| <b>Distribution</b>             | Protein Binding                            | Modification of the half-life   | No evidence of influence on the efficiency or toxicity   |
|                                 | Sarcopenia                                 | The combination of sarcopenia and BMI < 25 is a good predictor of PKI's toxicity  | Sarcopenic patients should have a closer clinical monitoring. Consider beginning at lower dose.  |
|                                 | Obesity                                    | Reduced absorption of oral drugs across the gut wall because of visceral fat, modified volume of distribution, increased drug metabolism, decreased clearance | Consider TDM when no adverse effects are seen  |
|                                 | Blood-brain barrier                        | Ability to cross the blood-brain barrier modify the efficiency of PKI on brain metastases and is critical for leptomeningeal diseases                         | PKI's BBB diffusion should always be considered for the treatment of any cancer with a brain lesion  |
| <b>Metabolism / Elimination</b> | Cytochromes mediated drug-drug interaction | Most PKIs are at least partially metabolised through CYP3A4   | Any drug that alters the CYP3A4 function should be suspected of drug interaction when a concomitant treatment with a PKI is started  |
|                                 | UGT  | Inhibitory effects of PKIs on UDP-glucuronosyltransferase (UGT) activities  | No evidence of influence on the efficiency or toxicity   |
|                                 | ABC transporters                           | Some PKIs are ABC transporters substrates and inhibitors  | Avoid concomitant use of p-gp inhibitors with afatinib   |
|                                 | Genetic polymorphism                       | Patients can be poor metabolizers, intermediate metabolizers, extensive metabolizers, or ultra-extensive metabolizers   | Not indicated in daily care  |
|                                 | Tobacco                                    | Induction of CYP1A2   | Whenever possible, consider using alternatives to erlotinib with smokers (>10cig/day). Consider increasing the dosage if erlotinib is maintained   |
|                                 | Renal failure                              | Patients at risk of cardio-vascular complications for anti-angiogenics. No significant or mild pharmacokinetic modifications for most PKIs                    | Consider beginning at lower dose. For PKIs with no data, consider TDM. For anti-angiogenics, monitor closely cardio-vascular complications   |
|                                 | Hepatic failure                            | Decreased clearance   | For Child-pugh A patients: normal dose and closer clinical monitoring. For more important hepatic failure, begin at lower dose and consider TDM, when the drug is not clearly contre-indicated |

## References

- Abou-Alfa, G.K., Schwartz, L., Ricci, S., Amadori, D., Santoro, A., Figer, A., De Greve, J., Douillard, J.-Y., Lathia, C., Schwartz, B., Taylor, I., Moscovici, M., Saltz, L.B., 2006. Phase II study of sorafenib in patients with advanced hepatocellular carcinoma. *J. Clin. Oncol.* 24, 4293–4300. <https://doi.org/10.1200/JCO.2005.01.3441>
- Al-Jenoobi, F.I., Al-Thukair, A.A., Abbas, F.A., Ansari, M.J., Alkharfy, K.M., Al-Mohizea, A.M., Al-Suwayeh, S.A., Jamil, S., 2010. Effect of black seed on dextromethorphan O- and N-demethylation in human liver microsomes and healthy human subjects. *Drug metabolism letters* 4, 51–5.
- Antoun, S., Baracos, V.E., Birdsall, L., Escudier, B., Sawyer, M.B., 2010. Low body mass index and sarcopenia associated with dose-limiting toxicity of sorafenib in patients with renal cell carcinoma. *Ann. Oncol.* 21, 1594–1598. <https://doi.org/10.1093/annonc/mdp605>
- Arrondeau, J., Mir, O., Boudou-Rouquette, P., Coriat, R., Ropert, S., Dumas, G., Rodrigues, M.J., Rousseau, B., Blanchet, B., Goldwasser, F., 2012. Sorafenib exposure decreases over time in patients with hepatocellular carcinoma. *Invest New Drugs* 30, 2046–2049. <https://doi.org/10.1007/s10637-011-9764-8>
- Bailey, D.G., Dresser, G.K., Bend, J.R., 2003. Bergamottin, lime juice, and red wine as inhibitors of cytochrome P450 3A4 activity: comparison with grapefruit juice. *Clin. Pharmacol. Ther.* 73, 529–537. [https://doi.org/10.1016/S0009-9236\(03\)00051-1](https://doi.org/10.1016/S0009-9236(03)00051-1)
- Bárány, P., Stenvinkel, P., Ottosson-Seeberger, A., Alvestrand, A., Morrow, J., Roberts, J.J., Salahudeen, A.K., 2001. Effect of 6 weeks of vitamin E administration on renal haemodynamic alterations following a single dose of neoral in healthy volunteers. *Nephrol. Dial. Transplant.* 16, 580–584.
- Bauer, S., Hagen, V., Pielken, H.J., Bojko, P., Seeber, S., Schütte, J., 2002. Imatinib mesylate therapy in patients with gastrointestinal stromal tumors and impaired liver function. *Anticancer Drugs* 13, 847–849.
- Bedada, S.K., Nearati, P., 2015. Effect of resveratrol on the pharmacokinetics of carbamazepine in healthy human volunteers. *Phytother Res* 29, 701–706. <https://doi.org/10.1002/ptr.5302>
- Bersanelli, M., Tiseo, M., Artioli, F., Lucchi, L., Ardizzoni, A., 2014. Gefitinib and afatinib treatment in an advanced non-small cell lung cancer (NSCLC) patient undergoing hemodialysis. *Anticancer Res.* 34, 3185–3188.
- Borges, S., Desta, Z., Li, L., Skaar, T.C., Ward, B.A., Nguyen, A., Jin, Y., Storniolo, A.M., Nikoloff, D.M., Wu, L., Hillman, G., Hayes, D.F., Stearns, V., Flockhart, D.A., 2006. Quantitative effect of CYP2D6 genotype and inhibitors on tamoxifen metabolism: implication for optimization of breast cancer treatment. *Clin. Pharmacol. Ther.* 80, 61–74. <https://doi.org/10.1016/j.clpt.2006.03.013>
- Boudou-Rouquette, P., Narjoz, C., Golmard, J.L., Thomas-Schoemann, A., Mir, O., Taieb, F., Durand, J.-P., Coriat, R., Dauphin, A., Vidal, M., Tod, M., Lorient, M.-A., Goldwasser, F., Blanchet, B., 2012. Early sorafenib-induced toxicity is associated with drug exposure and UGT1A9 genetic polymorphism in patients with solid tumors: a preliminary study. *PLoS ONE* 7, e42875. <https://doi.org/10.1371/journal.pone.0042875>
- Brill, M.J., van Rongen, A., van Dongen, E.P., van Ramshorst, B., Hazebroek, E.J., Darwich, A.S., Rostami-Hodjegan, A., Knibbe, C.A., 2015. The Pharmacokinetics of the CYP3A Substrate Midazolam in Morbidly Obese Patients Before and One Year After Bariatric Surgery. *Pharm. Res.* 32, 3927–3936. <https://doi.org/10.1007/s11095-015-1752-9>
- Brill, M.J.E., van Rongen, A., Houwink, A.P.I., Burggraaf, J., van Ramshorst, B., Wiezer, R.J., van Dongen, E.P.A., Knibbe, C.A.J., 2014. Midazolam Pharmacokinetics in Morbidly Obese Patients Following Semi-Simultaneous Oral and Intravenous Administration: A Comparison with Healthy Volunteers. *Clin Pharmacokinet* 53, 931–941. <https://doi.org/10.1007/s40262-014-0166-x>
- Brown, K., Comisar, C., Witjes, H., Maringwa, J., de Greef, R., Vishwanathan, K., Cantarini, M., Cox, E., 2017. Population pharmacokinetics and exposure-response of osimertinib in patients with non-small cell lung cancer. *Br J Clin Pharmacol* 83, 1216–1226. <https://doi.org/10.1111/bcp.13223>
- Bruix, J., Qin, S., Merle, P., Granito, A., Huang, Y.-H., Bodoky, G., Pracht, M., Yokosuka, O., Rosmorduc, O., Breder, V., Gerolami, R., Masi, G., Ross, P.J., Song, T., Bronowicki, J.-P., Ollivier-Hourmand, I., Kudo, M., Cheng, A.-L., Llovet, J.M., Finn, R.S., LeBerre, M.-A., Baumhauer, A., Meinhardt, G., Han, G., RESORCE Investigators, 2017. Regorafenib for patients with hepatocellular carcinoma who progressed on sorafenib treatment (RESORCE): a randomised, double-blind, placebo-controlled, phase 3 trial. *Lancet* 389, 56–66. [https://doi.org/10.1016/S0140-6736\(16\)32453-9](https://doi.org/10.1016/S0140-6736(16)32453-9)
- Budha, N.R., Frymoyer, A., Smelick, G.S., Jin, J.Y., Yago, M.R., Dresser, M.J., Holden, S.N., Benet, L.Z., Ware, J.A., 2012. Drug absorption interactions between oral targeted anticancer agents and PPIs: is pH-dependent solubility the Achilles heel of targeted therapy? *Clin. Pharmacol. Ther.* 92, 203–213. <https://doi.org/10.1038/clpt.2012.73>
- Burger, H., van Tol, H., Brok, M., Wiemer, E.A.C., de Bruijn, E.A., Guetens, G., de Boeck, G., Sparreboom, A., Verweij, J., Nooter, K., 2005. Chronic imatinib mesylate exposure leads to reduced intracellular drug accumulation by induction of the ABCG2 (BCRP) and ABCB1 (MDR1) drug transport pumps. *Cancer Biol. Ther.* 4, 747–752.
- Camidge, D.R., Kim, H.R., Ahn, M.-J., Yang, J.C.-H., Han, J.-Y., Lee, J.-S., Hochmair, M.J., Li, J.Y.-C., Chang, G.-C., Lee, K.H., Gridelli, C., Delmonte, A., Garcia Campelo, R., Kim, D.-W., Bearz, A., Griesinger, F., Morabito, A.,



- Felip, E., Califano, R., Ghosh, S., Spira, A., Gettinger, S.N., Tiseo, M., Gupta, N., Haney, J., Kerstein, D., Papat, S., 2018. Brigatinib versus Crizotinib in ALK-Positive Non-Small-Cell Lung Cancer. *New England Journal of Medicine* 379, 2027–2039. <https://doi.org/10.1056/NEJMoa1810171>
- Charles, K.A., Rivory, L.P., Stockler, M.R., Beale, P., Beith, J., Boyer, M., Clarke, S.J., 2006. Predicting the toxicity of weekly docetaxel in advanced cancer. *Clin Pharmacokinet* 45, 611–622. <https://doi.org/10.2165/00003088-200645060-00004>
- Choo, E.F., Ly, J., Chan, J., Shahidi-Latham, S.K., Messick, K., Plise, E., Quiason, C.M., Yang, L., 2014. Role of P-glycoprotein on the brain penetration and brain pharmacodynamic activity of the MEK inhibitor cobimetinib. *Mol. Pharm.* 11, 4199–4207. <https://doi.org/10.1021/mp500435s>
- Chow, H.-H.S., Garland, L.L., Hsu, C.-H., Vining, D.R., Chew, W.M., Miller, J.A., Perloff, M., Crowell, J.A., Alberts, D.S., 2010. Resveratrol Modulates Drug- and Carcinogen-Metabolizing Enzymes in a Healthy Volunteer Study. *Cancer Prev. Res.* 3, 1168–1175. <https://doi.org/10.1158/1940-6207.CAPR-09-0155>
- Chow, H.-H.S., Hakim, I.A., Vining, D.R., Crowell, J.A., Cordova, C.A., Chew, W.M., Xu, M.-J., Hsu, C.-H., Ranger-Moore, J., Alberts, D.S., 2006. Effects of repeated green tea catechin administration on human cytochrome P450 activity. *Cancer Epidemiol. Biomarkers Prev.* 15, 2473–2476. <https://doi.org/10.1158/1055-9965.EPI-06-0365>
- Clarke, J.L., Pao, W., Wu, N., Miller, V.A., Lassman, A.B., 2010. High dose weekly erlotinib achieves therapeutic concentrations in CSF and is effective in leptomeningeal metastases from epidermal growth factor receptor mutant lung cancer. *J. Neurooncol.* 99, 283–286. <https://doi.org/10.1007/s11060-010-0128-6>
- Costa, D.B., Kobayashi, S., Pandya, S.S., Yeo, W.-L., Shen, Z., Tan, W., Wilner, K.D., 2011. CSF concentration of the anaplastic lymphoma kinase inhibitor crizotinib. *J. Clin. Oncol.* 29, e443–445. <https://doi.org/10.1200/JCO.2010.34.1313>
- Darwich, A.S., Ogungbenro, K., Hatley, O.J., Rostami-Hodjegan, A., 2017. Role of pharmacokinetic modeling and simulation in precision dosing of anticancer drugs. *Translational Cancer Research* 6, S1512–S1529–S1529. <https://doi.org/10.21037/17108>
- Dayer, L., Heldenbrand, S., Anderson, P., Gubbins, P.O., Martin, B.C., 2013. Smartphone medication adherence apps: Potential benefits to patients and providers. *J Am Pharm Assoc (2003)* 53, 172–181. <https://doi.org/10.1331/JAPhA.2013.12202>
- de Wit, D., van Erp, N.P., den Hartigh, J., Wolterbeek, R., den Hollander-van Deursen, M., Labots, M., Guchelaar, H.-J., Verheul, H.M., Gelderblom, H., 2015. Therapeutic drug monitoring to individualize the dosing of pazopanib: a pharmacokinetic feasibility study. *Ther Drug Monit* 37, 331–338. <https://doi.org/10.1097/FTD.0000000000000141>
- Deenen, M.J., Cats, A., Beijnen, J.H., Schellens, J.H.M., 2011. Part 2: pharmacogenetic variability in drug transport and phase I anticancer drug metabolism. *Oncologist* 16, 820–834. <https://doi.org/10.1634/theoncologist.2010-0259>
- Di Marco, M.P., Edwards, D.J., Wainer, I.W., Ducharme, M.P., 2002. The effect of grapefruit juice and seville orange juice on the pharmacokinetics of dextromethorphan: the role of gut CYP3A and P-glycoprotein. *Life Sci.* 71, 1149–1160.
- Doucette, W.R., Farris, K.B., Youland, K.M., Newland, B.A., Egerton, S.J., Barnes, J.M., 2012. Development of the Drug Adherence Work-up (DRAW) tool. *J Am Pharm Assoc (2003)* 52, e199–204. <https://doi.org/10.1331/JAPhA.2012.12001>
- Dresser, G.K., Wachter, V., Wong, S., Wong, H.T., Bailey, D.G., 2002. Evaluation of peppermint oil and ascorbyl palmitate as inhibitors of cytochrome P4503A4 activity in vitro and in vivo. *Clin. Pharmacol. Ther.* 72, 247–255. <https://doi.org/10.1067/mcp.2002.126409>
- Duan, K.-M., Wang, S.-Y., Ouyang, W., Mao, Y.-M., Yang, L.-J., 2012. Effect of quercetin on CYP3A activity in Chinese healthy participants. *J Clin Pharmacol* 52, 940–946. <https://doi.org/10.1177/0091270011406278>
- Durmus, S., Hendriks, J.J.M.A., Schinkel, A.H., 2015. Apical ABC transporters and cancer chemotherapeutic drug disposition. *Adv. Cancer Res.* 125, 1–41. <https://doi.org/10.1016/bs.acr.2014.10.001>
- Edgar, B., Bailey, D., Bergstrand, R., Johnsson, G., Regårdh, C.G., 1992. Acute effects of drinking grapefruit juice on the pharmacokinetics and dynamics of felodipine--and its potential clinical relevance. *Eur. J. Clin. Pharmacol.* 42, 313–317.
- El-Sankary, W., Bombail, V., Gibson, G.G., Plant, N., 2002. Glucocorticoid-mediated induction of CYP3A4 is decreased by disruption of a protein: DNA interaction distinct from the pregnane X receptor response element. *Drug Metab. Dispos.* 30, 1029–1034.
- Fukudo, M., Ikemi, Y., Togashi, Y., Masago, K., Kim, Y.H., Mio, T., Terada, T., Teramukai, S., Mishima, M., Inui, K.-I., Katsura, T., 2013. Population pharmacokinetics/pharmacodynamics of erlotinib and pharmacogenomic analysis of plasma and cerebrospinal fluid drug concentrations in Japanese patients with non-small cell lung cancer. *Clin Pharmacokinet* 52, 593–609. <https://doi.org/10.1007/s40262-013-0058-5>
- Gao, B., Yeap, S., Clements, A., Balakrishnar, B., Wong, M., Gurney, H., 2012. Evidence for therapeutic drug monitoring of targeted anticancer therapies. *J. Clin. Oncol.* 30, 4017–4025. <https://doi.org/10.1200/JCO.2012.43.5362>
- Gelal, A., Balkan, D., Ozzeybek, D., Kaplan, Y.C., Gurler, S., Guven, H., Benowitz, N.L., 2005. Effect of menthol on the pharmacokinetics and pharmacodynamics of felodipine in healthy subjects. *Eur. J. Clin. Pharmacol.* 60, 785–790. <https://doi.org/10.1007/s00228-004-0847-8>

- Ghiculescu, R.A., 2008. Therapeutic drug monitoring: which drugs, why, when and how to do it. *Australian Prescriber* 31, 42–4. <https://doi.org/10.18773/austprescr.2008.025>
- Gorski, J.C., Huang, S.-M., Pinto, A., Hamman, M.A., Hilligoss, J.K., Zaheer, N.A., Desai, M., Miller, M., Hall, S.D., 2004. The effect of echinacea (*Echinacea purpurea* root) on cytochrome P450 activity in vivo. *Clin. Pharmacol. Ther.* 75, 89–100. <https://doi.org/10.1016/j.clpt.2003.09.013>
- Gougis, P., Wassermann, J., Spano, J.P., Keynan, N., Funck-Brentano, C., Salem, J.E., 2017. Clinical pharmacology of anti-angiogenic drugs in oncology. *Crit. Rev. Oncol. Hematol.* 119, 75–93. <https://doi.org/10.1016/j.critrevonc.2017.08.010>
- Greiff, J.M., Rowbotham, D., 1994. Pharmacokinetic drug interactions with gastrointestinal motility modifying agents. *Clin Pharmacokinet* 27, 447–461. <https://doi.org/10.2165/00003088-199427060-00004>
- Grenier, J., Fradette, C., Morelli, G., Merritt, G.J., Vranderick, M., Ducharme, M.P., 2006. Pomelo juice, but not cranberry juice, affects the pharmacokinetics of cyclosporine in humans. *Clin. Pharmacol. Ther.* 79, 255–262. <https://doi.org/10.1016/j.clpt.2005.11.010>
- Gurley, B.J., Gardner, S.F., Hubbard, M.A., Williams, D.K., Gentry, W.B., Khan, I.A., Shah, A., 2005. In vivo effects of goldenseal, kava kava, black cohosh, and valerian on human cytochrome P450 1A2, 2D6, 2E1, and 3A4/5 phenotypes. *Clin. Pharmacol. Ther.* 77, 415–426. <https://doi.org/10.1016/j.clpt.2005.01.009>
- Gurley, B.J., Swain, A., Hubbard, M.A., Hartsfield, F., Thaden, J., Williams, D.K., Gentry, W.B., Tong, Y., 2008. Supplementation with goldenseal (*Hydrastis canadensis*), but not kava kava (*Piper methysticum*), inhibits human CYP3A activity in vivo. *Clin. Pharmacol. Ther.* 83, 61–69. <https://doi.org/10.1038/sj.clpt.6100222>
- Ha, V.H., Ngo, M., Chu, M.P., Ghosh, S., Sawyer, M.B., Chambers, C.R., 2015. Does gastric acid suppression affect sunitinib efficacy in patients with advanced or metastatic renal cell cancer? *J Oncol Pharm Pract* 21, 194–200. <https://doi.org/10.1177/1078155214527145>
- Hamilton, M., Wolf, J.L., Rusk, J., Beard, S.E., Clark, G.M., Witt, K., Cagnoni, P.J., 2006. Effects of smoking on the pharmacokinetics of erlotinib. *Clin. Cancer Res.* 12, 2166–2171. <https://doi.org/10.1158/1078-0432.CCR-05-2235>
- Hayato, S., Shumaker, R., Ferry, J., Binder, T., Dutcus, C.E., Hussein, Z., 2018. Exposure–response analysis and simulation of lenvatinib safety and efficacy in patients with radioiodine-refractory differentiated thyroid cancer. *Cancer Chemother Pharmacol* 82, 971–978. <https://doi.org/10.1007/s00280-018-3687-4>
- He, M., Wei, M.-J., 2012. Reversing multidrug resistance by tyrosine kinase inhibitors. *Chin J Cancer* 31, 126–133. <https://doi.org/10.5732/cjc.011.10315>
- Hellriegel, E.T., Bjornsson, T.D., Hauck, W.W., 1996. Interpatient variability in bioavailability is related to the extent of absorption: implications for bioavailability and bioequivalence studies. *Clin. Pharmacol. Ther.* 60, 601–607. [https://doi.org/10.1016/S0009-9236\(96\)90208-8](https://doi.org/10.1016/S0009-9236(96)90208-8)
- Hilger, R.A., Richly, H., Grubert, M., Kredtke, S., Thyssen, D., Eberhardt, W., Hense, J., Schuler, M., Scheulen, M.E., 2009. Pharmacokinetics of sorafenib in patients with renal impairment undergoing hemodialysis. *Int J Clin Pharmacol Ther* 47, 61–64.
- Hirose, T., Fujita, K., Kusumoto, S., Oki, Y., Murata, Y., Sugiyama, T., Ishida, H., Shirai, T., Nakashima, M., Yamaoka, T., Okuda, K., Ohmori, T., Sasaki, Y., 2016. Association of pharmacokinetics and pharmacogenomics with safety and efficacy of gefitinib in patients with EGFR mutation positive advanced non-small cell lung cancer. *Lung Cancer* 93, 69–76. <https://doi.org/10.1016/j.lungcan.2016.01.005>
- Hornecker, M., Blanchet, B., Billefont, B., Sassi, H., Ropert, S., Taieb, F., Mir, O., Abbas, H., Harcouet, L., Coriat, R., Dauphin, A., Goldwasser, F., Tod, M., 2012. Saturable absorption of sorafenib in patients with solid tumors: a population model. *Invest New Drugs* 30, 1991–2000. <https://doi.org/10.1007/s10637-011-9760-z>
- Houk, B.E., Bello, C.L., Poland, B., Rosen, L.S., Demetri, G.D., Motzer, R.J., 2010. Relationship between exposure to sunitinib and efficacy and tolerability endpoints in patients with cancer: results of a pharmacokinetic/pharmacodynamic meta-analysis. *Cancer Chemother. Pharmacol.* 66, 357–371. <https://doi.org/10.1007/s00280-009-1170-y>
- Hughes, A.N., O'Brien, M.E.R., Petty, W.J., Chick, J.B., Rankin, E., Woll, P.J., Dunlop, D., Nicolson, M., Boinpally, R., Wolf, J., Price, A., 2009. Overcoming CYP1A1/1A2 mediated induction of metabolism by escalating erlotinib dose in current smokers. *J. Clin. Oncol.* 27, 1220–1226. <https://doi.org/10.1200/JCO.2008.19.3995>
- Huillard, O., Mir, O., Peyromaure, M., Tlemsani, C., Giroux, J., Boudou-Rouquette, P., Ropert, S., Delongchamps, N.B., Zerbib, M., Goldwasser, F., 2013. Sarcopenia and body mass index predict sunitinib-induced early dose-limiting toxicities in renal cancer patients. *Br. J. Cancer* 108, 1034–1041. <https://doi.org/10.1038/bjc.2013.58>
- Israilli, Z.H., Dayton, P.G., 2001. Human Alpha-1-Glycoprotein and Its Interactions with Drugs†,‡. *Drug Metabolism Reviews* 33, 161–235. <https://doi.org/10.1081/DMR-100104402>
- Izzedine, H., Derosa, L., Le Teuff, G., Albiges, L., Escudier, B., 2015. Hypertension and angiotensin system inhibitors: impact on outcome in sunitinib-treated patients for metastatic renal cell carcinoma. *Ann. Oncol.* 26, 1128–1133. <https://doi.org/10.1093/annonc/mdv147>
- Izzedine, H., Etienne-Grimaldi, M.C., Renée, N., Vignot, S., Milano, G., 2009. Pharmacokinetics of sunitinib in hemodialysis. *Ann. Oncol.* 20, 190–192. <https://doi.org/10.1093/annonc/mdn626>
- Jabbour, E., Saglio, G., Radich, J., Kantarjian, H., 2012. Adherence to BCR-ABL inhibitors: issues for CML therapy. *Clin Lymphoma Myeloma Leuk* 12, 223–229. <https://doi.org/10.1016/j.clml.2012.04.002>
- Janus, N., Launay-Vacher, V., Deray, G., Islam, M.S., Thyss, A., Thariat, J., 2012. [Management of targeted therapies in

- hemodialysis patients]. *Bull Cancer* 99, 381–388. <https://doi.org/10.1684/bdc.2011.1484>
- Jiang, W., Wang, X., Xu, X., Kong, L., 2010. Effect of Schisandra sphenanthera extract on the concentration of tacrolimus in the blood of liver transplant patients. *Int. J. Clin. Pharmacol. Ther.* 48, 224–229.
- Judson, I., Ma, P., Peng, B., Verweij, J., Racine, A., di Paola, E.D., van Glabbeke, M., Dimitrijevic, S., Scurr, M., Dumez, H., van Oosterom, A., 2005. Imatinib pharmacokinetics in patients with gastrointestinal stromal tumour: a retrospective population pharmacokinetic study over time. *EORTC Soft Tissue and Bone Sarcoma Group. Cancer Chemother. Pharmacol.* 55, 379–386. <https://doi.org/10.1007/s00280-004-0876-0>
- Kang, S.P., Ratain, M.J., 2010. Inconsistent labeling of food effect for oral agents across therapeutic areas: differences between oncology and non-oncology products. *Clin. Cancer Res.* 16, 4446–4451. <https://doi.org/10.1158/1078-0432.CCR-10-0663>
- Kennoki, T., Kondo, T., Kimata, N., Murakami, J., Ishimori, I., Nakazawa, H., Hashimoto, Y., Kobayashi, H., Iizuka, J., Takagi, T., Yoshida, K., Tanabe, K., 2011. Clinical results and pharmacokinetics of sorafenib in chronic hemodialysis patients with metastatic renal cell carcinoma in a single center. *Jpn. J. Clin. Oncol.* 41, 647–655. <https://doi.org/10.1093/jjco/hyr015>
- Khosravan, R., Toh, M., Garrett, M., La Fargue, J., Ni, G., Marbury, T.C., Swan, S.K., Lunde, N.M., Bello, C.L., 2010. Pharmacokinetics and safety of sunitinib malate in subjects with impaired renal function. *J Clin Pharmacol* 50, 472–481. <https://doi.org/10.1177/0091270009347868>
- Kim, A., McCully, C., Cruz, R., Cole, D.E., Fox, E., Balis, F.M., Widemann, B.C., 2012. The plasma and cerebrospinal fluid pharmacokinetics of sorafenib after intravenous administration in non-human primates. *Invest New Drugs* 30, 524–528. <https://doi.org/10.1007/s10637-010-9585-1>
- Kim, K., Ryu, M.-H., Yoo, C., Ryoo, B.-Y., Choi, D.R., Chang, H.M., Lee, J.-L., Beck, M.Y., Kim, T.W., Kang, Y.-K., 2011. Nilotinib in patients with GIST who failed imatinib and sunitinib: importance of prior surgery on drug bioavailability. *Cancer Chemother. Pharmacol.* 68, 285–291. <https://doi.org/10.1007/s00280-010-1479-6>
- Kletzl, H., Giraudon, M., Ducray, P.S., Abt, M., Hamilton, M., Lum, B.L., 2015. Effect of gastric pH on erlotinib pharmacokinetics in healthy individuals: omeprazole and ranitidine. *Anticancer Drugs* 26, 565–572. <https://doi.org/10.1097/CAD.0000000000000212>
- Kloth, J.S.L., Binkhorst, L., de Wit, A.S., de Bruijn, P., Hamberg, P., Lam, M.H., Burger, H., Chaves, I., Wiemer, E.A.C., van der Horst, G.T.J., Mathijssen, R.H.J., 2015. Relationship Between Sunitinib Pharmacokinetics and Administration Time: Preclinical and Clinical Evidence. *Clin Pharmacokinet* 54, 851–858. <https://doi.org/10.1007/s40262-015-0239-5>
- Kloth, J.S.L., Verboom, M.C., Swen, J.J., van der Straaten, T., Sleijfer, S., Reyners, A.K.L., Steeghs, N., Gelderblom, H., Guchelaar, H.J., Mathijssen, R.H.J., 2018. Genetic polymorphisms as predictive biomarker of survival in patients with gastrointestinal stromal tumors treated with sunitinib. *Pharmacogenomics J.* 18, 49–55. <https://doi.org/10.1038/tpj.2016.83>
- Klümper, H.-J., Samer, C.F., Mathijssen, R.H.J., Schellens, J.H.M., Gurney, H., 2011. Moving towards dose individualization of tyrosine kinase inhibitors. *Cancer Treat. Rev.* 37, 251–260. <https://doi.org/10.1016/j.ctrv.2010.08.006>
- Kobayashi, H., Sato, K., Niioka, T., Miura, H., Ito, H., Miura, M., 2015. Relationship Among Gefitinib Exposure, Polymorphisms of Its Metabolizing Enzymes and Transporters, and Side Effects in Japanese Patients With Non-Small-Cell Lung Cancer. *Clin Lung Cancer* 16, 274–281. <https://doi.org/10.1016/j.clcc.2014.12.004>
- Kroiss, M., Quinkler, M., Johanssen, S., van Erp, N.P., Lankheet, N., Pöllinger, A., Laubner, K., Strasburger, C.J., Hahner, S., Müller, H.-H., Allolio, B., Fassnacht, M., 2012. Sunitinib in refractory adrenocortical carcinoma: a phase II, single-arm, open-label trial. *J. Clin. Endocrinol. Metab.* 97, 3495–3503. <https://doi.org/10.1210/jc.2012-1419>
- Lacy, S., Nielsen, J., Yang, B., Miles, D., Nguyen, L., Hutmacher, M., 2018. Population exposure-response analysis of cabozantinib efficacy and safety endpoints in patients with renal cell carcinoma. *Cancer Chemother. Pharmacol.* 81, 1061–1070. <https://doi.org/10.1007/s00280-018-3579-7>
- Lankheet, N. a. G., Kloth, J.S.L., Gadellaa-van Hooijdonk, C.G.M., Cirkel, G.A., Mathijssen, R.H.J., Lolkema, M.P.J.K., Schellens, J.H.M., Voest, E.E., Sleijfer, S., de Jonge, M.J.A., Haanen, J.B. a. G., Beijnen, J.H., Huitema, A.D.R., Steeghs, N., 2014. Pharmacokinetically guided sunitinib dosing: a feasibility study in patients with advanced solid tumours. *British Journal of Cancer* 110, 2441–2449. <https://doi.org/10.1038/bjc.2014.194>
- Lemahieu, W.P.D., Maes, B.D., Ghoo, Y., Rutgeerts, P., Verbeke, K., Vanrenterghem, Y., 2003. Measurement of hepatic and intestinal CYP3A4 and PGP activity by combined po + iv [14C]erythromycin breath and urine test. *Am. J. Physiol. Gastrointest. Liver Physiol.* 285, G470–482. <https://doi.org/10.1152/ajpgi.00028.2003>
- Lin, N.U., Carey, L.A., Liu, M.C., Younger, J., Come, S.E., Ewend, M., Harris, G.J., Bullitt, E., Van den Abbeele, A.D., Henson, J.W., Li, X., Gelman, R., Burstein, H.J., Kasparian, E., Kirsch, D.G., Crawford, A., Hochberg, F., Winer, E.P., 2008. Phase II trial of lapatinib for brain metastases in patients with human epidermal growth factor receptor 2-positive breast cancer. *J. Clin. Oncol.* 26, 1993–1999. <https://doi.org/10.1200/JCO.2007.12.3588>
- Lin, N.U., Diéras, V., Paul, D., Lossignol, D., Christodoulou, C., Stemmler, H.-J., Roché, H., Liu, M.C., Greil, R., Ciruelos, E., Loibl, S., Gori, S., Wardley, A., Yardley, D., Brufsky, A., Blum, J.L., Rubin, S.D., Dharan, B., Stepkowski, K., Zembryki, D., Oliva, C., Roychowdhury, D., Paoletti, P., Winer, E.P., 2009. Multicenter phase

- II study of lapatinib in patients with brain metastases from HER2-positive breast cancer. *Clin. Cancer Res.* 15, 1452–1459. <https://doi.org/10.1158/1078-0432.CCR-08-1080>
- Liu, H., Artz, A.S., 2011. Reduction of imatinib absorption after gastric bypass surgery. *Leuk. Lymphoma* 52, 310–313. <https://doi.org/10.3109/10428194.2010.532890>
- Llovet, J.M., Ricci, S., Mazzaferro, V., Hilgard, P., Gane, E., Blanc, J.-F., de Oliveira, A.C., Santoro, A., Raoul, J.-L., Forner, A., Schwartz, M., Porta, C., Zeuzem, S., Bolondi, L., Greten, T.F., Galle, P.R., Seitz, J.-F., Borbath, I., Häussinger, D., Giannaris, T., Shan, M., Moscovici, M., Voliotis, D., Bruix, J., SHARP Investigators Study Group, 2008. Sorafenib in advanced hepatocellular carcinoma. *N. Engl. J. Med.* 359, 378–390. <https://doi.org/10.1056/NEJMoa0708857>
- Malati, C.Y., Robertson, S.M., Hunt, J.D., Chairez, C., Alfaro, R.M., Kovacs, J.A., Penzak, S.R., 2012. Influence of Panax ginseng on cytochrome P450 (CYP)3A and P-glycoprotein (P-gp) activity in healthy participants. *J Clin Pharmacol* 52, 932–939. <https://doi.org/10.1177/0091270011407194>
- Manning, G., Whyte, D.B., Martinez, R., Hunter, T., Sudarsanam, S., 2002. The protein kinase complement of the human genome. *Science* 298, 1912–1934. <https://doi.org/10.1126/science.1075762>
- Marcum, Z.A., Hanlon, J.T., Murray, M.D., 2017. Improving Medication Adherence and Health Outcomes in Older Adults: An Evidence-Based Review of Randomized Controlled Trials. *Drugs Aging* 34, 191–201. <https://doi.org/10.1007/s40266-016-0433-7>
- Markowitz, J.S., DeVane, C.L., Boulton, D.W., Carson, S.W., Nahas, Z., Risch, S.C., 2000. Effect of St. John's wort (*Hypericum perforatum*) on cytochrome P-450 2D6 and 3A4 activity in healthy volunteers. *Life Sci.* 66, PL133-139.
- Markowitz, J.S., Donovan, J.L., Lindsay DeVane, C., Sipkes, L., Chavin, K.D., 2003. Multiple-dose administration of Ginkgo biloba did not affect cytochrome P-450 2D6 or 3A4 activity in normal volunteers. *J Clin Psychopharmacol* 23, 576–581. <https://doi.org/10.1097/01.jcp.0000095340.32154.c6>
- Masini, C., Sabbatini, R., Porta, C., Procopio, G., Di Lorenzo, G., Onofri, A., Buti, S., Iacovelli, R., Invernizzi, R., Moschetti, L., Aste, M.G., Pagano, M., Grosso, F., Lucia Manenti, A., Ortega, C., Cosmai, L., Del Giovane, C., Conte, P.F., 2012. Use of tyrosine kinase inhibitors in patients with metastatic kidney cancer receiving haemodialysis: a retrospective Italian survey. *BJU Int.* 110, 692–698. <https://doi.org/10.1111/j.1464-410X.2012.10946.x>
- McCue, D.A., Lohr, L.K., Pick, A.M., 2014. Improving adherence to oral cancer therapy in clinical practice. *Pharmacotherapy* 34, 481–494.
- Miller, A.A., Murry, D.J., Owzar, K., Hollis, D.R., Kennedy, E.B., Abou-Alfa, G., Desai, A., Hwang, J., Villalona-Calero, M.A., Dees, E.C., Lewis, L.D., Fakih, M.G., Edelman, M.J., Millard, F., Frank, R.C., Hohl, R.J., Ratain, M.J., 2009. Phase I and pharmacokinetic study of sorafenib in patients with hepatic or renal dysfunction: CALGB 60301. *J. Clin. Oncol.* 27, 1800–1805. <https://doi.org/10.1200/JCO.2008.20.0931>
- Miller, A.A., Murry, D.J., Owzar, K., Hollis, D.R., Lewis, L.D., Kindler, H.L., Marshall, J.L., Villalona-Calero, M.A., Edelman, M.J., Hohl, R.J., Lichtman, S.M., Ratain, M.J., 2007. Phase I and pharmacokinetic study of erlotinib for solid tumors in patients with hepatic or renal dysfunction: CALGB 60101. *J. Clin. Oncol.* 25, 3055–3060. <https://doi.org/10.1200/JCO.2007.11.6210>
- Milton, D.T., Azzoli, C.G., Heelan, R.T., Venkatraman, E., Gomez, J.E., Kris, M.G., Krug, L.M., Pao, W., Rizvi, N.A., Dunne, M., Miller, V.A., 2006. A phase I/II study of weekly high-dose erlotinib in previously treated patients with nonsmall cell lung cancer. *Cancer* 107, 1034–1041. <https://doi.org/10.1002/cncr.22088>
- Mir, O., Blanchet, B., Goldwasser, F., 2011. Drug-induced effects on erlotinib metabolism. *N. Engl. J. Med.* 365, 379–380. <https://doi.org/10.1056/NEJMc1105083>
- Mir, O., Poinsignon, V., Arnedos, M., Delalogue, S., Paci, A., 2015. Pharmacokinetic interaction involving fenofibrate and everolimus. *Ann. Oncol.* 26, 248–249. <https://doi.org/10.1093/annonc/mdu492>
- Mittapalli, R.K., Vaidhyanathan, S., Dudek, A.Z., Elmquist, W.F., 2013. Mechanisms limiting distribution of the threonine-protein kinase B-RaF(V600E) inhibitor dabrafenib to the brain: implications for the treatment of melanoma brain metastases. *J. Pharmacol. Exp. Ther.* 344, 655–664. <https://doi.org/10.1124/jpet.112.201475>
- Mittapalli, R.K., Vaidhyanathan, S., Sane, R., Elmquist, W.F., 2012. Impact of P-glycoprotein (ABCB1) and breast cancer resistance protein (ABCG2) on the brain distribution of a novel BRAF inhibitor: vemurafenib (PLX4032). *J. Pharmacol. Exp. Ther.* 342, 33–40. <https://doi.org/10.1124/jpet.112.192195>
- Nanjo, S., Hata, A., Okuda, C., Kaji, R., Okada, H., Tamura, D., Irie, K., Okada, H., Fukushima, S., Katakami, N., 2018. Standard-dose osimertinib for refractory leptomeningeal metastases in T790M-positive EGFR-mutant non-small cell lung cancer. *Br. J. Cancer* 118, 32–37. <https://doi.org/10.1038/bjc.2017.394>
- Ngo, N., Yan, Z., Graf, T.N., Carrizosa, D.R., Kashuba, A.D.M., Dees, E.C., Oberlies, N.H., Paine, M.F., 2009. Identification of a cranberry juice product that inhibits enteric CYP3A-mediated first-pass metabolism in humans. *Drug Metab. Dispos.* 37, 514–522. <https://doi.org/10.1124/dmd.108.024968>
- Oberoi, R.K., Mittapalli, R.K., Elmquist, W.F., 2013. Pharmacokinetic assessment of efflux transport in sunitinib distribution to the brain. *J. Pharmacol. Exp. Ther.* 347, 755–764. <https://doi.org/10.1124/jpet.113.208959>
- Onaka, T., Takahashi, N., Miura, M., Yonezawa, A., Imada, K., Sawada, K., 2012. Pharmacokinetics of nilotinib in imatinib-resistant/intolerant chronic myeloid leukemia patients on hemodialysis for chronic renal failure. *Am. J. Hematol.* 87, 451. <https://doi.org/10.1002/ajh.23125>
- Pavlovsky, C., Egorin, M.J., Shah, D.D., Beumer, J.H., Rogel, S., Pavlovsky, S., 2009. Imatinib mesylate

- pharmacokinetics before and after sleeve gastrectomy in a morbidly obese patient with chronic myeloid leukemia. *Pharmacotherapy* 29, 1152–1156. <https://doi.org/10.1592/phco.29.9.1152>
- Penzak, S.R., Robertson, S.M., Hunt, J.D., Chairez, C., Malati, C.Y., Alfaro, R.M., Stevenson, J.M., Kovacs, J.A., 2010. Echinacea purpurea significantly induces cytochrome P450 3A activity but does not alter lopinavir-ritonavir exposure in healthy subjects. *Pharmacotherapy* 30, 797–805. <https://doi.org/10.1592/phco.30.8.797>
- Peters, S., Camidge, D.R., Shaw, A.T., Gadgeel, S., Ahn, J.S., Kim, D.-W., Ou, S.-H.I., Pérol, M., Dziadziuszko, R., Rosell, R., Zeaiter, A., Mitry, E., Golding, S., Balas, B., Noe, J., Morcos, P.N., Mok, T., 2017. Alectinib versus Crizotinib in Untreated ALK-Positive Non-Small-Cell Lung Cancer. *New England Journal of Medicine* 377, 829–838. <https://doi.org/10.1056/NEJMoa1704795>
- Planchard, D., 2017. AZD3759 for CNS metastases in EGFR-mutant lung cancer. *The Lancet Respiratory Medicine* 5, 841–842. [https://doi.org/10.1016/S2213-2600\(17\)30395-8](https://doi.org/10.1016/S2213-2600(17)30395-8)
- Poulton, E.J., Levy, L., Lampe, J.W., Shen, D.D., Tracy, J., Shuhart, M.C., Thummel, K.E., Eaton, D.L., 2013. Sulforaphane is not an effective antagonist of the human pregnane X-receptor in vivo. *Toxicol. Appl. Pharmacol.* 266, 122–131. <https://doi.org/10.1016/j.taap.2012.10.029>
- Reinwald, M., Schleyer, E., Kiewe, P., Blau, I.W., Burmeister, T., Pursche, S., Neumann, M., Notter, M., Thiel, E., Hofmann, W.-K., Kolb, H.-J., Burdach, S., Bender, H.-U., 2014. Efficacy and pharmacologic data of second-generation tyrosine kinase inhibitor nilotinib in BCR-ABL-positive leukemia patients with central nervous system relapse after allogeneic stem cell transplantation. *Biomed Res Int* 2014, 637059. <https://doi.org/10.1155/2014/637059>
- Reungwetwattana, T., Nakagawa, K., Cho, B.C., Cobo, M., Cho, E.K., Bertolini, A., Bohnet, S., Zhou, C., Lee, K.H., Nogami, N., Okamoto, I., Leighl, N., Hodge, R., McKeown, A., Brown, A.P., Rukazenkov, Y., Ramalingam, S.S., Vansteenkiste, J., 2018. CNS Response to Osimertinib Versus Standard Epidermal Growth Factor Receptor Tyrosine Kinase Inhibitors in Patients With Untreated EGFR-Mutated Advanced Non-Small-Cell Lung Cancer. *J. Clin. Oncol.* JCO2018783118. <https://doi.org/10.1200/JCO.2018.78.3118>
- Rezaee, M.M., Kazemi, S., Kazemi, M.T., Gharooee, S., Yazdani, E., Gharooee, H., Shiran, M.R., Moghadammia, A.A., 2014. The effect of piperine on midazolam plasma concentration in healthy volunteers, a research on the CYP3A-involving metabolism. *Daru* 22, 8. <https://doi.org/10.1186/2008-2231-22-8>
- Robertson, G.R., Liddle, C., Clarke, S.J., 2008a. Inflammation and altered drug clearance in cancer: transcriptional repression of a human CYP3A4 transgene in tumor-bearing mice. *Clin. Pharmacol. Ther.* 83, 894–897. <https://doi.org/10.1038/clpt.2008.55>
- Robertson, G.R., Liddle, C., Clarke, S.J., 2008b. Inflammation and Altered Drug Clearance in Cancer: Transcriptional Repression of a Human CYP3A4 Transgene in Tumor-bearing Mice. *Clinical Pharmacology & Therapeutics* 83, 894–897. <https://doi.org/10.1038/clpt.2008.55>
- Sakai, H., Hayashi, H., Iwasa, T., Hasegawa, Y., Takeda, M., Nakagawa, K., 2017. Successful osimertinib treatment for leptomeningeal carcinomatosis from lung adenocarcinoma with the T790M mutation of EGFR. *ESMO Open* 2, e000104. <https://doi.org/10.1136/esmoopen-2016-000104>
- Saleem, M., Dimeski, G., Kirkpatrick, C.M., Taylor, P.J., Martin, J.H., 2012. Target concentration intervention in oncology: where are we at? *Ther Drug Monit* 34, 257–265. <https://doi.org/10.1097/FTD.0b013e3182557342>
- Schmidinger, M., Vogl, U.M., Bojic, M., Lamm, W., Heinzl, H., Haitel, A., Clodi, M., Kramer, G., Zielinski, C.C., 2011. Hypothyroidism in patients with renal cell carcinoma. *Cancer* 117, 534–544. <https://doi.org/10.1002/cncr.25422>
- Shetty, A.V., Matrana, M.R., Atkinson, B.J., Flaherty, A.L., Jonasch, E., Tannir, N.M., 2014. Outcomes of patients with metastatic renal cell carcinoma and end-stage renal disease receiving dialysis and targeted therapies: a single institution experience. *Clin Genitourin Cancer* 12, 348–353. <https://doi.org/10.1016/j.clgc.2014.01.004>
- Shibata, S.I., Chung, V., Synold, T.W., Longmate, J.A., Suttle, A.B., Ottesen, L.H., Lenz, H.-J., Kummar, S., Harvey, R.D., Hamilton, A.L., O'Neil, B.H., Sarantopoulos, J., LoRusso, P., Rudek, M.A., Dowlati, A., Mulkerin, D.L., Belani, C.P., Gandhi, L., Lau, S.C., Ivy, S.P., Newman, E.M., 2013. Phase I study of pazopanib in patients with advanced solid tumors and hepatic dysfunction: a National Cancer Institute Organ Dysfunction Working Group study. *Clin. Cancer Res.* 19, 3631–3639. <https://doi.org/10.1158/1078-0432.CCR-12-3214>
- Solms, A., Reinecke, I., Fiala-Buskies, S., Keunecke, A., Drenth, H.-J., Bruix, J., Meinhardt, G., Cleton, A., Ploeger, B., 2017. Exposure-response relationship of regorafenib efficacy in patients with hepatocellular carcinoma. *Eur J Pharm Sci* 109S, S149–S153. <https://doi.org/10.1016/j.ejps.2017.05.050>
- Sternberg, C.N., Donskov, F., Haas, N.B., Doehn, C., Russo, P., Elmeliogy, M., Baneyx, G., Banerjee, H., Aimone, P., Motzer, R.J., 2018. Pazopanib Exposure Relationship with Clinical Efficacy and Safety in the Adjuvant Treatment of Advanced Renal Cell Carcinoma. *Clin. Cancer Res.* 24, 3005–3013. <https://doi.org/10.1158/1078-0432.CCR-17-2652>
- Strumberg, D., Clark, J.W., Awada, A., Moore, M.J., Richly, H., Hendlisch, A., Hirte, H.W., Eder, J.P., Lenz, H.-J., Schwartz, B., 2007. Safety, pharmacokinetics, and preliminary antitumor activity of sorafenib: a review of four phase I trials in patients with advanced refractory solid tumors. *Oncologist* 12, 426–437. <https://doi.org/10.1634/theoncologist.12-4-426>
- Szałek, E., Karbownik, A., Sobańska, K., Połom, W., Grabowski, T., Wolc, A., Matuszewski, M., Grześkowiak, E., 2014. The influence of the time-of-day administration of the drug on the pharmacokinetics of sunitinib in rabbits. *Eur Rev Med Pharmacol Sci* 18, 2393–2399.

- Tan, A.R., Gibbon, D.G., Stein, M.N., Lindquist, D., Edenfield, J.W., Martin, J.C., Gregory, C., Suttle, A.B., Tada, H., Botbyl, J., Stephenson, J.J., 2013. Effects of ketoconazole and esomeprazole on the pharmacokinetics of pazopanib in patients with solid tumors. *Cancer Chemother. Pharmacol.* 71, 1635–1643. <https://doi.org/10.1007/s00280-013-2164-3>
- Tod, M., Mir, O., Bancelin, N., Coriat, R., Thomas-Schoemann, A., Taieb, F., Boudou-Rouquette, P., Ropert, S., Michels, J., Abbas, H., Durand, J.P., Dauphin, A., Vidal, M., Goldwasser, F., Blanchet, B., 2011. Functional and clinical evidence of the influence of sorafenib binding to albumin on sorafenib disposition in adult cancer patients. *Pharm. Res.* 28, 3199–3207. <https://doi.org/10.1007/s11095-011-0499-1>
- Togashi, Y., Masago, K., Fukudo, M., Terada, T., Ikemi, Y., Kim, Y.H., Fujita, S., Irisa, K., Sakamori, Y., Mio, T., Inui, K.-I., Mishima, M., 2010. Pharmacokinetics of erlotinib and its active metabolite OSI-420 in patients with non-small cell lung cancer and chronic renal failure who are undergoing hemodialysis. *J Thorac Oncol* 5, 601–605. <https://doi.org/10.1097/JTO.0b013e3181d32287>
- Togashi, Y., Masago, K., Masuda, S., Mizuno, T., Fukudo, M., Ikemi, Y., Sakamori, Y., Nagai, H., Kim, Y.H., Katsura, T., Mishima, M., 2012. Cerebrospinal fluid concentration of gefitinib and erlotinib in patients with non-small cell lung cancer. *Cancer Chemother. Pharmacol.* 70, 399–405. <https://doi.org/10.1007/s00280-012-1929-4>
- Treiber, G., Wex, T., Schleyer, E., Troeger, U., Hosius, C., Malfertheiner, P., 2008. Imatinib for hepatocellular cancer--focus on pharmacokinetic/pharmacodynamic modelling and liver function. *Cancer Lett.* 260, 146–154. <https://doi.org/10.1016/j.canlet.2007.10.041>
- Tu, J.-H., Hu, D.-L., Dai, L.-L., Sun, Y., Fan, L., Zhang, M., Tan, Z.-R., Chen, Y., Li, Z., Zhou, H.-H., 2010. Effect of glycyrrhizin on CYP2C19 and CYP3A4 activity in healthy volunteers with different CYP2C19 genotypes. *Xenobiotica* 40, 393–399. <https://doi.org/10.3109/00498251003748095>
- Uchida, S., Yamada, H., Li, X.D., Maruyama, S., Ohmori, Y., Oki, T., Watanabe, H., Umegaki, K., Ohashi, K., Yamada, S., 2006. Effects of Ginkgo biloba extract on pharmacokinetics and pharmacodynamics of tolbutamide and midazolam in healthy volunteers. *J Clin Pharmacol* 46, 1290–1298. <https://doi.org/10.1177/0091270006292628>
- Vaidhyanathan, S., Mittapalli, R.K., Sarkaria, J.N., Elmquist, W.F., 2014. Factors influencing the CNS distribution of a novel MEK-1/2 inhibitor: implications for combination therapy for melanoma brain metastases. *Drug Metab. Dispos.* 42, 1292–1300. <https://doi.org/10.1124/dmd.114.058339>
- van Erp, N., Gelderblom, H., van Glabbeke, M., Van Oosterom, A., Verweij, J., Guchelaar, H.-J., Debiec-Rychter, M., Peng, B., Blay, J.-Y., Judson, I., 2008. Effect of cigarette smoking on imatinib in patients in the soft tissue and bone sarcoma group of the EORTC. *Clin. Cancer Res.* 14, 8308–8313. <https://doi.org/10.1158/1078-0432.CCR-08-1303>
- van Erp, N.P., Guchelaar, H.-J., Ploeger, B.A., Romijn, J.A., Hartigh, J. den, Gelderblom, H., 2011. Mitotane has a strong and a durable inducing effect on CYP3A4 activity. *Eur. J. Endocrinol.* 164, 621–626. <https://doi.org/10.1530/EJE-10-0956>
- van Leeuwen, R.W.F., van Gelder, T., Mathijssen, R.H.J., Jansman, F.G.A., 2014. Drug-drug interactions with tyrosine-kinase inhibitors: a clinical perspective. *Lancet Oncol.* 15, e315-326. [https://doi.org/10.1016/S1470-2045\(13\)70579-5](https://doi.org/10.1016/S1470-2045(13)70579-5)
- van Leeuwen RW, Peric R, Hussaarts KG, Kienhuis E, IJzerman NS, de Bruijn P. Influence of the Acidic Beverage Cola on the Absorption of Erlotinib in Patients With Non-Small-Cell Lung Cancer. *J Clin Oncol.* 2016 Apr 20;34(12):1309-14.
- van Rongen, A., Brill, M.J.E., Vaughns, J.D., Väitalo, P.A.J., van Dongen, E.P.A., van Ramshorst, B., Barrett, J.S., van den Anker, J.N., Knibbe, C.A.J., 2018. Higher Midazolam Clearance in Obese Adolescents Compared with Morbidly Obese Adults. *Clin Pharmacokinet* 57, 601–611. <https://doi.org/10.1007/s40262-017-0579-4>
- Verboom, M.C., Kloth, J.S.L., Swen, J.J., van der Straaten, T., Bovée, J.V.M.G., Sleijfer, S., Reyners, A.K.L., Mathijssen, R.H.J., Guchelaar, H.-J., Steeghs, N., Gelderblom, H., 2017. Genetic polymorphisms in angiogenesis-related genes are associated with worse progression-free survival of patients with advanced gastrointestinal stromal tumours treated with imatinib. *Eur. J. Cancer* 86, 226–232. <https://doi.org/10.1016/j.ejca.2017.09.025>
- Verheijen, R.B., Bins, S., Mathijssen, R.H.J., Lolkema, M.P., van Doorn, L., Schellens, J.H.M., Beijnen, J.H., Langenberg, M.H.G., Huitema, A.D.R., Steeghs, N., Dutch Pharmacology Oncology Group, 2016. Individualized Pazopanib Dosing: A Prospective Feasibility Study in Cancer Patients. *Clin. Cancer Res.* 22, 5738–5746. <https://doi.org/10.1158/1078-0432.CCR-16-1255>
- Visser, M., Kritchevsky, S.B., Newman, A.B., Goodpaster, B.H., Tylavsky, F.A., Nevitt, M.C., Harris, T.B., 2005. Lower serum albumin concentration and change in muscle mass: the Health, Aging and Body Composition Study. *Am. J. Clin. Nutr.* 82, 531–537. <https://doi.org/10.1093/ajcn.82.3.531>
- Wang, D., Wang, M.-L., Li, Y.-H., 2017. Quantitative MRI study of the permeability of peritumoral brain edema in lung cancer patients with brain metastases. *Brain Res.* 1669, 126–130. <https://doi.org/10.1016/j.brainres.2017.06.016>
- Weinstein, I.B., Joe, A., 2008. Oncogene Addiction. *Cancer Res* 68, 3077–3080. <https://doi.org/10.1158/0008-5472.CAN-07-3293>
- Wind, S., Giessmann, T., Jungnik, A., Brand, T., Marzin, K., Bertulis, J., Hocke, J., Gansser, D., Stopfer, P., 2014. Pharmacokinetic drug interactions of afatinib with rifampicin and ritonavir. *Clin Drug Investig* 34, 173–182.

<https://doi.org/10.1007/s40261-013-0161-2>

- Wind, S., Schnell, D., Ebner, T., Freiwald, M., Stopfer, P., 2017. Clinical Pharmacokinetics and Pharmacodynamics of Afatinib. *Clin Pharmacokinet* 56, 235–250. <https://doi.org/10.1007/s40262-016-0440-1>
- Xiao, C.-Q., Chen, R., Lin, J., Wang, G., Chen, Y., Tan, Z.-R., Zhou, H.-H., 2012. Effect of genistein on the activities of cytochrome P450 3A and P-glycoprotein in Chinese healthy participants. *Xenobiotica* 42, 173–178. <https://doi.org/10.3109/00498254.2011.615954>
- Xin, H.-W., Wu, X.-C., Li, Q., Yu, A.-R., Xiong, L., 2009. Effects of Schisandra sphenanthera extract on the pharmacokinetics of midazolam in healthy volunteers. *Br. J. Clin. Pharmacol.* 67, 541–546. <https://doi.org/10.1111/j.1365-2125.2009.03383.x>
- Xin, H.-W., Wu, X.-C., Li, Q., Yu, A.-R., Zhong, M.-Y., Liu, Y.-Y., 2006. The effects of berberine on the pharmacokinetics of cyclosporin A in healthy volunteers. *Methods Find Exp Clin Pharmacol* 28, 25–29. <https://doi.org/10.1358/mf.2006.28.1.962774>
- Xin, S., Zhao, Y., Wang, X., Huang, Y., Zhang, J., Guo, Y., Li, J., Li, H., Ma, Y., Chen, L., Hu, Z., Huang, M., Zhang, L., 2015. The Dissociation of Gefitinib Trough Concentration and Clinical Outcome in NSCLC Patients with EGFR Sensitive Mutations. *Sci Rep* 5. <https://doi.org/10.1038/srep12675>
- Yang, J.C.-H., Cho, B.C., Kim, D.-W., Kim, S.-W., Lee, J.-S., Su, W.-C., John, T., Kao, S.C.-H., Natale, R., Goldman, J.W., Overend, P., Vishwanathan, K., Ye, X., Yang, Z., Ahn, M.-J., 2017. Osimertinib for patients (pts) with leptomeningeal metastases (LM) from EGFR-mutant non-small cell lung cancer (NSCLC): Updated results from the BLOOM study. *JCO* 35, 2020–2020. [https://doi.org/10.1200/JCO.2017.35.15\\_suppl.2020](https://doi.org/10.1200/JCO.2017.35.15_suppl.2020)
- Ye, L., Yang, X., Guo, E., Chen, W., Lu, L., Wang, Y., Peng, X., Yan, T., Zhou, F., Liu, Z., 2014. Sorafenib metabolism is significantly altered in the liver tumor tissue of hepatocellular carcinoma patient. *PLoS ONE* 9, e96664. <https://doi.org/10.1371/journal.pone.0096664>
- Yu H, van Erp N, Bins S, Mathijssen RHJ, Schellens JHM, Beijnen JH, et al. Development of a pharmacokinetic model to describe the complex pharmacokinetics of pazopanib in cancer patients. *Clin Pharmacokinet* 2016 Aug 17
- Yin, O.Q.P., Gallagher, N., Fischer, D., Demirhan, E., Zhou, W., Golor, G., Schran, H., 2010. Effect of the proton pump inhibitor esomeprazole on the oral absorption and pharmacokinetics of nilotinib. *J Clin Pharmacol* 50, 960–967. <https://doi.org/10.1177/0091270009346061>
- Zevin, S., Benowitz, N.L., 1999. Drug interactions with tobacco smoking. An update. *Clin Pharmacokinet* 36, 425–438. <https://doi.org/10.2165/00003088-199936060-00004>
- Zhang, J., Yu, J., Sun, X., Meng, X., 2014. Epidermal growth factor receptor tyrosine kinase inhibitors in the treatment of central nerve system metastases from non-small cell lung cancer. *Cancer Lett.* 351, 6–12. <https://doi.org/10.1016/j.canlet.2014.04.019>
- Zheng, M., Sun, H., Xu, J., Yang, G., Huo, L., Zhang, P., Tian, J., Yang, K., 2016. Combining Whole-Brain Radiotherapy with Gefitinib/Erlotinib for Brain Metastases from Non-Small-Cell Lung Cancer: A Meta-Analysis. *Biomed Res Int* 2016. <https://doi.org/10.1155/2016/5807346>