Variation exists in patient response on analgesic treatment in terms of efficacy and safety. This variation may be in part explained by pharmacogenomics. This paper aimed to review data on pharmacogenomics of opioid analgesics focusing on the effect of genetic variation on the efficacy and safety of these agents. Current evidence suggests that pharmacogenomics contribute to variation in efficacy and safety of opioids. However, most data come from case control studies and case reports. In addition, a recognized drawback in the field of pharmacogenomics is the common occurrence of false positive association between polymorphisms and the investigated outcome. Prospective studies are needed to further elucidate the clinical implications of available data as well as to define the guidelines for the clinical application of pharmacogenomic data. Furthermore, basic research should focus on the identification of biologically meaningful polymorphisms enabling a hypothesis with biological plausibility driven research in the field of pharmacogenomics of analgesics. Moreover, the publication of relevant negative results should be favoured.

1. Introduction

There is great variation in the response of individuals to standard doses of drug therapy that can lead to treatment failure or to life-threatening adverse drug reactions among patients with identical doses of the same drug. A drug's activity is the result of the interaction of the drug with proteins involved in absorption, distribution, metabolism, elimination (ADME proteins), and molecular drug targets or target pathways. Genetic variation in these proteins, that is, single nucleotide polymorphisms in genes coding for metabolizing enzymes or drug transporters, might have a significant influence on the drug effect. Pharmacogenomics investigates interindividual genetic variability in DNA sequence of drug targets, drug metabolizing enzymes or disease genes, RNA expression, or protein translation of genes affecting drug response and drug safety [1].

Although clinical trials including thousands of patients may generally indicate efficacy and lack of toxicity of drugs, it is well known that it is not possible to predict a priori whether an individual patient will respond to a given medication without adverse effects. Individual variability in drug response can be explained by a number of parameters including age, gender, weight, pharmacokinetics, disease severity, concomitant diseases, and environmental factors. Moreover, genetic differences among individuals in drug metabolism and/or cellular drug targets may explain a significant component of this variability [2]. In particular interindividual variability in drug metabolism is a major cause of adverse drug effects. In many cases, such variability is linked to polymorphisms in genes coding for drug-metabolizing enzymes. Individuals carrying enzyme-inactivating mutations display impaired drug metabolism. Thus, carriers of inactivating mutations when treated at standard doses have higher plasma drug concentrations and lower clearance rates, rendering them susceptible to adverse drug reactions [3]. There are two types of adverse drug reactions, Type A and Type B. Type A adverse drug reactions are dose-dependent, referring to the augmentation of pharmacological action. Polymorphisms of pharmacokinetic genes may be important for narrow therapeutic window drugs, with poor metabolizers having increased risk of Type A adverse drug reactions. Polymorphisms of drug targets may be also important for this type of adverse drug reactions. Type B idiosyncratic adverse drug reactions are not predicted by the pharmacological action. Idiosyncratic adverse drug reactions are thought to account for up to
20% of all adverse drug reactions, although some researchers regard this as an overestimate, with 5% being closer to reality [4]. Genetic variations of pharmacokinetic genes have been implicated in the aetiology of some idiosyncratic adverse drug reactions.

Narcotic analgesics are widely used for the treatment of severe pain, especially cancer pain. Morphine and other mu-opioid agonists are among the most commonly prescribed narcotic analgesics for moderate to severe pain. There is great variation in human response to opioid analgesia. This variation could be explained by genetic variation in metabolizing enzymes and transporters mediating opioid pharmacokinetics as well as by genetic variation in receptors and signal transduction elements mediating pharmacodynamics. This paper aims to review data on pharmacogenomics of opioid analgesics.

2. Pharmacogenomics of Opioid Receptors and Opioid Analgesics

The pharmacologic actions of opioids are mediated through their interaction with the opioid receptors that are G-protein coupled receptors located in the brain and spinal cord. Three subtypes have been cloned, mu-opioid receptors, kappa-opioid receptors, and delta-opioid receptors. Delta receptors are the natural targets of enkephalins. The mu-opioid receptor is the primary site of action of opioid analgesics including morphine, fentanyl, and methadone. Although most of the currently prescribed opioids are mu-opioid receptor agonists, it has been well demonstrated that they exhibit overlapping affinity with kappa- and delta-opioid receptors.

More thoroughly investigated are polymorphisms of mu-opioid receptor gene that have been implicated in variation in opioid response. Data on polymorphisms of kappa- and delta-opioid receptors are quite scarce. More than 100 polymorphisms have been identified in the human mu-opioid peptide receptor gene (OPRM1). A well-studied polymorphism of the mu-opioid receptor, the A118G polymorphism, has been described. Depending on the ethnicity, this polymorphism can be found in 2% to 48% of the population. This polymorphism has been associated with both agonistic and antagonistic opioid effects. For example, it has well been demonstrated that the mu-opioid receptor single nucleotide polymorphism (rs number 1799971) at nucleotide position 118 (OPRM1 118A>G) resulting in the substitution of one amino acid has been associated with decrease in the analgesic effect of opioids. Data from clinical trials suggest the A118G polymorphism has clinical implication in pain treatment [5]. A cohort study of patients submitted to arthroplasty surgery and treated for postoperative pain with patient controlled analgesia was genotyped for the A118G polymorphism in OPRM1. The study demonstrated that homozygous GG patients required higher doses of morphine during the first 24 hours [6]. This effect of A118G variant was also verified in a cohort of patients submitted to abdominal surgery [7]. Another study of postoperative pain has shown that patients with the AA genotype need lower doses of morphine but have higher incidence of postoperative nausea and vomit [8].

This finding indicates that OPRM1 pharmacogenomics might have relevance for opioid side effects. However, there are also studies that demonstrated no effect of A118G polymorphism on opioid induced postoperative nausea and vomit [9].

Studies performed in cancer patients have also indicated the relevance of A118G polymorphism of OPRM1 in opioid efficacy in pain management [10]. Interestingly, a very recent study has suggested that mu-opioid receptor A118G polymorphism predicts survival in patients with breast cancer [11].

In conclusion, available data indicate that genotyping for mu-opioid receptor A118G polymorphism might have clinical implications in pain management. However, this is a suggestion that needs to be further investigated. Defining OPRM1 haplotypes might be more clinically relevant as has been suggested by studies of postoperative pain after major abdominal surgery [12]. In addition other common mu-opioid receptor polymorphisms have been associated with reduced pain relief to alfentanil or morphine. In addition, polymorphisms of the mu-opioid receptor have been identified in the third intracellular loop of the receptor that affect receptor signalling, but it is not known if these polymorphisms affect treatment efficacy.

2.1. Pharmacogenomics of Phase I Drug Metabolizing Enzymes and Opioid Analgesics. Most Phase I metabolizing enzymes belong to the cytochrome P450 (CYP) family. CYPs (e.g., CYP3A4, CYP3A5, CYP2D6, CYP1A1, CYP1B1, and CYP2E1) recognize a wide range of chemicals as substrates, usually converting them into a more water soluble form. Phase I pathways include oxidative, reductive, and hydrolytic reactions.

2.1.1. Codeine. Codeine is an important P450 2D6 (CYP2D6) substrate. It is activated to morphine exclusively by CYP2D6. Codeine has only mild opioid properties, while most of its analgesia and central nervous system depressant effects are based to its biotransformation to morphine, a reaction catalyzed by CYP2D6 [13]. Genetic polymorphisms of this enzyme result in three phenotypes: poor metabolizer phenotype, extensive metabolizer phenotype, and ultrarapid metabolizer phenotype. Ultrarapid metabolizers have duplication of the gene, resulting in increased enzymatic activity. On the other hand, poor metabolizers are homozygous for an inactive or deficient CYP2D6 enzyme due to mutations in the CYP2D6 gene [14]. Poor metabolizers have decreased activation of CYP2D6-dependent analgesic prodrugs such as codeine [15]. It is estimated that 7–10% of the population does not express functional CYP2D6. Data from a relevant randomized, placebo-controlled, double-blind clinical trial that investigated the effect of CYP2D6 polymorphisms on codeine analgesia using an experimental pain model, indicated that codeine administration resulted in analgesia in extensive metabolizers but had no effect in poor metabolizer patients [16]. Furthermore, although poor metabolizers did not receive any analgesic benefit, they had the same frequency of side effects with extensive metabolizers [16]. In a small study of 11 patients treated with codeine for analgesia after hysterectomy, two patients had no analgesic effect from the codeine, one of whom was subsequently shown to be a
poor metabolizer [17]. However, other studies have shown no difference in the effect of codeine on postoperative pain intensity between extensive and poor metabolizers in both adults and children [18, 19].

CYP2D6 ultrarapid metabolizers (in an estimated 1% of people in Finland and Denmark, 10% of people in Greece and Portugal, and 29% of people in Ethiopia) have the potential for increased production of morphine from codeine and thus might be at greater risk for opioid related adverse events and might benefit from a lower dose of opioids [20]. The most common adverse reactions to codeine include drowsiness, lightheadedness, dizziness, sedation, shortness of breath, nausea, vomiting, and sweating. Serious adverse reactions include respiratory depression, circulatory depression, respiratory arrest, shock, and cardiac arrest. Excessive activation of codeine in ultrarapid metabolizers with one additional copy of CYP2D6 has been reported in case reports (Table I). The first described a patient prescribed a cough medicine containing codeine for bilateral pneumonia, who suffered from a life-threatening opioid intoxication. Upon genotyping, it was shown that the patient had at least three copies of CYP2D6, a finding consistent with ultrarapid metabolism of codeine [21]. The patient was also treated with a macrolide and an azole derivative; medicines that, being inhibitors of CYP3A4, might have further reduced the clearance of codeine and increased the risk of an opioid overdose associated with the CYP2D6 gene duplication. In addition, the patient was suffering from renal insufficiency that rendered him prone to the accumulation of codeine metabolites.

Another case report concerns the death of a two year old boy that developed fever and wheezing and finally respiratory arrest two days after elective tonsillectomy. The boy had been prescribed codeine and acetaminophen for analgesia at recommended doses, that is, 10 to 12.5 mg of codeine and 120 mg of acetaminophen orally every 4 to 6 hours as needed. Codeine and morphine were detected at peripheral blood and CYP2D6 genotyping revealed functional duplication of the CYP2D6 allele, resulting in the ultrarapid-metabolizer phenotype [22]. In addition, the child had a history of recurrent episodes of hypoxemia due to bronchopneumonia that could possibly have led to alterations in the μ-opioid receptor and increased sensitivity to morphine. Voronov et al. have reported another case report of a 29 month old previously healthy child who experienced apnea resulting in brain injury following a dose of acetaminophen and codeine 2 days after tonsillectomy. A genetic polymorphism leading to ultrarapid metabolism of codeine into morphine was again confirmed in this child [23].

Another case report concerned the death of a breast fed baby 13 days after birth. His mother was prescribed codeine as an analgesic after delivery. Postmortem examination of stored breast milk samples showed morphine levels 4 times higher than expected. Upon genotyping, the mother was found to be heterozygous for a CYP2D6*2A allele and a CYP2D6*2 × 2 gene duplication. Thus the mother had three functional CYP2D6 alleles and was classified as an ultrarapid metabolizer [24]. The extra CYP2D6 enzyme resulted in increased O-demethylation of codeine to morphine, and consequently, very high concentrations of morphine were found in both the breast milk and in the blood from the child. Following this fatal case, a case control study investigated the characteristics of mothers and infants with or without signs and symptoms of central nervous system depression following codeine exposure during breast feeding. According to the study, breastfed infants of mothers who are CYP2D6 poor metabolizer phenotype or ultrarapid metabolizer phenotype. Opioids not metabolized by CYP2D6, including morphine, oxymorphone, buprenorphine, fentanyl, methadone, and hydromorphone combined with nonopioid analgesics, have

| Author          | Metabolizing enzyme | Polymorphism                                                                 | Adverse event                      |
|-----------------|--------------------|------------------------------------------------------------------------------|-----------------------------------|
| Gasche et al., 2004 [21] | CYP2D6             | CYP2D6*1 × 3, in a patient suffering from renal insufficiency and cotreated with CYP3A4 inhibitors | Life-threatening intoxication      |
| Voronov et al., 2007 [23] | CYP2D6             | CYP2D6 × 2                                                                    | Apnea and brain injury            |
| Madadi et al., 2007 [24] | CYP2D6             | CYP2D6*2A and CYP2D6*2 × 2                                                  | Death of the breastfed 13-day-old boy |
| Ciszkowski et al., 2009 [22] | CYP2D6             | CYP2D6*1 × N                                                                 | Death due to respiratory arrest    |
| Kelly et al., 2012 [26] | CYP2D6             | CYP2D6*1 × N                                                                 | Two deaths, one case of severe respiratory depression |
been proposed as alternative medications instead of codeine for patients prone to codeine toxicity or for those expected to be unresponsive in codeine treatment [27].

2.1.2. Oxycodone. Oxycodone is a semisynthetic opioid prescribed for moderate to severe pain. Oxycodone is similar in structure to codeine, but in contrast, it has an analgesic potency in humans similar to morphine. Both the parent compound and the metabolites of oxycodone are equally active in the opioid receptor. The principal metabolic pathway of oxycodone is the cytochrome P450 3A4 (CYP3A) accounting for approximately 50% of the dose. Furthermore, the drug undergoes metabolism to oxymorphone via CYP2D6. The effect of polymorphisms of CYP enzymes on oxycodone safety and efficacy has been investigated, but results are discordant [28–30].

2.1.3. Hydrocodone. Hydrocodone is hemisynthetic oral opioid structurally related to codeine. It is approximately 12 times more potent in the mu-opioid receptor than codeine. Hydrocodone is metabolized by oxidative metabolism via cytochrome CYP2D6 and cytochrome P450 3A4 (CYP3A4) into hydromorphone and norhydrocodone, respectively. These metabolites undergo conjugation by uridine diphosphate glucuronosyltransferases (UGTs) before excretion. Both the parent compounds and the metabolites of hydrocodone are equally active in opioid receptors. An effect of CYP2D6 polymorphism on hydrocodone metabolite production has been demonstrated. However, evidence suggests that analgesic efficacy of hydrocodone is not affected by metabolism via CYP2D6. Effect of CYP2D6 polymorphisms on hydrocodone toxicity has also been reported (Table 2). Madadi et al. reported a case of fatal opioid toxicity that occurred in a developmentally delayed child aged 5 years 9 months who was inadvertently administered high doses of hydrocodone for a respiratory tract infection. Genotyping was performed for CYP2D6*4, CYP2D6*9, CYP2D6*10, and CYP2D6*41 by using predesigned TaqMan allelic discrimination assays. Furthermore, the following assays were applied: (1) CYP2D6 copy number attributable to the CYP2D6*5 deletion allele (2) gene duplication (3) gene multiduplication. The analysis demonstrated that the child carried the allele CYP2D6*41 allele and 1 fully functional wild-type allele. Therefore, the child genotype was CYP2D6*2A/41 and the child was designated as a poor CYP2D6 metabolizer. Drug–drug interactions contributed to this fatal event, since the child was prescribed clarithromycin (a CYP3A4 inhibitor) for an ear infection and valproic acid, an inhibitor of UGT enzymes for seizures, since birth [31,32].

2.1.4. Tramadol. Tramadol is a synthetic, centrally acting analgesic for the treatment of moderate to severe pain. This analgesic is a racemic mixture containing 50% (+)-tramadol and 50% (−)-tramadol. Tramadol produces analgesia by the synergistic action of its two enantiomers and their metabolites. Its affinity for opioid receptors is 6000 times lower than that of morphine. Tramadol is an example of an analgesic drug that is metabolized by CYP2D6, to generate a pharmacologically active product, the analgesic opioid receptor agonist O-desmethyltramadol [33]. Genetic variations in CYP2D6 have been shown to account for some of the variable pain response in the postoperative period because the CYP2D6 activity has a clinically relevant impact on the level of analgesia mediated by the μ-opioid receptor [34–36] (Table 3). The effect of CYP2D6*10 polymorphism has been investigated in Chinese patients recovering from gastrectomy performed for gastric cancer [37]. Patients were treated with self-administered tramadol via patient controlled analgesia. Patients homozygous for CYP2D6*10 displayed higher consumption of tramadol in comparison with heterozygous group and with patient group without CYP2D6*10. Furthermore, tramadol is metabolized to N-demethyl tramadol by N-demethylation via CYP3A.

In addition genetic variations in CYP2D6 affect the safety profile of tramadol. Thus, case reports have indicated that the carriers of gene duplications, being CYP2D6 ultrarapid metabolizers, are at high risk for toxic responses to tramadol treatment [38]. A case report described a man with renal insufficiency and CYP2D6 UM genotype who developed postoperative opioid related respiratory insufficiency under intravenous patient controlled tramadol analgesia [39]. Genotyping was performed by polymerase chain reaction and real-time polymerase chain reaction for the single

| Author                     | Metabolizing enzyme | Polymorphism                       | Adverse event                                                                 |
|----------------------------|---------------------|------------------------------------|-------------------------------------------------------------------------------|
| Madadi et al., 2010 [32]   | CYP2D6              | CYP2D6*41                          | Volunteers who were CYP2D6 ultrarapid metabolizers experienced higher toxicity especially after CYP3A blockade with ketoconazole |
| Samer et al., 2010 [28]    | CYP2D6              | 32 alleles using the AmpliChip TMCYP450 DNA microarray | No effect of genotype in patients treated for malignant and nonmalignant chronic pain |
| Lemberg et al., 2010 [29]  | CYP2D6, CYP3A4, CYP3A5 |                                    | No effect of genotype in patients treated for malignant and nonmalignant chronic pain |
| Andreassen et al., 2012 [30] | CYP2D6              | CYP2D6*2 × 2                       | Genotype did not affect safety profile that is the incidence of nausea, tiredness, or cognitive failure in a cohort of cancer patients |
nucleotide polymorphisms CYP2D6*3, *4, *5, *6, *7, and *8, associated with poor metabolizer phenotype and for the SNP CYP2D6*10 and *41 associated with the intermediate-metabolizer phenotype. The result of these tests was negative, while the duplication/multiduplication assay revealed a CYP2D6 gene duplication resulting in ultrarapid metabolism of tramadol to its active metabolite (+)-O-desmethyltramadol. The opioid toxicity was enhanced by the decreased metabolic clearance due to renal insufficiency.

In another publication, El kalioufie et al. have reported a near fatal case of tramadol induced cardiotoxicity in an ultrarapid CYP2D6 metabolizer [40]. A 22-year-old girl was transferred to the ICU with cardiac arrest. The aetiology was suggested by the high concentrations of both tramadol and its main metabolite O-desmethyltramadol identified in the blood tests. Genotyping was performed and the patient was found to be heterozygous for a wild-type allele duplication. The patient admitted occasional abuse of tramadol. Cardiotoxicity could be explained by high levels of norepinephrine due to tramadol induced inhibition of norepinephrine reuptake.

Motivated by the above mentioned reports, Kirchheiner et al. systematically investigated the effect of CYP2D6 duplication on the pharmacodynamics and pharmacokinetics of tramadol after a single dose of 100 mg racemic tramadol in 11 carriers of a CYP2D6 gene duplication and compared with 11 carriers of 2 active CYP2D6 genes [38]. In addition, Siew et al. investigated the effect of CYP2D6 polymorphisms on tramadol pharmacokinetics and pharmacodynamics in Malaysian patients with different genotypes [35]. Both studies demonstrated pharmacokinetic differences between the genotype groups as well as differences in the safety profile of tramadol. According to Gal et al. intermediate metabolizers experienced more adverse effects than extensive metabolizers and extensive metabolizers experienced more adverse effects than ultrarapid metabolizers. However, in the study of Kirchheiner et al., ultrarapid metabolizers experienced more adverse events than extensive metabolizers. The discrepancies may be due to differences in the method of genotype determination, in the different polymorphisms investigated, and in the type of assessed adverse events. Given that these results have not been verified in a large population study, at present, CYP2D6 genotyping cannot be recommended for tramadol dosing.

### 2.1.5. Methadone

Methadone metabolism is attributed primarily to cytochrome P450 enzymes CYP3A4, CYP2B6, and CYP2D6 [41, 42]. Interindividual differences in sensitivity to methadone have been observed. Fatal poisonings occur typically at concentrations between 0.4 and 1.8 mg/mL. However, in susceptible individuals, death may occur at much lower concentrations. In a study, 40 postmortem cases have been reported, in which methadone had been implicated in the cause of death. The CYP2B6*6 allele that results in slow metabolism was associated with highest postmortem methadone concentration [43].

### 2.2. Pharmacogenomics of Phase II Drug Metabolizing Enzymes and Opioid Analgesics

Phase II enzymes conjugate phase I metabolites, other intermediates, or the parent compound for renal or biliary excretion. Phase II enzymes include glutathione S transferases (GSTs), UDP glycosyltransferases (UGT), N-acetyltransferases (NAT), glutathione S transferases GSTs, NADH quinone oxidases, and others. Knowledge on pharmacogenomics of phase II enzymes is not extensive. Thus, the relevance of the pharmacogenomics of the enzymes of the uridine diphosphoglucuronosyltransferase (UGT) superfamily in opioid disposition has been investigated, although it is not currently elucidated [44–47]. Several polymorphisms of UGT1A1 have been described with the best studied the one defined by a variable length “TA” tandem repeat in the regulatory TATA box of the UGT1A1 gene promoter (UGT1A1*28) that leads to reduced expression of the isozyme, associated with Gilbert syndrome, the most common inherited cause of unconjugated hyperbilirubinemia. UGT1A1 catalyzes the glucuronidation of opioids including morphine, buprenorphine, and norbuprenorphine, hemisynthetic derivatives of the morphine alkaloid thebaine with partial agonist properties on opioid receptors. The effect of UGT1A1*28 polymorphism in the pharmacokinetics of morphine has been investigated in cancer patients, but no association has been demonstrated [45]. Another enzyme involved in opioid metabolism is UGT2B7. The association of polymorphisms of this enzyme with morphine metabolism has been investigated. It has been shown that the UGT2B7 promoter variant −840 G is associated with reduced glucuronidation of morphine contributing thus in variability in hepatic clearance of morphine in patients with sickle cell

### Table 3: Prospective studies providing evidence on the impact of polymorphisms of CYP2D6 on the analgesic efficacy of tramadol.

| Author                | Polymorphism                                      | Effect                                                                 |
|-----------------------|---------------------------------------------------|------------------------------------------------------------------------|
| Stamer et al., 2003   | CYP2D6*1, *3, *4, *5, *9, *10, CYP2D6*17, CYP2D6*1 × N | Poor metabolizers for CYP2D6 showed a lower response rate to tramadol analgesia for postoperative pain after abdominal surgery |
| Wang et al., 2006     | CYP2D6*10 C188T                                    | This SNP reduced tramadol analgesic efficacy in a Chinese patients treated for postoperative pain after major abdominal surgery |
| Siew et al., 2007     | CYP2D6*1, *3, *4, *5, *9, *10, CYP2D6*17, CYP2D6*1 × N | The analgesic effects of tramadol were not measured adequately. Therefore the effect of genotype on tramadol analgesic efficacy was not demonstrated |
| Slanar et al., 2012   | CYP2D6*3, CYP2D6*4, CYP2D6*5, CYP2D6*6 CYP2D6*1 × N | CYP2D6 genotype did not affect tramadol analgesic efficacy in postoperative patients after knee arthroplasty |
anaemia [46]. Genetic modeling approaches integrating prior physiologic knowledge have shown that decreased UGT2B7 activity is associated with a decrease in active opioid exposure. The C802T exonic single nucleotide polymorphism (SNP) of UGT2B7 has been shown to alter UGT2B7 affinity for buprenorphine.

3. Pharmacogenomics of Drug Transporters and Opioid Analgesics

Transport of drugs across cell membranes is determined by molecular weight, lipid solubility, ionization, and protein binding. Opioid analgesics are hydrophilic agents and thus the drug transporters mediate their entrance through cell membranes. Multidrug resistance proteins (MDR), multidrug resistance associated proteins (MRP), and organic anion transporting polypeptides (OATPs) contribute to opioid analgesic transport through cell membranes. Polymorphisms in these transporter genes may account for variation in analgesic efficacy of opioids. MDRs are ATP dependent efflux pumps. P-glycoprotein is encoded by the multidrug resistance gene MDR1 (ABCB1). The clinical relevance of ABCB1 pharmacogenomics in the case of opioids has not been elucidated. Evidence suggests that the variations in the P-glycoprotein gene, ABCB1 polymorphisms, influence opioid pharmacodynamics and dosage requirements. However, there are also studies that failed to demonstrate an effect of ABCB1 polymorphisms on morphine pharmacodynamics or pharmacokinetics. Fentanyl may be a substrate of ABCB1 and it has been shown that ABCB1 polymorphisms conferring decreased transporter function have been associated with increased respiratory depressive effects of fentanyl in Korean patients [48]. A cohort study of patients submitted to colorectal surgery demonstrated that two SNPs of ABCB1, C3435T (in exon 24) and G2677T/A (in exon 21), were associated with opioid induced side effects. In particular, homozygous patients (GG and CC, resp.) required less often ondansetron treatment, suggesting that the diplotype GG-CC was associated with fewer side effects of morphine [49]. However, a recent study in Turkish patients failed to demonstrate an effect of ABCB1 polymorphisms on respiratory depression caused by intravenous fentanyl [50].

Further research is needed in order to elucidate the clinical relevance of MRP and OATP polymorphisms in the context of opioid analgesics efficacy and safety.

4. Conclusion

Undoubtedly, the application of personalized medicine is anticipated to improve treatment efficacy and safety. Pharmacogenomics may be a critical pathway to personalized medicine. Current evidence suggests that pharmacogenomics contribute to variation in efficacy and safety of opioids. However, most data come from case control studies and case reports. In addition, a recognized drawback in the field of pharmacogenomics is the common occurrence of false positive association between polymorphisms and the investigated outcome. Prospective studies are needed to further elucidate the clinical implications of available data as well as to define the guidelines for the clinical application of pharmacogenomic data. Furthermore, basic research should focus on the identification of biologically meaningful polymorphisms enabling a hypothesis with biological plausibility driven research in the field of pharmacogenomics of analgesics. Moreover, the publication of relevant negative results should be favored.

Conflict of Interests

The author declares no conflict of interests.

References

[1] W. E. Evans and M. V. Relling, “Pharmacogenomics: translating functional genomics into rational therapeutics,” Science, vol. 286, no. 5439, pp. 487–491, 1999.
[2] C. Siva, W. M. Yokoyama, and H. L. McLeod, “Pharmacogenetics in rheumatology: the prospects and limitations of an emerging field,” Rheumatology, vol. 41, no. 11, pp. 1273–1279, 2002.
[3] C. Martínez, G. Blanco, J. M. Ladero et al., “Genetic predisposition to acute gastrointestinal bleeding after NSAIDs use,” British Journal of Pharmacology, vol. 141, no. 2, pp. 205–208, 2004.
[4] M. Pirmohamed, “Pharmacogenetics of idiosyncratic adverse drug reactions,” in Adverse Drug Reactions Handbook of Experimental Pharmacology, J. Uetrecht, Ed., pp. 478–491, Springer, 2010.
[5] A. de Capraris, G. Cinnella, A. Marolla et al., “Micro opioid receptor A118G polymorphism and post-operative pain: opioids’ effects on heterozygous patients,” International Journal of Immunopathology and Pharmacology, vol. 24, no. 4, pp. 993–1004, 2011.
[6] W.-Y. Chou, L.-C. Yang, H.-F. Lue et al., “Association of μ-opioid receptor gene polymorphism (A118G) with variations in morphine consumption for analgesia after total knee arthroplasty,” Acta Anaesthesiologica Scandinavica, vol. 50, no. 7, pp. 787–792, 2006.
[7] W. Y. Chou, C. H. Wang, P. H. Liu, C. C. Liu, C. C. Tseng, and B. Jawan, “Human opioid receptor A118G polymorphism affects intravenous patient-controlled analgesia morphine consumption after total abdominal hysterectomy,” Anesthesiology, vol. 105, no. 2, pp. 334–337, 2006.
[8] A. T. Sia, Y. Lim, E. C. P. Lim et al., “A118G single nucleotide polymorphism of human μ-opioid receptor gene influences pain perception and patient-controlled intravenous morphine consumption after intrathecal morphine for postcesarean analgesia,” Anesthesiology, vol. 109, no. 3, pp. 520–526, 2008.
[9] W. Zhang, J.-J. Yuan, Q.-C. Kan, L.-R. Zhang, Y.-Z. Chang, and Z.-Y. Wang, “Study of the OPRM1 A118G genetic polymorphism associated with postoperative nausea and vomiting induced by fentanyl intravenous analgesia,” Minerva Anestesiologica, vol. 77, no. 1, pp. 33–39, 2011.
[10] P. Klepstad, T. T. Rakvåg, S. Kaasa et al., “The I18 A > G polymorphism in the human μ-opioid receptor gene may increase morphine requirements in patients with pain caused by malignant disease,” Acta Anaesthesiologica Scandinavica, vol. 48, no. 10, pp. 1232–1239, 2004.
[11] A. V. Bortsov, R. C. Millikan, I. Belfer, R. L. Boortz-Marx, H. Arora, and S. A. McLean, “μ-opioid receptor gene A118G
polymorphism predicts survival in patients with breast cancer,” Anesthesiology, vol. 116, no. 4, pp. 896–902, 2012.

[12] M. Hayashida, M. Nagashima, Y. Satoh et al., “Analgesic requirements after major abdominal surgery are associated with OPRM1 gene polymorphism genotype and haplotype,” Pharmacogenomics, vol. 9, no. 11, pp. 1605–1616, 2008.

[13] U. A. Meyer, “Pharmacogenetics and adverse drug reactions,” The Lancet, vol. 356, no. 9242, pp. 1667–1671, 2000.

[14] W. W. Weber, “Populations and genetic polymorphisms,” Molecular Diagnosis, vol. 4, no. 4, pp. 299–307, 1999.

[15] R. A. Wilcox and H. Owen, “Variable cytochrome P450 2D6 expression and metabolism of codeine and other opioid prodrugs: implications for the Australian anaesthetist,” Anaesthesia and Intensive Care, vol. 28, no. 6, pp. 611–619, 2000.

[16] K. Eckhardt, S. Li, S. Ammon, G. Schänzle, G. Mikus, and M. Eichelbaum, “Same incidence of adverse drug events after codeine administration irrespective of the genetically determined differences in morphine formation,” Pain, vol. 76, no. 1-2, pp. 27–33, 1998.

[17] K. Persson, S. Sjostrom, I. Sigurdardottir, V. Molnar, M. Hammarsland-Udenaes, and A. Rane, “Patient-controlled analgesia (PCA) with codeine for postoperative pain relief in ten extensive metabolisers and one poor metaboliser of dextromethorphan,” British Journal of Clinical Pharmacology, vol. 39, no. 2, pp. 182–186, 1995.

[18] A. Gaedigk, L. D. Bradford, K. A. Marcucci, and J. S. Leeder, “Unique CYP2D6 activity distribution and genotype-phenotype discordance in black Americans,” Clinical Pharmacology & Therapeutics, vol. 72, no. 1, pp. 76–89, 2002.

[19] L. Poulsen, L. Riishede, K. Brosen, S. Clemensen, and S. H. Sprintz, “CYP2D6 polymorphism genotype and haplotype,” Molecular Diagnostics and Therapy, vol. 1, no. 1, pp. 24–33, 2010.

[20] T. N. Andreasen, I. Eftedal, P. Klepstad et al., “Do CYP2D6 genotypes reflect oxycodone requirements for cancer patients treated for cancer pain? A cross-sectional multicentre study,” European Journal of Clinical Pharmacology, vol. 68, no. 1, pp. 55–64, 2012.

[21] M. R. Hutchinson, A. Menelaou, D. J. R. Foster, J. K. Coller, and A. A. Somogyi, “CYP2D6 and CYP3A4 involvement in the primary oxidative metabolism of hydrocodone by human liver microsomes,” British Journal of Clinical Pharmacology, vol. 57, no. 3, pp. 287–297, 2004.

[22] P. Madadi, D. Hildebrandt, I. Y. Gong et al., “Fatal hydrocodone overdose in a child: pharmacogenetics and drug interactions,” Pediatrics, vol. 126, no. 4, pp. e896–e899, 2010.

[23] H. F. Galley, A. Mahdy, and D. A. Lowes, “Pharmacogenetics and anesthesiologists,” Pharmacogenomics, vol. 6, no. 8, pp. 849–856, 2005.

[24] U. M. Stamer, K. Lehnen, F. Höthker et al., “Impact of CYP2D6 genotype on postoperative tramadol analgesia,” Pain, vol. 105, no. 1-2, pp. 231–238, 2003.

[25] H. G. Siew, R. Ismail, W. A. W. Adnan, and W. Zulmi, “Impact of CYP2D6 genetic polymorphism on tramadol pharmacokinetics and pharmacodynamics,” Molecular Diagnosis and Therapy, vol. 11, no. 3, pp. 171–181, 2007.

[26] O. Slanar, P. Dupal, O. Matouskova, H. Vondrackova, P. Pafko, and F. Perlik, “Tramadol efficacy in patients with postoperative pain—study of the influence of sparteine phenotype and serum concentrations of morphine and morphine-6-glucuronide,” European Journal of Clinical Pharmacology, vol. 54, no. 6, pp. 451–454, 1998.

[27] D. G. Williams, A. Patel, and R. F. Howard, “Pharmacogenetics of codeine metabolism in an urban population of children and its implications for analgesic reliability,” British Journal of Anaesthesia, vol. 89, no. 6, pp. 839–845, 2002.

[28] Y. Gasche, Y. Daali, M. Fathi et al., “Codeine intoxication associated with ultrarapid CYP2D6 metabolism,” The New England Journal of Medicine, vol. 351, no. 27, pp. 2827–2831, 2004.

[29] C. Ciszkowski, P. Madadi, M. S. Phillips, A. E. Lauwers, and G. Koren, “Codeine, ultrarapid-metabolism genotype, and postoperative death,” The New England Journal of Medicine, vol. 361, no. 8, pp. 827–828, 2009.

[30] P. Voronov, H. J. Przybylo, and N. Jagnannathan, “Apnea in a child after oral codeine: a genetic variant—an ultra-rapid metabolizer,” Paediatric Anaesthesia, vol. 17, no. 7, pp. 684–687, 2007.

[31] P. Madadi, G. Koren, J. Cairns et al., “Safety of codeine during breastfeeding: fatal morphine poisoning in the breastfed neonate of a mother prescribed codeine,” Canadian Family Physician, vol. 53, no. 1, pp. 33–35, 2007.

[32] P. Madadi, C. J. D. Ross, M. R. Hayden et al., “Pharmacogenetics of neonatal opioid toxicity following maternal use of codeine during breastfeeding: a case-control study,” Clinical Pharmacology and Therapeutics, vol. 85, no. 1, pp. 31–35, 2009.

[33] L. E. Kelly, M. Rieder, J. van den Anker et al., “More codeine fatalities after tonsillec tomoy in North American children,” Pediatrics, vol. 129, no. 5, pp. e1343–e1346, 2012.

[34] K. R. Crews, A. Gaedigk, H. M. Dunnenberger et al., “Clinical pharmacogenetics implementation consortium (CPIC) guidelines for codeine therapy in the context of cytochrome P450 2D6 (CYP2D6) genotype,” Clinical Pharmacology & Therapeutics, vol. 91, no. 2, pp. 321–326, 2012.

[35] C. F. Samer, Y. Daali, M. Wagner et al., “The effects of CYP2D6 and CYP3A activities on the pharmacokinetics of immediate release oxycodone,” British Journal of Pharmacology, vol. 160, no. 4, pp. 907–918, 2010.

[36] K. K. Lemberg, T. E. Heiskanen, M. Neuvonen et al., “Does co-administration of paroxetine change oxycodone analgesia: an interaction study in chronic pain patients,” Scandinavian Journal of Pain, vol. 1, no. 1, pp. 24–33, 2010.

[37] O. Slanar, P. Dupal, O. Matouskova, H. Vondrackova, P. Pafko, and F. Perlik, “Tramadol efficacy in patients with postoperative pain in relation to CYP2D6 and MDRI polymorphisms,” Bratislavské lekárské listy, vol. 113, no. 3, pp. 152–155, 2012.

[38] G. Wang, H. Zhang, F. He, and X. Fang, “Effect of the CYP2D6*10 C188T polymorphism on postoperative tramadol analgesia in a Chinese population,” European Journal of Clinical Pharmacology, vol. 62, no. 11, pp. 927–931, 2006.

[39] J. Kircheiner, J. T. H. A. Keulen, S. Bauer, I. Roots, and J. Brockmöller, “Effects of the CYP2D6 gene duplication on the pharmacokinetics and pharmacodynamics of tramadol,” Journal of Clinical Psychopharmacology, vol. 28, no. 1, pp. 78–83, 2008.

[40] U. M. Stamer, F. Stüber, T. Muders, and F. Musshoff, “Respiratory depression with tramadol in a patient with renal impairment and CYP2D6 gene duplication,” Anesthesia & Analgesia, vol. 107, no. 3, pp. 926–929, 2008.

[41] A. Elkaluibie, D. Allorge, L. Robriquet et al., “Near-fatal tramadol cardiotoxicity in a CYP2D6 ultrarapid metabolizer,” European Journal of Clinical Pharmacology, vol. 67, no. 8, pp. 855–858, 2011.

[42] S. H. Wong, M. A. Wagner, J. M. Lentzen et al., “Pharmacogenomics as an aspect of molecular autopsy for forensic pathology/toxicology: does genotyping CYP 2D6 serve as an adjunct for certifying methadone toxicity?” Journal of Forensic Sciences, vol. 48, no. 6, pp. 1406–1415, 2003.
required for effective treatment of opioid addiction,” *Addiction Biology*, vol. 18, no. 4, pp. 709–716, 2013.

[43] M. A. Hammam, G. A. Thompson, and S. D. Hall, “Regioselective and stereoselective metabolism of ibuprofen by human cytochrome P450 2C,” *Biochemical Pharmacology*, vol. 54, no. 1, pp. 33–41, 1997.

[44] B. L. Coffman, C. D. King, G. R. Rios, and T. R. Tephly, “The glucuronidation of opioids, other xenobiotics, and androgens by human UGT2B7(Y268) and UGT2B7H(268),” *Drug Metabolism and Disposition*, vol. 26, no. 1, pp. 73–77, 1998.

[45] M. Holthe, P. Klepstad, K. Zahlsen et al., “Morphine glucuronide-to-morphine plasma ratios are unaffected by the UGT2B7 H268Y and UGT1A1*28 polymorphisms in cancer patients on chronic morphine therapy,” *European Journal of Clinical Pharmacology*, vol. 58, no. 5, pp. 353–356, 2002.

[46] D. S. Darbari, R. H. N. van Schaik, E. V. Capparelli, S. Rana, R. McCarter, and J. Van Den Anker, “UGT2B7 promoter variant -840G>A contributes to the variability in hepatic clearance of morphine in patients with sickle cell disease,” *American Journal of Hematology*, vol. 83, no. 3, pp. 200–202, 2008.

[47] K. Rouguieg, N. Picard, F.-L. Sauvage, J.-M. Gaulier, and P. Marquet, “Contribution of the different UDP-glucuronosyltransferase (UGT) isoforms to buprenorphine and norbuprenorphine metabolism and relationship with the main UGT polymorphisms in a bank of human liver microsomes,” *Drug Metabolism and Disposition*, vol. 38, no. 1, pp. 40–45, 2010.

[48] H.-J. Park, H. K. Shinn, S. H. Ryu, H.-S. Lee, C.-S. Park, and J.-H. Kang, “Genetic polymorphisms in the ABCB1 gene and the effects of fentanyl in Koreans,” *Clinical Pharmacology and Therapeutics*, vol. 81, no. 4, pp. 539–546, 2007.

[49] L. Coulbault, M. Beaussier, C. Verstuyft et al., “Environmental and genetic factors associated with morphine response in the postoperative period,” *Clinical Pharmacology & Therapeutics*, vol. 79, no. 4, pp. 316–324, 2006.

[50] E. Kesimci, A. B. Engin, O. Kanbak, and B. Karahalil, “Association between ABCB1 gene polymorphisms and fentanyl’s adverse effects in Turkish patients undergoing spinal anesthesia,” *Gene*, vol. 493, no. 2, pp. 273–277, 2012.