Pharmacogenomics of G Protein-Coupled Receptor Ligands in Cardiovascular Medicine

DIETER ROSSKOPF AND MARTIN C. MICHEL

Abstract—Agonists and antagonists of G protein-coupled receptors are important drugs for the treatment of cardiovascular disease, but the therapeutic response of any given patient remains difficult to predict because of large interindividual variability. Among the factors potentially contributing to such variability, we have reviewed the evidence for a role of pharmacodynamic pharmacogenetics (i.e., polymorphisms in the cognate receptors for such drugs as well as other proteins potentially modifying their action). Based upon the availability of data and the prevalence of use, we have focused on ligands at adrenergic and angiotensin II receptors (including the indirectly acting angiotensin-converting enzyme inhibitors). The vast majority of gene polymorphisms reviewed here have shown only inconsistent effects on drug action, which does not make these polymorphisms useful genetic markers to predict treatment responses. We conclude that considerable additional research, partly involving other types of study than those available now, will be necessary to allow a definitive judgment whether pharmacodynamic pharmacogenetic markers are useful in an individualized approach to cardiovascular therapy. Moreover, we predict that even such additional research will result in only few cases where the promise of tailored treatment can be fulfilled; however, some of these few cases may be of major clinical relevance.

I. Introduction

G protein-coupled receptors (GPCRs)1 are of prime importance for cardiovascular homeostasis under physiological and pathophysiological conditions (Insel et al., 2007; Hendriks-Balk et al., 2008). Although a considerable number of the more than a thousand different human GPCRs have been identified in cardiovascular tissues or have been implicated in the control of cardiovascular function, only a few GPCRs are actual direct targets of currently available drugs. In this regard, the sympathetic nervous system and the renin-angiotensin-
Aldosterone system (RAAS) are of key importance, and directly and indirectly acting agonists, as well as antagonists, of these systems are the most frequently used classes of drugs in the treatment of cardiovascular diseases.

It has long been recognized that treatment responses to drugs acting on cardiovascular GPCRs vary markedly among individual subjects. Although part of this variability has been attributed to disease-associated alterations of corresponding receptors and their signal transduction mechanisms (Brodde, 2007), it has long been speculated that genetic heterogeneity also contributes to the observed variability in drug responses. Pharmacogenomics is the science that systematically studies the role of such genetic heterogeneity on beneficial and adverse drug responses. It is a promising field because it theoretically allows improving the risk-benefit ratio of treatment. This can occur by selecting patients more likely to be good therapeutic responders and/or by selecting against patients prone to experience adverse treatment effects. Such individualized medicine may help to improve health as well as cost-effectiveness of treatment.

Our current pharmacogenomic knowledge mirrors the historical developments in this rather young specialty. A key discovery was the observation that acetylation of isoniazid is genetically determined, a first example that the pharmacokinetics of a given drug is affected by inherited mechanisms (Goedde et al., 1964). Genetically determined profound toxicities of the antihypertensive sympatholytic debrisoquine and the antiarrhythmic sparteine, both no longer on the market, further fostered prime concepts of pharmacogenomics and led to the discovery of individual variances in the activities of P450 enzymes, CYP2D6 (Mahgoub et al., 1977; Eichelbaum et al., 1979; Gonzalez et al., 1988). In addition to variant drug metabolism, genetically determined differences in drug transporter activities have been identified as an additional source of the individual heterogeneity in drug disposition (for review, see Eichelbaum et al., 2006). Whereas the pharmacokinetic branch of pharmacogenomics accumulated considerable knowledge based on the availability of large amounts of data from drug monitoring, the investigation of genetic variances in pharmacodynamics started roughly a decade ago. The cloning of drug targets (e.g., GPCRs or components of the RAAS) sparked the search for genetic polymorphisms in their genes and the association of such polymorphisms with physiological or pharmacological phenotypes. Admittedly, the contribution of genetic polymorphisms in these genes to the observed variances remained modest in most cases. Integrative concepts extended research on signaling mechanisms involved in drug actions. In the field of GPCRs this includes not only variants in the receptors but also polymorphisms in genes contributing to the signal transduction of such receptors (e.g., G proteins and other genes linked physiologically to those GPCRs). The disadvantage of such candidate gene approaches is that we basically do not comprehend the complex system of the biology of drug actions in vivo. An alternative approach for the investigation of complex genetic diseases or phenotypes, including drug responses, is genome-wide association studies that do not rely on prespecified hypotheses. Present, we experience exciting discoveries in the field of complex diseases (e.g., the identification of genes apparently involved in cardiometabolic diseases, including obesity, diabetes, myocardial infarction, or aneurysms) (Frayling et al., 2007; Sladek et al., 2007; Helgadottir et al., 2008). In the end, these discoveries will also affect pharmacogenomics and individualized therapy. Available data now support long proposed concepts that variants in different genes may lead to the same disease phenotype. Future personalized medicine will take such information into account for making therapeutic decisions. Genome-wide association studies have not only been used for the identification of disease genes, two examples underscore the power of this new method for pharmacogenomics research itself. Hence, one genome-wide association study confirmed the contribution of a gene (VKORC1) to the anticoagulant responses to warfarin and its derivatives (Cooper et al., 2008). Another study associated variants in the gene of a hepatic drug transporter (SLCO1B1) with statin-induced myopathy (The SEARCH Collaborative Group, 2008). Such genome-wide association studies will also contribute to the future identification of novel genes relevant to the pharmacogenomics of the drugs discussed here.

Despite these encouraging developments, the promise of current pharmacogenomics to provide tailored therapies remains to be fulfilled for most cardiovascular drugs because of various stumbling blocks. First, the observed contributions of single genes to explain therapeutic effects are of modest degree and do not allow for individual predictions of responder state, occurrence of adverse effects, or dosing regimens. Second, particularly for well tolerated drugs for which a therapeutic response can be assessed quickly, it remains open whether pharmacogenomic information is advantageous compared with trial-and-error treatment. The balance between the two approaches will depend on several factors, including the predictive value and the cost of the genetic test as well as the cost and risk of exploratory treatment. Third, much of the pharmacogenomic information available so far has remained equivocal, thereby questioning one of the key premises of pharmacogenomic-based treatment (i.e., whether a given genetic test is indeed predictive). Such controversial data may be due to many factors, including lack of solid knowledge on the biology of a given polymorphism and statistical under-powering of many studies. Finally, almost all pharmacodynamic pharmacogenomics studies in the cardiovascular system have focused on desired drug effects, whereas only little information is available on the potential flip side of the...
coin (i.e., pharmacogenomic information on adverse effects).

Against this background, the present article reviews the current state of the evidence for a role of pharmacodynamic pharmacogenomics in response to GPCR ligands in the cardiovascular system. Reflecting both their prominent role in cardiovascular therapy and the available amount of data, ligands at adrenergic receptors (ARs) and at angiotensin II (AT) receptors will be the main focus. With regard to AT receptors, we not only look at direct ligands (i.e., AT receptor blockers) but also address indirectly acting inhibitors [i.e., the angiotensin-converting enzyme (ACE) inhibitors]. The much more limited information from other receptor systems will be summarized only briefly. Where applicable, we also include data on GPCR signaling mechanisms.

II. Adrenergic Receptor Ligands

The sympathoadrenal system plays a major role in the control of cardiovascular functions. It largely does so through the neurotransmitter norepinephrine (NE) and the adrenal hormone epinephrine (EPI). NE and EPI act via three subfamilies of ARs, with three subtypes each, termed α₁A,B,D, α₂A,B,C, and β₁,2,3 (Bylund et al., 1994). The most frequently used drug class in cardiovascular medicine acting on these receptors is the β-AR antagonists, such as atenolol, bisoprolol, and metoprolol. Typical indications of β-AR antagonists are long-term treatment of coronary heart disease and congestive heart failure, chronotropic control, and arterial hypertension, the latter with increasing controversy (Messerli et al., 2005). β-AR agonists, such as EPI, are sometimes used in the short-term treatment of heart failure, resuscitation, or shock. α₁-AR antagonists, such as doxazosin and terazosin, are indicated for the treatment of hypertension, although they are no longer considered a first-line treatment, or shock. α₁-AR agonists, such as EPI, are sometimes used to elevate low blood pressure. α₂-AR agonists, such as clonidine, lower blood pressure, but there is continuing debate whether their effects may also involve nonadrenergic mechanisms often referred to as “imidazoline sites.” α₁-AR signal mainly via G proteins of the Gs/11 family coupled to activation of a phospholipase C. α₂-AR are predominantly coupled to G proteins of the Gi/o family, mediating the modulation of various ion channel activities and the inhibition of adenylyl cyclase isoforms, whereas β-AR mainly activate G proteins of the Gs family, thus stimulating adenylyl cyclase isoforms of some of the ion channels. Most studies on the pharmacogenomics of AR ligands have focused on polymorphisms in the corresponding AR. The role of genetic variants in the signaling cascades of ARs has only been addressed in some smaller studies.

A. α₁-Adrenergic Receptor Ligands

Among the α₁-AR subtypes, the α₁A-AR has received the most attention, with regard to genetic heterogeneity (Kirstein and Insel, 2004). Nine naturally occurring single nucleotide polymorphism (SNPs) have been identified in the coding region of the gene for this subtype (ADRA1A), of which seven result in amino acid changes. Upon heterologous transfection, some of them yield altered responses to agonists; however, the extent of alterations is small in each case (Lei et al., 2005). Polymorphisms in the promoter of the α₁A-AR gene have also been identified but similarly remain of uncertain biological relevance (Huang et al., 2008). With regard to cardiovascular drug responses, only information on the frequent R492C SNP (rs1048101; polymorphism is also referred to as R347C given the occurrence of various splice variants; Fig. 1) is available. The frequency of the Cys allele varies with the investigated ethnicity and ranges from 10% in Asians to 57% in Europeans (Table 1). This variant was apparently not associated with alterations of agonist-induced contraction of the dorsal hand vein in situ (Sofowora et al., 2004) and did not exhibit significantly altered blood pressure responses to EPI in one small study with healthy volunteers (Table 2) (Snapir et al., 2003). Likewise, a study in patients with voiding dysfunction attributed to benign prostatic hyperplasia did not detect a relationship between α₁A-AR polymorphisms and the clinical response to treatment with α₁-AR antagonists (Mochtar et al., 2006). Whereas a few polymorphisms have also been identified in the α₁B-AR gene (ADRA1B) (Kirstein and Insel, 2004), they were not associated with alterations of blood pressure responses to infusion of the agonist phenylephrine (Büscher et al., 1999). Although β₂-AR can counteract vascular effects of α₁-AR stimulation, an R166G polymorphism in the β₂-AR (see section II.D) was reported not to affect the pressor response to the α₁-AR agonist phenylephrine (Herrmann et al., 2000). Therefore, the presently available data do not support a role of identified genetic factors in the heterogeneity of cardiovascular responses to α₁-AR ligands.

With regard to the α₁D-receptor, two SNPs in the 3'-untranslated region (UTR) of its gene (ADRA1D), rs2236554 (A1848T) and rs709524 (A1905G), have been associated alone and in concert with a promoter polymorphism in the norepinephrine transporter (NET) gene, with differential improvement of ventricular shortening in patients with dilated cardiomyopathy upon treatment with β-blockers (Nonen et al., 2008). This result awaits independent verification and clarification of the involved mechanisms on how the α₁D-AR contributes to hemodynamic control under β-blockade.

In summary, a relevant contribution of variants in the α₁-AR genes to the effects of α₁-AR ligands has not been demonstrated so far. It is noteworthy that it remains
largely unknown whether genetic variants in α1-AR genes modulate the actions of α1-AR blockers.

B. α2-Adrenergic Receptor Ligands

Apart from their involvement in the central regulation of blood pressure, α2-AR can contribute to cardiovascular function in four main ways: prejunctional inhibition of transmitter release involving multiple subtypes but mostly α2A-AR (Trendelenburg et al., 2003), promotion of platelet aggregation exclusively via α2A-AR (Bylund et al., 1988), endothelium-dependent vasodilatation, and endothelium-independent vasoconstriction, the last two potentially involving multiple subtypes (Guimaraes and Moura, 2001). Sequence variants have been identified in each of the three α2-AR genes (Kirstein and Insel, 2004). Early work on the α2A-AR has used restriction fragment length polymorphisms to explore variants in its gene (ADRA2A), specifically using the restriction enzyme Dral (Michel et al., 1999). Although this polymorphism was associated with differences in catecholamine-induced platelet aggregation (Freeman et al., 1995), no additional studies on its role in cardiovascular drug responses have been reported. Meanwhile, other polymorphisms in the ADRA2A have been identified at the nucleotide level, but their relationship to cardiovascular drug responses remains unclear (Kirstein and Insel, 2004).

Several polymorphisms have been described in the promoter of the α2B-AR gene (ADRA2B); the most prevalent among them (−98G/C; rs3111873) had no effect on promoter activity but was in linkage disequilibrium, with a deletion polymorphism (del301-303; rs29000568; Table 1) in the coding region (Fig. 2) (Cayla et al., 2004). The latter is located in a region of the α2B-AR, which is important for receptor phosphorylation and desensitization. Hence, the del301-303 variant is expected to enhance receptor function (Small and Liggett, 2001). Actually, the del301-303 variant was reported to be associated with several physiological alterations, but these did not necessarily reflect an enhanced receptor function (Kirstein and Insel, 2004). Carriers of the deletion variant exhibited an increased blood pressure ele-
### Table 1: Allele frequencies of common variations in different ethnicities

| Gene Variation (rs Nomenclature) | Common Designation | Reference | Allele Frequency
<table>
<thead>
<tr>
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<tr>
<td>ADRA1A rs1048101</td>
<td>R492C</td>
<td></td>
<td>African Americans</td>
</tr>
<tr>
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<tr>
<td>ADRA2C rs61767072</td>
<td>del322-325 del</td>
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<td>African Americans</td>
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<tr>
<td>ADRB1 rs1801252</td>
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<td></td>
<td>African Americans</td>
</tr>
<tr>
<td>ADRB1 rs1801253</td>
<td>R389G Arg</td>
<td></td>
<td>African Americans</td>
</tr>
<tr>
<td>ADRB2 rs1042713</td>
<td>R16G Gly</td>
<td></td>
<td>African Americans</td>
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<td>Q27E Glu</td>
<td></td>
<td>African Americans</td>
</tr>
<tr>
<td>ADRB2 rs1800888</td>
<td>I164T Ile</td>
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<td>T393C T</td>
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<td>G(1211)A A</td>
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<td>M235T Thr</td>
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<td>ACE rs5186</td>
<td>A1166C C</td>
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<td>AGTR1 rs1799752</td>
<td>I/D I</td>
<td></td>
<td>African Americans</td>
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Note: Allele frequencies were accessed from the HapMap data phases II and III (accessed October 2008).

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- Small et al. (2001b); Muszkat et al. (2005).
- Brodde (2008); Kirstein and Insel (2004).
- Haiman et al. (2003).
- Results in increased heart rate responses in healthy volunteers in response to EPI (administered in the presence of propranolol), whereas they had a smaller increase in coronary blood flow in the absence but not the presence of propranolol (Table 3) (Snapir et al., 2003). In another trial, intravenous administration of the α2-agonist dexametomidine to 80 anesthetized patients resulted in an enhanced initial vasoconstriction in homozygous carriers of the deletion allele after 3 min, an effect that was not sustained after this period (Table 3) (Talke et al., 2005). On the other hand, studies using the α2-agonist azepexole (BHT933) in the dorsal human hand vein in situ did not detect significant contributions of this polymorphism to the vasoconstriction response (King et al., 2005). Studies using the same technique but dexametomidine as the agonist also found no relationship between any of the nine common variants in the α2B-AR gene and vasoconstriction; however, a haplotype occurring only in African Americans characterized by two SNPs in the promoter and one in the 3'-UTR of ADRA2B was associated with a smaller maximal vasoconstriction response (Muszkat et al., 2005). On the other hand, hemodynamic effects of the α2-AR antagonist yohimbine were not associated with this and other genetic variants in ADRA2B (Etzel et al., 2005). Table 3 summarizes key findings relating to the ADRA2B del301-303 variants.

A deletion mutant involving 12 nucleotides and 4 encoded amino acids (Fig. 2, Del322-325; I/D variant) has been found in the gene of the α2C-AR (ADRA2C) and apparently is more prevalent in African Americans than in white persons (Table 1). Whereas this variant exhibits a reduced affinity for and functional response to agonists in transfected cells (Table 4) (Small et al., 2000), little is known about possible implications of this polymorphism for cardiovascular drug responses. In theory, the reduced activity of the α2C-AR, with the deletion of amino acids 322 to 325, should lead to a reduced inhibition of NE release from the presynaptic nerve terminals and ultimately result in increased adrenergic drive. However, in healthy persons, basal parameters of the sympathetic nervous system, including heart rate, heart rate variability, blood pressure, and concentrations of NE and EPI were not affected by this variant (Table 4) (Kurnik et al., 2007). Intravenous administration of the α2-agonist dexametomidine to healthy subjects results in blood pressure lowering and a decrease in plasma catecholamine concentrations. These effects exhibit a considerable interindividual variability; however, the I/D polymorphism in the α2C-AR gene did not contribute to this heterogeneity (Table 4) (Kurnik et al., 2008a). Another group reported enhanced sympathetic nervous and adrenomedullary activities in carriers of the deletion variant. In the presence of the α2-AR blocker yohimbine, catecholamine release and heart rate were higher in persons with the deletion variant (Neumeister et al., 2005). Likewise, application of a cold pressure test resulted in increased heart rate responses in healthy vol-
unteers carrying the deletion variant (Table 4) (Kurnik et al., 2008b).

Apart from its effects on ligand activities, the ADRA2C deletion variant has been identified to increase the risk for congestive heart failure, an effect that is further augmented in presence of the β2-AR Arg389 variant. Based on these data, it has been proposed to guide preventive treatment regimes by pharmacogenomic measures (i.e., genotyping of both variants in patients at risk) (Small et al., 2002). In a later trial, patients with heart failure who had α2c-AR deletion variant actually exhibited a more pronounced increase in the ejection fraction upon treatment with β-blockers (Lobmeyer et al., 2007). However, the original observation of an increased risk for heart failure in carriers of the deletion allele has not been confirmed in other studies, particularly in non-African American populations (Nonen et al., 2005; Metra et al., 2006; Canham et al., 2007). Key findings relating to the ADRA2C del322-325 variant are summarized in Table 4.

Independent from polymorphisms in their cognate receptors, responses to α2-AR ligands may be affected by genetic variability in elements of their signaling cascade. Several studies have addressed potential effects of a common genetic variant in the gene for the G protein β3 subunit (Table 5, GNB3). G proteins consist of a Ga subunit that carries the enzymatic activity and a stable Gβγ dimer. In its inactive GDP-bound state, Ga subunits form heterotrimers with free Gβγ subunits. Upon ligand binding to a GPCR, a conformational change of the receptor occurs that is transmitted to an interacting G protein. This favors the exchange of Ga-bound GDP for GTP, which is the active state of the Ga subunit. Subsequently, the GTP-bound Ga separates from the Gβγ dimer. In case of active GTP-bound GaGβ, stimulation of adenyl cyclase isoforms is the next step of the signaling cascade. Free Gβγ subunits are themselves key regulators of numerous effector systems, including adenyl cyclases, ion channels, and phospholipase C isoforms. The catalytic GTPase activity of the Ga subunit mediates the hydrolysis of GTP to GDP and induces the inactive GDP-bound Ga state in which it reassociates with a Gβγ dimer (for review, see Wettschureck and Offermanns, 2005). A common polymorphism (C825T, rs5443) in the GNB3 has been associated with increased signal transduction (Fig. 3) (Siffert et al., 1998). Major ethnic differences exist in the prevalence of this variant (Table 1). A consistent mechanistic explanation for this observation is still lacking. Available evidence suggests that the 825T allele favors alternative splicing, ultimately resulting in two protein variants termed Gβ3s and Gβ3s2 (Roskopf et al., 2003; Fig. 4). Because G proteins are involved in the signaling cascades of more than a thousand different receptors, complex phenotypes in association with the Gβ3 rs5443 alleles have been described, although not without controversy (for review, see Siffert, 2005). Variants in GNB3 have also been attributed to pharmacogenomic effects, particularly on adrenergic and serotonergic mechanisms (Hauner et al., 2003; Schürks et al., 2007; Wilkie et al., 2007). With regard to ARs, intracoronary administration of the α2a-AR agonist azepexole was associated with increased vasoconstriction in carriers of the 825T allele compared with persons with the wild-type C variant (Table 5) (Baumgart et al., 1999). It is interesting that coronary vasoconstriction induced by the α1-AR agonist methoxamine was not affected by GNB3 variants, potentially indicating a differential coupling of Gβ3 to α1- and α2-ARs (Baumgart et al., 1999). In an independent study of 131 patients, an increased coronary vasoconstrictor response was observed in association with the 825T allele upon injection of methylergonovine, a semisynthetic ergot alkaloid that acts as an agonist on α1- and α2-ARs and on serotonin receptors (Table 5) (Meirhaeghe et al., 2001). Additional evidence for pharmacogenomic modulation of α2-AR responses by GNB3 variants has been provided by a clinical trial in 30 young healthy subjects who were treated with clonidine. Carriers of the 825T allele exhibited an increased lowering of systolic blood pressure, a greater reduction in peripheral resistance, and a more pronounced slowing of pulse wave velocity (Table 5) (Nürnberger et al., 2003). Likewise, NE-induced vasoconstriction in the microcirculation was increased in carriers of the 825T allele (Table 5) (Wenzel et al., 2002). In contrast, hand vein vasoconstriction upon administration of the α2-AR agonist azepexole and changes in total peripheral resistance in the presence of α-methylnorepinephrine were similar in carriers of the C and T alleles of the C825T variant (Schäfers et al., 2001). A similar finding was observed with NE-induced vasoconstriction, which was not different between carriers of the

**TABLE 2**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Result</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Association study with benign prostate hyperplasia in Japanese; expression studies with recombinant receptor variants</td>
<td>No association with prostate hyperplasia; no differences in ligand binding or signal transduction</td>
<td>Shibata et al., 1996</td>
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<tr>
<td>Hand vein constriction in response to phenylephrine in 74 healthy adults</td>
<td>No effects on investigated parameters</td>
<td>Sofowora et al., 2004</td>
</tr>
<tr>
<td>Hemodynamic epinephrine response in 16 young healthy men</td>
<td>CysCys Genotype, longer ECG PR interval; no effect on blood pressure response</td>
<td>Snapir et al., 2003</td>
</tr>
<tr>
<td>Association study with hypertension in 480 Chinese patients with hypertension and control subjects</td>
<td>Arg allele more frequent in patients with hypertension</td>
<td>Gu et al., 2006</td>
</tr>
</tbody>
</table>
T and C alleles (Table 5) (Mitchell et al., 2006). On the other hand, these investigators reported that, after systemic treatment with an endothelin receptor antagonist, NE-induced vasoconstriction of the dorsal hand vein was much more pronounced in T allele carriers, discrepancies that are not easily explained (Mitchell et al., 2004). In contrast to the effects on vasoconstriction, clonidine-mediated antilipolytic responses were less potent in carriers of the 825T allele compared with persons with the wild-type allele (Ryden et al., 2002). Although the possibility of genetic heterogeneity in receptor signaling molecules, rather than in the receptors, is intriguing and deserves further investigation, the inconclusive data on the C825T polymorphism are far from being understood. The possibility of tissue-specific signaling mechanisms has to be taken into account. On the other hand, effects of the \textit{GNB3} C825T polymorphism seem to be of only moderate degree as recently shown in a meta-analysis for hypertension, the most frequently studied phenotype in association with the \textit{GNB3} variants (Bagos et al., 2007).

In summary, there is good evidence that the ε2C-AR deletion variant prevailing in African ethnicities is of functional relevance. Several independent studies underscore that the \textit{GNB3} 825T allele further modulates effects of ε2C-AR agonists (Table 5). ARs and G proteins are interacting partners in signal transduction. The observed effects of both, the \textit{GNB3} C825T and the \textit{ADRA2C} del322-325 variants, are of moderate degree (Tables 4 and 5). Hence, it is sensible to search for interactions of such variants, as recently demonstrated for these polymorphisms in \textit{GNB3} and \textit{ADRA2C} (Kurnik et al., 2008b). The major drawback of such approaches is of course the necessity for much larger cohorts.

C. \textit{β}-Adrenergic Receptor Ligands

Several polymorphisms have been described in the human \textit{β}1-AR gene (\textit{ADRB1}), among which S49G and G389R have been studied most intensively (Fig. 4) (Brodde, 2008). Other SNPs within the coding region of the \textit{β}1-AR, such as A59S, R399C, H402R, T404A, or P418A, have allele frequencies of only approximately 1%, and little information is available regarding their functional role, particularly with regard to drug effects (Leineweber et al., 2004). Besides these SNPs in the coding sequence, numerous variants in the 5'-flanking region of the \textit{β}1-AR gene have been identified and clustered in haplotypes. In vitro transfection experiments of whole-gene constructs revealed major differences in \textit{β}1-AR expression levels. At present, it remains open how this translates in altered function in vivo (Small et al., 2008).

The S49G and G389R SNPs are in tight linkage disequilibrium, and a haplotype with a homozygous Gly in both positions exists very rarely, if at all. The Gly49 and Gly389 variants are found with allele frequencies of 25 and 27%, respectively, in white populations (Brodde, 2008). Although both variants are cosmopolitan, allele frequencies vary to a minor extent in other ethnicities (Table 1) (Moore et al., 1999; Xie et al., 2001; Belfer et al., 2005; Nonen et al., 2005). The Ser49 and Gly49 variants apparently respond similarly to agonists at
physiological expression levels; however, the Gly49 variant is more susceptible to agonist-induced down-regulation, leading to lower receptor densities in vivo (Table 6) (Levin et al., 2002; Rathz et al., 2002). An enhanced susceptibility toward agonist-induced down-regulation may not only manifest during extended treatment with exogenous agonists but also in the presence of endogenous agonists, particularly during states of chronically enhanced sympathoadrenal activity. In contrast, the Arg389 variant seems to couple more effectively to Go protein and adenylyl cyclase stimulation; hence, it is considered to be a gain of function variant (Table 6) (Mason et al., 1999).

A range of polymorphisms in the human β2-AR gene (ADRB2) has been identified, among which the R16G, Q27E, and T164I have received the most attention (Fig. 4). More than a dozen additional SNPs have been reported, but many of them are rare, and the available knowledge on their functional relevance is limited for all of them, particularly with regard to drug-response studies (Brodde, 2008). The genotypes Gly16 and Glu27 are frequent in whites (approximately 50%), but a somewhat different prevalence may exist in other ethnicities (Table 1) (Hawkins et al., 2006; Lima et al., 2006; Wu et al., 2006). Genotype-phenotype association studies for the frequent R16G and Q27E variants have largely remained inconclusive with regard to arterial hypertension and other cardiovascular diseases (Hahntow et al., 2006; Rosskopf et al., 2007). Neither of the variants in position 16 or 27 is associated with major alterations in ligand affinity or in vitro signaling potency. However, the Gly16 variant has been shown to be more susceptible to agonist-induced down-regulation, whereas the Glu27 variant is relatively resistant to agonist-mediated desensitization processes (Table 7) (Green et al., 1994). If the two variant alleles occur in combination, the Gly16 effects dominate the phenotype; i.e., a Gly16/Glu27 double mutant also exhibits enhanced agonist-induced down-regulation; in contrast, the Arg16/Glu27 double mutant was completely resistant to down-regulation (Green et al., 1994). The T164I polymorphism has been consistently associated with altered receptor function both in vitro and in vivo (Table 7). Clinical phenotypes have been reported much more consistently, but because of its low prevalence (approximately 3% in whites; never
FIG. 3. Gene structure and proposed three-dimensional structure of Gβ3 and its splice variants, Gβ3s and Gβ3s2. Top, the Gβ3 gene consists of 11 exons; coding exons are indicated in black. The frequently investigated SNP C825T (rs5443) is almost completely linked to four additional variants (rs11064426, rs2301339, rs13306405, and rs5446). Pre-mRNA transcripts carrying the 825T allele favor alternative splicing at two sites indicated by hatched boxes. Bottom, Gβ3 proteins belong to the superfamily of propeller proteins. They comprise seven “propeller blades,” each formed by the equivalent of a WD protein domain. Shown is the entire Gβ3/H9253 dimer composed of a Gβ3 subunit (cyan) and a Gβ3 subunit (blue). Splicing of the 5’ part of exon 9 of the Gβ3 gene leads to transcripts for Gβ3s. Deletion of an internal part of exon 10 gives rise to transcripts for Gβ3s2. In both cases, the exact equivalent of one WD domain is missing, which affects different propeller blades in Gβ3s and Gβ3s2, as denoted. Propeller proteins with 4 to 12 WD domains have been described. Hence, Gβ3s and Gβ3s2 may form a six-blade structure. Free Gβγ dimers play important roles in the coordination of multiprotein complexes. Together with a Go subunit in its GDP state, they form a stable heterotrimer. It has been hypothesized that Gβ3 variants are less capable of stabilizing the Go subunit in its GDP state, thus giving rise to enhanced signal transduction.

TABLE 5

<table>
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<tr>
<th>Parameters Analyzed</th>
<th>Results</th>
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<tr>
<td>Association study with hypertension; functional analyses of variant</td>
<td>T allele associated with hypertension, occurrence of altered splice variant and increased signal transduction in association with T allele</td>
<td>Siffert et al., 1998</td>
</tr>
<tr>
<td>Coronary vasoconstriction in response to α1-AR agonist azepexole in 48 patients with coronary artery disease</td>
<td>T allele, increased coronary blood flow reduction</td>
<td>Baumgart et al., 1999</td>
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<td>Coronary vasoconstriction in response to methylergonovine in 131 patients with healthy coronary arteries</td>
<td>T allele, increased susceptibility to vasoconstriction</td>
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<td>Hemodynamic parameters in 70 volunteers upon administration of propranolol and α-methylnorepinephrine</td>
<td>T allele, higher stroke volume &amp; lower peripheral resistance; propranolol evokes greater fall in stroke volume. No effect on hand vein constriction.</td>
<td>Schäfers et al., 2001</td>
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<tr>
<td>Effects of endothelin-1, angiotensin II, and norepinephrine on skin microcirculation in 25 volunteers</td>
<td>T allele, enhanced vasoconstriction to endothelin-1, angiotensin II and norepinephrine</td>
<td>Wenzel et al., 2002</td>
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<tr>
<td>Hemodynamic clonidine responses in 30 young healthy individuals</td>
<td>T allele, greater fall in blood pressure &amp; total peripheral resistance; slowing of pulse wave velocity.</td>
<td>Nurnberger et al., 2003</td>
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<tr>
<td>Interactions of endothelin A receptor antagonist darusentan with endothelin-1, norepinephrine and angiotensin II in 37 volunteers</td>
<td>No effects on systemic or local responses to endothelin A receptor blockade</td>
<td>Mitchell et al., 2004</td>
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<tr>
<td>Interactions of angiotensin II receptor antagonents with endothelin 1, norepinephrine and angiotensin II in 25 volunteers</td>
<td>T allele, more pronounced inhibition by valsartan of angiotensin II- or endothelin 1-mediated vasoconstriction in the microcirculation.</td>
<td>Mitchell et al., 2006</td>
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<tr>
<td>Blood pressure and heart rate response to cold pressure test in 79 healthy subjects</td>
<td>TT genotype: greater positive chronotropic response</td>
<td>Kurnik et al., 2008b</td>
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<tr>
<td>Hemodynamic dexmedetomidine responses in 73 healthy subjects</td>
<td>No effects on investigated parameters</td>
<td>Kurnik et al., 2008b</td>
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</table>

Fig. 3. Gene structure and proposed three-dimensional structure of Gβ3 and its splice variants, Gβ3s and Gβ3s2. Top, the Gβ3 gene consists of 11 exons; coding exons are indicated in black. The frequently investigated SNP C825T (rs5443) is almost completely linked to four additional variants (rs11064426, rs2301339, rs13306405, and rs5446). Pre-mRNA transcripts carrying the 825T allele favor alternative splicing at two sites indicated by hatched boxes. Bottom, Gβ3 proteins belong to the superfamily of propeller proteins. They comprise seven “propeller blades,” each formed by the equivalent of a WD protein domain. Shown is the entire Gβ3/H9253 dimer composed of a Gβ3 subunit (cyan) and a Gβ3 subunit (blue). Splicing of the 5’ part of exon 9 of the Gβ3 gene leads to transcripts for Gβ3s. Deletion of an internal part of exon 10 gives rise to transcripts for Gβ3s2. In both cases, the exact equivalent of one WD domain is missing, which affects different propeller blades in Gβ3s and Gβ3s2, as denoted. Propeller proteins with 4 to 12 WD domains have been described. Hence, Gβ3s and Gβ3s2 may form a six-blade structure. Free Gβγ dimers play important roles in the coordination of multiprotein complexes. Together with a Go subunit in its GDP state, they form a stable heterotrimer. It has been hypothesized that Gβ3 variants are less capable of stabilizing the Go subunit in its GDP state, thus giving rise to enhanced signal transduction.
found homozygously, so far), it has been studied less extensively (Michel and Büscher, 2008).

The \(\beta_3\)-AR plays a much smaller role in the regulation of cardiovascular functions than the other two \(\beta\)-AR subtypes. Whereas some investigators have proposed presence and functional role of \(\beta_3\)-AR in the human heart, the overall evidence in this regard remains equivocal (Brodde and Michel, 1999). \(\beta_3\)-AR may also contribute to the regulation of vascular tone in some mammals, but only little data on humans are available (Rozec and Gauthier, 2006). Among polymorphisms in the \(\beta_3\)-AR gene (ADRB3), only the W64R variant has been investigated in greater detail, predominantly in the context of metabolic regulation (Arch, 2008). Hence, little information is available addressing the potential effects of this SNP on drug responses in the cardiovascular system, at least partly reflecting the general paucity of data with \(\beta_3\)-selective ligands, which have been investigated in humans (Vrydag and Michel, 2007). Therefore, the following will focus on the pharmacogenomics of human \(\beta_1\) and \(\beta_2\)-ARs.

1. \(\beta\)-Agonist Responses. With regard to agonist responses, most studies on \(\beta_1\)-AR polymorphisms have investigated a possible role of the R389G variant. Using right atria from patients undergoing coronary bypass grafting, one group of investigators demonstrated that the Gly389 variant was associated with smaller cAMP and inotropic responses (Table 6) (Sandilands et al., 2003), but other investigators did not find such differences (Table 6) (Molenaar et al., 2002; Sarsero et al., 2003). Four different in vivo studies reported that the R389G polymorphism does not affect heart rate or inotropic or plasma renin activity responses to bicycle exercise, which presumably reflects responses to the endogenous agonist NE (Table 6) (Büscher et al., 2001; Xie et al., 2001; Liu et al., 2003; Sofowora et al., 2003). Likewise, two studies published in abstract form reported that this SNP does not affect chronotropic or renin responses to infusion of the agonist dobutamine, although one of them reported an effect on cardiac contractility (Leineweber et al., 2004). On the other hand, carriers of the \(\beta_1\)-AR Gly389 or Ser49 variants had a higher need for an increase in heart failure medication during metoprolol therapy (Terra et al., 2005). Likewise, the demand for inotropic catecholamine support after coronary artery bypass grafting was higher in homozygous carriers of the Gly389 variant compared with homozygous carriers of the Arg389 variant, both treated with metoprolol (Table 6) (Leineweber et al., 2007). In both studies, however, it remains unclear whether these genotype-dependent effects reflect altered agonist and/or antagonist responses.

With regard to variants in the \(\beta_2\)-AR gene ex vivo studies from genotyped subjects using circulating mononuclear cells (mostly lymphocytes), airway smooth muscle cells, lung mast cells, or adipocytes demonstrated that neither the R16G nor the Q27E SNP affected \(\beta_2\)-AR expression (Lipworth et al., 1999) or basal or maximally stimulated adenylyl cyclase activity (Table 7) (Large et al., 1997; Lipworth et al., 1999; Moore et al., 2000; Bruck et al., 2003a). In line with findings from transfected cells,
the Gly16 genotype exhibited greater agonist-induced desensitization in human airway smooth muscle cells (Table 7) (Moore et al., 2000), although that was not confirmed in a study on human lung mast cells (Table 7) (Chong et al., 2000). Likewise, a greater agonist-induced desensitization was reported for the Glu27 variant in human airway smooth muscle cells (Moore et al., 2000), whereas less desensitization was found for the Gly16 genotype. These data suggest the possibility that the effects of these SNPs in the amino terminus of the β2-AR may depend on the cell type in which it is expressed. In contrast, the Ile164 variant, even if present in the heterozygote state only, was consistently associated with lower potency and/or maximal responses to various β-AR agonists in lymphocytes (Buscher et al., 2002), human lung mast cells (Kay et al., 2003), or adipocytes (Table 7) (Hoffstedt et al., 2001).

Most in vivo studies in volunteers reported a lack of effect of the R16G or the Q27E SNP on chronotropic and inotropic responses to agonists, such as terbutaline (Table 7) (Gratze et al., 1999; Hoit et al., 2000; Bruck et al., 2003a). In light of the limited role of β2-AR in the human heart (Brodde and Michel, 1999), this is not surprising. Studies on vascular function have reported that the Glu27 variant is associated with higher responsiveness (Cockcroft et al., 2000; Dishy et al., 2001), whereas reports on the R16G SNP are equivocal with lower responsiveness of the Gly16 allele (Gratze et al., 1999; Hoit et al., 2000), no difference (Dishy et al., 2001), or higher responsiveness in carriers of the Gly16 allele being reported (summarized in Table 7) (Cockcroft et al., 2000; Garovic et al., 2003). This apparent contradiction with the in vitro data could be explained by the finding that β2-AR are always exposed to some down-regulation

<table>
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<th>Variant</th>
<th>Parameters Analyzed</th>
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<td>G389R</td>
<td>Expression of receptor variants in cell lines</td>
<td>Arg389, gain of function; increased adenylyl cyclase activation</td>
<td>Mason et al., 1999</td>
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<tr>
<td>G389R</td>
<td>β-Blocker responses in 147 patients with hypertension</td>
<td>No effects on investigated parameters</td>
<td>O'Shaughnessy et al., 2000</td>
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<tr>
<td>G389R</td>
<td>Exercise-induced heart rate response in 24 volunteers</td>
<td>No effects on investigated parameters</td>
<td>Xie et al., 2001</td>
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<tr>
<td>G389R</td>
<td>Exercise-induced heart rate response in 17 volunteers</td>
<td>No effects on investigated parameters</td>
<td>Buscher et al., 2001</td>
</tr>
<tr>
<td>S49G</td>
<td>Expression of receptor variants in cell lines</td>
<td>Gly49, higher basal and stimulated adenylyl cyclase activity; more sensitive toward inhibition by metoprolol; higher desensitization</td>
<td>Levin et al., 2002</td>
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<td>S49G</td>
<td>Expression of receptor variants in cell lines</td>
<td>Similar ligand binding affinities; Gly49 enhanced down-regulation</td>
<td>Rathz et al., 2002</td>
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<td>S49G/G389R</td>
<td>Norepinephrine actions on atrial muscle from 87 patients undergoing coronary artery bypass surgery</td>
<td>No effects on investigated parameters</td>
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<td>G389R</td>
<td>Exercise-induced heart rate response in 16 volunteers</td>
<td>No effects on exercise-induced heart rate; enhanced response to metoprolol in Arg389</td>
<td>Liu et al., 2003 R</td>
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<tr>
<td>G389R</td>
<td>Analysis of receptor function in human atria from 54 patients</td>
<td>Arg389 enhanced CAMP and inotropic responses</td>
<td>Sandilands et al., 2003</td>
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<tr>
<td>S49G/G389R</td>
<td>Analysis of receptor function in human atria</td>
<td>No effects on investigated parameters</td>
<td>Sarsero et al., 2003 G</td>
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<tr>
<td>G389R</td>
<td>Exercise-induced heart rate response in 34 volunteers</td>
<td>No effects on investigated parameters</td>
<td>Sofowora et al., 2003</td>
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<td>G389R</td>
<td>Treatment of 40 patients with hypertension with metoprolol</td>
<td>Arg389 larger reduction in diastolic blood pressure upon atenolol; no effect on exercise-induced responses</td>
<td>Johnson et al., 2003</td>
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<tr>
<td>G389R</td>
<td>Hemodynamic parameters and mortality during metoprolol treatment in 600 patients</td>
<td>No effects on investigated parameters</td>
<td>White et al., 2003</td>
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<tr>
<td>S49G/G389R</td>
<td>Treatment of 101 patients with hypertension with left ventricular hypertrophy with atenolol</td>
<td>No effects on investigated parameters</td>
<td>Karlsson et al., 2004</td>
</tr>
<tr>
<td>S49G/G389R</td>
<td>Analysis of 61 patients with heart failure on therapy with metoprolol</td>
<td>No difference in rate of cardiac decompensation; Gly389 and Ser49 required more heart failure medications</td>
<td>Terra et al., 2005</td>
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<tr>
<td>S49G/G389R</td>
<td>199 heart failure patients treated with β-blockers</td>
<td>No differences in heart rate and ejection fraction before and after β-blocker therapy</td>
<td>de Groot et al., 2005</td>
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<tr>
<td>S49G/G389R</td>
<td>Metoprolol titration in 54 untreated patients with hypertension</td>
<td>Ser49 higher baseline resting heart rates; no effect on response to β-blocker</td>
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<td>G389R</td>
<td>Analysis in cell transfected cells; outcome to bucindolol in 1040 heart failure patients</td>
<td>Agr389 carriers treated with bucindolol no clinical response</td>
<td>Liggett et al., 2006</td>
</tr>
<tr>
<td>G389R</td>
<td>Demand for catecholamine support in heart surgery patients</td>
<td>Arg389/G389 patients required less adrenaline support</td>
<td>Leineweber et al., 2007</td>
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<tr>
<td>G389R</td>
<td>Outcome of heart failure with carvedilol in 135 patients</td>
<td>Arg389/G389 greater improvement in left ventricular ejection fraction after 1.5 years of treatment</td>
<td>Chen et al., 2007</td>
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<tr>
<td>S49G/G389R</td>
<td>Patient registry study with 637 heart failure patients treated with metoprolol or carvedilol</td>
<td>No difference in survival rates</td>
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<td>S49G/G389R</td>
<td>Follow-up of 5895 coronary artery disease patients treated with atenolol or verapamil</td>
<td>Increased mortality risk in verapamil group with Ser49-Arg389; no effect in atenol group</td>
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stimuli by endogenous agonist and that the relative resistance toward agonist-induced down-regulation may result in greater responses (see below). In agreement with the in vitro data, the rare Ile164 variant of the β2-adrenoceptor was associated with reduced heart rate and contractile in vivo responses to terbutaline in healthy volunteers (Bruck et al., 2003b) and in patients with heart failure (Table 7) (Barbato et al., 2007).

Based upon the mentioned in vitro findings of altered susceptibility to agonist-induced desensitization in some (Moore et al., 2000) but not other cell types (Chong et al., 2000), other studies have assessed whether any of the above genotypes is also associated with alterations in in vivo desensitization upon extended agonist treatment. The results of such trials have remained equivocal. Thus, the Arg16 rather than the Gly16 variant of the β2-AR was reported to be associated with enhanced short-term agonist-induced desensitization in studies using the dorsal hand vein technique (Dishy et al., 2001). In other studies, volunteers were treated orally with terbutaline for up to 2 weeks with subsequent assessment of chronotropic and inotropic response to intravenous terbutaline (Bruck et al., 2003c). In these experiments, neither the R16G nor the Q27E polymorphism affected the extent of agonist-induced desensitization, but the Glu27 homozygotes exhibited a slower desensitization than the other groups. The same group of investigators also reported similar findings for the in vivo down-regulation of lymphocyte β2-AR (Bruck et al., 2003a, 2005).

Although β-AR agonists have a well established place in obstructive airway disease—which is out of the scope of this review—and may cause cardiovascular side effects such as tachycardia, their primary use for the treatment of cardiovascular disease is largely limited to settings of acute heart failure (e.g., immediately after cardiac surgery or in shock). With possible exception of the rare β2-AR T164I polymorphism, the overall, although not unequivocal, evidence suggests only a minor role, if any, of β-AR polymorphisms in short-term agonist responses. The case for an effect of β2-AR SNPs on susceptibility to agonist-induced desensitization is more convincing; however, its clinical relevance for agonist use in cardiovascular medicine remains unclear because such drugs typically are not administered long term. When such agonists are used long term in pulmonary medicine and exhibit cardiovascular side effects, the role of polymorphisms affecting desensitization also remains unclear in light of the frequent concomitant administra-

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<tr>
<td>R16G/Q27E</td>
<td>Expression of receptor variants in cell lines</td>
<td>Arg16, increased agonist-induced receptor down-regulation; Glu27 completely resistant to down-regulation</td>
<td>Green et al., 1994</td>
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<td>T164I</td>
<td>Functional analysis including transgenic animals</td>
<td>Ile164 is dysfunctional variant</td>
<td>Turki et al., 1996</td>
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<tr>
<td>R16G/Q27E</td>
<td>Functional analysis including transgenic animals</td>
<td>Glu27 is completely resistant to down-regulation</td>
<td>Turki et al., 1996</td>
</tr>
<tr>
<td>R16G/Q27E</td>
<td>Functional analysis of human lung mast cells</td>
<td>Ile164 is dysfunctional variant</td>
<td>Turki et al., 1996</td>
</tr>
<tr>
<td>R16G/Q27E</td>
<td>Functional analysis of human airway smooth muscle</td>
<td>Ile164 is dysfunctional variant</td>
<td>Turki et al., 1996</td>
</tr>
<tr>
<td>R16G/Q27E</td>
<td>Hemodynamic terbutaline responses in 20 volunteers</td>
<td>Ile164 is dysfunctional variant</td>
<td>Turki et al., 1996</td>
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<tr>
<td>R16G/Q27E</td>
<td>Brachial artery infusion with isoproterenol in 127</td>
<td>Ile164 is dysfunctional variant</td>
<td>Turki et al., 1996</td>
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<tr>
<td>R16G/Q27E</td>
<td>Isoproterenol-mediated venodilation in 26 volunteers</td>
<td>Arg16 increased agonist-mediated desensitization; Glu27 increased agonist-mediated responsiveness</td>
<td>Dishy et al., 2001</td>
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<td>R16G/Q27E</td>
<td>Down-regulation of β2-AR on lymphocytes upon</td>
<td>No difference in extent of down-regulation</td>
<td>Bruck et al., 2003a</td>
</tr>
<tr>
<td>R16G/Q27E</td>
<td>Hemodynamic terbutaline responses in 16 volunteers</td>
<td>Ile164 is dysfunctional variant</td>
<td>Dishy et al., 2003b</td>
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<tr>
<td>R16G/Q27E</td>
<td>Hemodynamic terbutaline responses in 32 volunteers</td>
<td>Ile164 is dysfunctional variant</td>
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<tr>
<td>R16G/Q27E</td>
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<td>R16G/Q27E</td>
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<td>R16G/Q27E</td>
<td>Registry study with 637 heart failure patients</td>
<td>Ile164 is dysfunctional variant</td>
<td>Barbato et al., 2007</td>
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<tr>
<td>R16G/Q27E</td>
<td>Follow-up of 5895 coronary artery disease patients</td>
<td>No difference in event rates</td>
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tion with glucocorticoids, which can counteract agonist-induced β2-AR desensitization (Postma et al., 2008).

2. β-Antagonist Responses. The interpretation of pharmacogenomic β-AR antagonist data are less straightforward than that of agonist data in several ways. For example, a functionally relevant polymorphism in a β2-AR may affect prejunctional control of NE release and, hence, may modulate antagonist responses by making it compete with altered amounts of agonist. Moreover, responses to β-AR agonists have mostly been studied upon short-term administration, whereas responses to antagonists, particularly in patients, have mostly been investigated upon long-term use. The latter implies the possibility that genetic variants may not primarily influence the drug response itself but rather homeostatic mechanisms occurring during prolonged drug treatment. Furthermore, clinical medicine uses β-AR antagonists that either have similar affinity for β1- and β2-AR or exhibit some degree of selectivity for β1-AR. In most cardiovascular indications, β1-selective and nonselective antagonists are similarly effective, indicating that blockade of β1-AR may be sufficient to reach a therapeutic response. Nevertheless, in some indications, such as congestive heart failure, not all β-AR antagonists are similarly effective (Brodde, 2007). Although the reasons for such compound-specific effects are not fully clear, they may relate to a phenomenon called ligand-directed signaling or biased agonism (Michel and Alewijnse, 2007). In this regard, it was reported that the β-AR antagonists bisoprolol and metoprolol exhibited similar inverse agonism at Gly389 and Arg389 variants of the β1-AR, whereas carvedilol showed significantly greater inverse agonism at the Arg389 variant (Rochais et al., 2003). Within the same study, carvedilol also had greater inhibitory effects on spontaneously beating cardiomyocytes transfected with the Arg389 compared with the Gly389 variant. Other investigators reported enhanced negative propranolol effects on inotropy in Arg389 transgenic mice (Mialet Perez et al., 2003). Thus, in vitro and animal data demonstrate that findings obtained with one β-AR antagonist are not necessarily predictive for those with other representatives from that class. Finally, it is being debated whether polymorphisms related to drug-metabolizing enzymes (i.e., CYP2D6 poor metabolizer state in the context of metoprolol or carvedilol administration) may alter clinical effects of β-AR antagonists in a way that overshadows those of polymorphisms in the receptors or their signal transduction pathways (Kirchheiner et al., 2004; Zineh et al., 2004; Terra et al., 2005; Ismail and Teh, 2006). Although some of these arguments on theoretical grounds should also be applicable to at least some β-AR agonists, until now they have been considered mainly in the context of antagonist exposure.

Several groups of investigators have studied clinical responses to β-AR antagonists depending on β1-AR genotype, most of which were performed in patients with hypertension. Two studies with short-term single dose administration of atenolol (Sofowora et al., 2003) or metoprolol (Liu et al., 2003) to healthy volunteers reported larger reductions of blood pressure and/or resting heart rate in homozygous Arg389 compared with homozygous Gly389 carriers (Table 6). Likewise, a patient study reported that long-term treatment with metoprolol yielded greater blood pressure reductions in Arg389 carriers (Johnson et al., 2003). However, four other studies did not confirm greater hemodynamic effects of β-AR antagonists in patients with an Arg389 compared with those with a Gly389 genotype (summarized in Table 6) (O’Shaughnessy et al., 2000; Filigheddu et al., 2004; Karlsson et al., 2004; Beitelshesee et al., 2006).

Given that variants in the AR genes affect hemodynamic responses in β-blocker therapy and that such variants also affect the risk of congestive heart failure as proposed for β1- and α2C-AR variants (Small et al., 2002)—although both notions are not without controversy—one major question is whether β-blocker therapy affects primary endpoints of patients with heart failure in a genotype-dependent fashion. In a study of the MERIT HF trial (Metoprolol CR/XL Randomized Intervention Trial in Chronic Heart Failure), 307 patients on metoprolol and 293 patients on placebo were genotyped for the ADRB1 G389R variant. After a follow-up period of 12 months, the ADRB1 variants were associated with neither the degree of heart rate reduction nor with all-cause death or hospitalization (Table 6) (White et al., 2003). One problem of this study is that outcomes were compared between ADRB1 genotypes irrespective of the respective treatment assignment, making it difficult to draw conclusions about β-blocker therapy. In contrast, the BEST study (β-blocker Evaluation of Survival Trial) enrolled 1040 patients with heart failure who were treated with bucindolol or placebo in addition to standard heart failure therapy. The patients were genotyped for the ADRB1 G389R variant. This phenotype did not affect hospitalization rates and survival in the placebo group. However, homozygous carriers of the Arg389 variant treated with bucindolol exhibited a significant reduction in mortality and hospitalizations, whereas β-blocker treatment with bucindolol was without effect in carriers of the Gly389 variant, indicating a strong pharmacogenomic effect (Liggett et al., 2006). Bucindolol is a nonselective β-blocker with additional sympatholytic effects (Liggett et al., 2006). It displays substantially higher intrinsic sympathomimetic activity (partial agonism) than metoprolol and carvedilol. However, depending on the examined tissue, it can also behave as a partial inverse agonist (Maack et al., 2000). Whereas metoprolol, bisoprolol, or carvedilol (i.e., β-blockers devoid of intrinsic sympathomimetic activity but with inverse agonistic activity) markedly reduced mortality in patients with heart failure, this was not the case for bucindolol (The Betablocker Evaluation Survival Trial Investigators, 2001). Together, the situation with bucind-
dolol may not be representative for other more frequently used compounds. An observational trial with 227 heart failure patients on standard therapy, including β-blockers, reported that carriers of two copies of the ADRB2 Arg16-Gln27 haplotype had a 2.5-fold increase in risk for adverse outcomes within 4 years. Variants in ADRB1, ADRA2C, and in components of the RAAS (ACE, AGTR1, AGT) had no effect on mortality (Shin et al., 2007). The problem of this work is that it does not allow us to classify observed pharmacogenomic effects to a definite class of drugs. In another study on the role of ADRB2 variants in heart failure therapy with carvedilol, homozygous and heterozygous carriers of the Glu27 allele had an almost 3-fold higher chance compared with homozygous carriers of the Gln27 allele to belong to the responder group defined by an improvement in ejection fraction of more than 10% (Table 7) (Kaye et al., 2003). In contrast, ADRB2 variants did not affect the degree of improvement in left ventricular ejection fraction during 18 months of carvedilol therapy in patients with heart failure in another study. Here, improvement in left ventricular ejection fraction was best in patients who were homozygous carriers of the gain-of-function Arg389 variant in ADRB1 (Tables 6 and 7) (Chen et al., 2007).

In a recent study, 637 patients with heart failure from two registries were discharged on a therapy with metoprolol or carvedilol in addition to standard RAAS inhibition and diuretic therapy. They were genotyped for propranolol or carvedilol in addition to standard RAAS inhibition. Two registries were discharged on a therapy with metoprolol (Chen et al., 2007). Improvement in left ventricular ejection fraction was best in patients with heart failure in another study. Here, improvement in left ventricular ejection fraction was best in patients who were homozygous carriers of the gain-of-function Arg389 variant in ADRB1 (Tables 6 and 7) (Chen et al., 2007).

A major problem of such a registry study is that adherence of the patients to drug therapy was tested only 60 days after enrollment. Furthermore, no adjustments for β-blocker dose was made. Nevertheless, this study is in accordance with a smaller trial that did not observe an effect of any of these variants on improvement in left ventricular ejection fraction upon β-blocker therapy in patients with heart failure (de Groote et al., 2005). In another recent study, 5895 patients with coronary artery disease and hypertension were treated with either atenolol or verapamil (sustained release) for blood pressure control. Patients with the ADRB1 Ser49G and G389R, the ADRB2 polymorphisms G16R and Q27E, and the ADRA2C variant del322-325 and followed for approximately 3 years. None of the investigated variants affected all-cause mortality or transplant-free survival (Sehnert et al., 2008).

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An important element in β-AR signaling—and also for many other GPCRs—is the function of G protein-coupled receptor kinases (GRKs) that were originally discovered by their ability to phosphorylate the activated forms of β-AR and related GPCR. Phosphorylation is followed by binding of arrestin proteins, which prevent receptors from activating downstream heterotrimeric G protein pathways while allowing activation of arrestin-dependent signaling pathways (e.g., cascades involved in cell proliferation or receptor trafficking) (for review see Premont and Gainetdinov, 2007; Moore et al., 2007). A L41Q variant has been identified in the gene of GRK5 (Liggett et al., 2008). GRK5 and GRK2 (also known as β-AR kinase) are involved in the phosphorylation of β-ARs and contribute to β-AR desensitization. The GRK5 Leu41 variant was more potent in uncoupling isoproterenol-stimulated responses than the GRK5 Gln41 variant. The GRK5 Leu41 variant occurs predominantly in persons with African descent. In patients treated with β-blockers for heart failure or cardiac ischemia, mortality was reduced in carriers of the GRK5 Leu41 variant (Liggett et al., 2008).

Other groups have analyzed variants in various genes not directly involved in β-AR signaling, including those for angiotensinogen (AGT), the AT1 receptor, and transforming growth factor β1 and for diverse outcome parameters, such as alterations of left ventricular mass index (for review, see Shin and Johnson, 2007). However, in most cases in which associations between variants and β-blocker responses were identified, the pathophysiological explanations remain unclear, and in most cases these reports await independent confirmation.

In conclusion, the clinical response to β-AR antagonist may be modulated by heterogeneity in a range of genes, but most of the proposed polymorphism effects in genes other than the β-AR remain to be confirmed. Among β-AR polymorphisms, the Arg389 variant of the β1-AR is hyperfunctional in preclinical studies. Although this has been proposed to translate into altered β-AR antagonist responses by some investigators, the majority of patient studies have not confirmed this finding.

III. Angiotensin II Receptor Ligands and Inhibitors of Angiotensin-Converting Enzyme

Inhibition of the RAAS is a mainstay of current cardiovascular therapy. Estimates based on prescription data suggest that approximately 10% of the population in industrialized countries such as Germany is treated long term with these compounds (Schwabe and Paffrath, 2008). ACE inhibitors and blockers of the AT1 receptor are used for the treatment of hypertension, congestive heart failure, and diabetic nephropathy, among other indications. Aliskiren, the first oral renin-inhibitor, has increased the armamentarium of RAAS inhibition. Furthermore, blockers of the mineralocorticoid receptor, such as spironolactone and eplerenone, which are now frequently used in the therapy of heart failure, also belong to this functional class of drugs. AT is an agonist at two GPCRs, the AT1 and AT2 receptors. AT1 antagonists and AT are ligands of these receptors. Both AT1 receptor function and the generation of AT are modulated by common genetic polymorphisms, which are reviewed in section III.A.

A. Angiotensin-Converting Enzyme Inhibitors and Genetic Variants in the Angiotensin-Converting Enzyme Gene

Given the key importance of the RAAS, many groups searched for genetic variants in the genes of its compounds upon cloning of the respective genes. One of the first widely investigated common variants in cardiovascular medicine is the I/D polymorphism in the ACE gene (ACE, rs1799752; allele frequencies see Table 1; Fig. 5). The deletion comprises 287 base pairs in intron 16 of ACE corresponding to an Alu repeat genetic element. The D allele of this polymorphism is associated with an enhanced enzyme activity (Marre et al., 1994). This I/D polymorphism itself may not directly cause increased ACE activity but it is in linkage disequilibrium with other polymorphisms directly affecting enzyme activity. In this regard, the A2350G SNP shows a tighter correlation with ACE activity than the I/D polymorphism (Narita et al., 2003). However, only little information is available on the role of this SNP in drug responses, and most studies still focus on the above I/D polymorphism.

The ACE I/D polymorphism has been associated with the risk for many cardiovascular disorders, although many observations remained unconfirmed. Cardiovascular and cardiometabolic disorders allegedly associated with the ACE alleles comprise atrial fibrillation (Ravn et al., 2008), impaired glucose tolerance (Bonnet et al., 2008), diabetes (Feng et al., 2002), diabetic nephropathy (Ng et al., 2005; Hadjadj et al., 2007), myocardial infarction (Niu et al., 2002), hypertension (Agerholm-Larsen et al., 2000), increased carotid artery wall thickness (Sayed-Tabatabaei et al., 2003), left ventricular hypertrophy (Kuznetsova et al., 2004), and Alzheimer’s disease (Meng et al., 2006).

Associations between ACE genotype and clinical response to ACE inhibitors have been tested for a range of diseases. Although most studies have focused on blood pressure lowering, many other studies have investigated preventive effects in (diabetic) nephropathy or other indications of this drug class. Associations between I/D genotype and blood pressure responses have been tested for a range of ACE inhibitors, including benazepril, captopril, enalapril, fosinopril, imidapril, lisinopril, and quinapril. With regard to the clinical response of blood pressure lowering, a systematic review has reported that of 11 retrieved studies, the D allele was associated with greater ACE inhibitor-induced blood pressure lowering in three studies, whereas it was associated with smaller blood pressure lowering in four other studies; four studies found no difference between genotypes.
Using a somewhat different search strategy, other investigators yielded similar conclusions (Mellen and Herrington, 2005). Many of the original studies had been based upon post hoc genotyping, and only few had been specifically designed to test genetic effects. Another systematic review analyzed randomized placebo-controlled trials of ACE inhibitors across a range of cardiovascular and renal indications (Scharplatz et al., 2005). Although a trend for greater antihypertensive responses in white DD carriers compared with II carriers was observed, this analysis also failed to detect consistent effects of the ACE I/D polymorphism in antihypertensive treatment. More recent clinical trials did not change this inconclusive picture (Harrap et al., 2003; Arnett et al., 2005; Bleumink et al., 2005; Schelleman et al., 2005).

This notion of inconclusive effects of the ACE I/D polymorphism also extends to other indications of ACE inhibitors, such as coronary artery disease and surrogate markers thereof (Tsikouris and Peeters, 2007). In a large study on 2089 Chinese patients with type 2 diabetes, carriers of the II and DI genotypes benefited significantly more from inhibition of the RAAS with regard to development of diabetic nephropathy (So et al., 2006). Despite these inconsistent results, it has been proposed that genotyping for the I/D polymorphism may be cost-effective for treatment allocations in the prevention of end-stage renal disease (Costa-Scharplatz et al., 2007).

A series of studies has addressed the effect of the ACE I/D variant on therapeutic responses to AT1 inhibitors. The rationale for these analyses is the hypothesis that increased generation of AT could compete with AT1 blockers at the AT1 receptor. Because diuretics sensitize the RAAS, some investigators have analyzed whether the ACE I/D variant affects blood pressure-lowering effects of diuretics. Whereas the number of available studies in these contexts is smaller than that on ACE inhibitors, they also yielded rather inconsistent results (Kurland et al., 2001, 2002, 2004; Koopmans et al., 2003; Coto et al., 2005). A study in 93 patients with chronic heart failure suggests a modulatory effect of the I/D polymorphism on the left ventricular ejection fraction during spironolactone therapy (Cicoira et al., 2004).

Another key component of the RAAS is AGT. A M235T (rs699) polymorphism in the AGT gene was the first and the most scrutinized candidate variant linked to essential hypertension (Fig. 5). It is in linkage disequilibrium with a T174M (rs4762) polymorphism, also frequently addressed (allele frequencies given in Table 1). Available evidence suggests that the T allele of the M235T variant is associated with higher circulating AGT levels (~20% in homozygous carriers) and increased blood pressure

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B. Variants in the AT\textsubscript{1} Receptor Gene and Responses to AT\textsubscript{1} Blockers

Many groups have intensively searched for genetic variants in the AT\textsubscript{1}R gene and potential associations with cardiovascular diseases or pharmacogenomic effects. Meanwhile more than 600 mostly rare variants have been identified in the AT\textsubscript{1} receptor gene (Oro et al., 2007). However, most studies focused on the only common variant of the AT\textsubscript{1}R gene, the A1166C SNP located in the 3′-UTR (Table 1; Fig. 5). Its functional significance has long been a matter of debate. Recent data indicate that this SNP interrupts the repression of receptor expression by microRNA-155 (Martin et al., 2007). This could contribute to the regulation of in vivo expression levels of the AT\textsubscript{1}R. Among the many other polymorphisms that have been described within the AT1R gene, functional implications have been demonstrated only for one very rare coding SNP of the AT1R gene (Hansen et al., 2004).

Similar to the studies on ACE gene polymorphisms, those for the A1166C SNP in the AT1R gene yielded conflicting results. Compared with the C allele carriers of the A1166C SNP, homozygous AA carriers showed blunted responses to the AT\textsubscript{1} receptor antagonist losartan in one study (Miller et al., 1999). A similarly reduced response was observed in AA carriers for irbesartan-induced regression of left ventricular hypertrophy (Kurland et al., 2002). On the other hand, the opposite (i.e., a significantly greater blood pressure-lowering response to losartan) was reported for AA carriers in another study (Coto et al., 2005). Finally, the blood pressure lowering or reduction of cardiac hypertrophy in response to irbesartan was not related to the A1166C or four other SNPs in the AT1R gene in three other reports (Kurland et al., 2001, 2004; Liljedahl et al., 2004).

In conclusion, a possible relationship between polymorphisms of the AT1R gene and clinical responses to drugs, which work via such receptors or which may involve such receptors indirectly, have not yielded consistent support for the relevance of these variants. Again, it should be noted that almost of all of these studies represent post hoc genotyping and, in most cases, involved only relatively small patient numbers. Although components of the RAAS are obvious candidate genes for the pharmacogenomics of ACE inhibitors, AT\textsubscript{1} blockers, diuretics—and given the effects of β-blockers on renin secretion—of other antihypertensive drugs, we have to conclude after many studies that the contribution of the known variations in these genes to the observed interindividual variance in drug responses is modest, if present at all. The reason for this sobering notion is most likely that we deal with a highly regulated system. From the many genetically engineered mouse models of the RAAS, it seems that sole changing of the expression levels of RAAS components (the suggested mechanisms of the common RAAS polymorphisms in man), as exemplified by mice harboring 1, 2, 3, or 4 ACE genes, does not change blood pressure as long as the secretion of renin and other pressure regulating systems is adapted to this situation (Bernstein et al., 2005). In this scenario, the effects of the identified variants in the candidate genes of the RAAS are of modest degree, which may easily be counteracted.
IV. Ligands at Other G Protein-Coupled Receptors

The extensive research related to ligands at AR and AT receptors reflects the fundamental importance of the sympathetic nervous system and the RAAS in cardiovascular regulation. Nevertheless, several other GPCR families also contribute in relevant ways to the maintenance of cardiovascular homeostasis and/or the pathophysiology of cardiovascular disease. However, much less is known regarding the pharmacogenomics of ligands at such GPCR. This relative scarcity of pharmacogenomics data, at least, partly reflects that ligands at those receptors are used on a much more restricted scale in cardiovascular medicine compared with those at AR and AT receptors.

A. Muscarinic Acetylcholine Receptors

Muscarinic acetylcholine receptor agonists play only a minor therapeutic role in cardiovascular disease, and data from other indications suggest that commonly used doses of such drugs actually may not be any more effective than placebo (Barendrecht et al., 2007). Although muscarinic receptor antagonists are important in pulmonary and urogenital medicine (Michel and Parra, 2008), their use in cardiovascular medicine is largely limited to the treatment of bradycardiac arrhythmia. Heart rate control by muscarinic receptors is largely mediated by the \( M_2 \) subtype of muscarinic receptors (Brodde and Michel, 1999). A rare mutation (C176W) in the \( M_2 \) muscarinic receptor gene (CHRM2) has recently been associated with the occurrence and course of dilated cardiomyopathy, potentially mediated by the generation of auto-antibodies against the mutant muscarinic receptor (Zhang et al., 2008). In contrast, common polymorphisms of functional relevance have not been reported for the coding region of the \( M_2 \) receptor (Fenech et al., 2001), however, a multiallelic CA tandem repeat polymorphism has been identified in the promoter region of \( CHRM2 \) (Fenech et al., 2004). Whereas this polymorphism has major effects on the transcription of \( CHRM2 \), its potential impact on tachycardiac responses to muscarinic receptor antagonists has not been investigated. The effects of two polymorphisms located in intron 5 (rs324640) or the 3'-untranslated region (rs8191992) of \( CHRM2 \), originally identified in a study on alcohol dependence and major depressive syndromes (Wang et al., 2004), were analyzed in volunteers undergoing maximal exercise testing (Hautala et al., 2006). A highly significant difference in heart rate recovery of 12 beats/min was observed in association with the various alleles of these SNPs. The effect increased upon further endurance training. Evidence is lacking whether these variants in \( CHRM2 \) also affect chronotropic responses of muscarinic agonists or antagonists or \( \beta \)-blockers.

In summary, the genetic variance of \( CHRM2 \) is only incompletely understood. Compared with the efforts to identify and characterize variants in \( AR \) genes, we are only at the beginning of research into \( CHRM2 \). Whereas apparently functional variants have been identified, detailed pharmacogenomics studies are required to investigate their potential effect on chronotropic responses, not only in response to muscarinic agonists and antagonists but also to \( \beta \)-AR agonists and, of particular importance, to \( \beta \)-blockers.

B. Vasopressin Receptors

Vasopressin acts via two types of receptors, termed \( V_1 \) and \( V_2 \). \( V_2 \) receptors play an important role in the regulation of renal fluid handling; numerous rare mutations of this subtype have been described and play important roles in the pathophysiology of renal diabetes insipidus (Insel et al., 2007). Agonists at \( V_1 \) receptors such as terlipressin are sometimes used because of their vasoconstricting properties (e.g., in the emergency treatment of esophageal variceal or other bleedings). Agonists at \( V_2 \) receptors such as desmopressin are used in the treatment of enuresis and nocturia (Cvetkovic and Plosker, 2005). \( V_2 \) receptor antagonists such as tolvaptan and lixivaptan, originally developed for the treatment of hyponatremia, are currently undergoing investigation for use in patients with heart failure (Schweiger and Zdanowicz, 2008). However, pharmacogenomic information is not available for any of the vasopressin receptor ligands. Accumulating evidence suggests that brain peptide hormones—including vasopressin and oxytocin—have major functions for the “social brain” for instance by modulation of pair bonding, social and sexual fidelity, assurance, and trust. This has sparked intensive efforts to unravel genetic factors in this system. A functional variant in the \( V_1 \) receptor has been described that affects such neuro-psychological traits (Walum et al., 2008). With a greater understanding of the genetic diversity in this system pharmacogenomic questions can in turn be readdressed in more detail.

C. Endothelin Receptors

Two subtypes of endothelin receptors exist, termed \( ET_A \) and \( ET_B \), and several mutations and polymorphism have been described in the corresponding genes (Rossi and Pitter, 2006). Although some of the \( ET_B \) receptor variants may be important in the pathogenesis of Hirschsprung’s disease, there are also several reports linking them to cardiovascular disease, such as arterial and pulmonary hypertension or congestive heart failure, but many of these associations are not unequivocal or remain to be replicated (Rossi and Pitter, 2006). The only endothelin receptor ligands used in clinical medicine are antagonists such as bosentan, which are used in the treatment of pulmonary hypertension. However, the genetic heterogeneity in these receptors has not been investigated relative to clinical responses to such drugs. On the other hand, one study in healthy volunteers has explored a role of the C825T polymorphism in the GPCR. This relative scarcity of pharmacogenomics data, at least, partly reflects that ligands at those receptors are used on a much more restricted scale in cardiovascular medicine compared with those at AR and AT receptors.
protein β3 subunit (see section II.B) on vascular responses to local administration of endothelin-1 and systemic administration of the ETA receptor antagonist darusentan (Mitchell et al., 2004). The effect of the same C825T polymorphism on the response to endothelin-1 in one of the two vascular beds (skin microcirculation) was also studied by these investigators in a later study (Mitchell et al., 2006). In one of these studies, carriers of the T allele exhibited enhanced dorsal hand vein vasoconstriction upon endothelin-1 administration (not darusentan-sensitive), whereas skin microcirculation responses to the agonist (darusentan-sensitive) were not affected by genotype in both studies; darusentan-induced blood pressure lowering was not related to genotype. These studies raise the possibility that vascular ET<sub>B</sub> but not ET<sub>A</sub> receptor agonist responses are affected by the C825T G protein β3 subunit polymorphism; however, these findings await independent confirmation.

V. Conclusions and Prospects

Until now, reports of altered cardiovascular drug responses based upon genetic polymorphisms in GPCRs and their signaling cascades have remained controversial. Common and frequently studied variants in these genes have only modest effects on gene function. Therefore, their effects on clinical responses are at best small relative to those of other factors affecting drug response, including life style, drug adherence, drug interactions, nutritional factors, hepatic and renal functions, drinking and smoking habits, age, and body composition, to name but a few. Effects of gender and ethnicity have also major impacts on drug responses (Rahemtulla and Bhopal, 2005; Duster, 2007; Franconi et al., 2007; Drake et al., 2008; McNamara, 2008). Although both factors have undoubtedly a genetic background, the involved genes and their mechanisms await further elucidation. Furthermore, the increasing understanding of epigenetic mechanisms at the cross-roads of genetics and environment requires an adjustment of the rather static concepts in current pharmacogenomics (Ingelman-Sundberg et al., 2007).

Together, the presented data do not support the concept that pharmacogenomics will drive the choice of drug and/or dosage in major cardiovascular indications for routine therapy in the immediate future. Nevertheless, the concept of personalized cardiovascular medicine remains attractive and may gain clinical relevance for some drugs. We are experiencing long-awaited and breathtaking new results in the field of complex diseases. Mass genotyping, whole-genome analyses with statistical power. Furthermore, meticulous characterization and phenotyping of patients is of utmost importance. Whereas these requirements can be fulfilled in part for scheduled controlled clinical trials for new compounds, the analysis for already introduced substances requires new controlled trials for which it is difficult to find sponsors.

For today’s clinical practice in cardiovascular medicine, it seems prudent to focus on well characterized robust genetic variants, the genotyping of which may be advantageous for actual treatment decisions. Genotyping of polymorphisms in VKORC1 and CYP2C9 for the dosage finding in oral anticoagulant therapy is a promising approach in this regard. With regard to variants in AR, prospective studies are needed to demonstrate (e.g., the value of genotyping at the β<sub>1</sub>-AR G389R locus) for differential therapy in heart failure.

Acknowledgments. This work is supported by the Bundesministerium fu¨r Bildung und Forschung (BMBF) [Grant 03IP612 (InnoProfile)] and the future fond of the state government of Mecklenburg-Vorpommern [Grant UG 07 034].

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