PARA-AND/OR autocrine factors that interact with receptors coupled to G proteins of the Gq/11 families are implicated in the development of myocardial hypertrophy and apoptosis. Whether hypertrophy renders cardiac myocytes more sensitive or resistant to apoptosis is still controversial. A delicate balance may exist among hypertrophy, apoptosis, and heart failure. However, the factors involved in the transition from compensatory hypertrophy to heart failure have not been elucidated yet in the context of Gq-coupled pathways. Overexpressing serotonin Gq–coupled 5-HT2B receptor in the mouse heart induces mitochondrial proliferation associated with hypertrophy, whereas ablation of this receptor leads to mitochondrial structural and functional impairments associated with myofibrillar breakdown and dilated cardiomyopathy. In this review, we discuss a novel role of mitochondria in the transition from hypertrophic to dilated cardiomyopathy that involves the Gq-coupled 5-HT2B receptor signaling pathway.

Role of Serotonin in the Heart
Serotonin (5-hydroxytryptamine [5-HT]) was first isolated from blood and found to function as a vasoconstrictor. 5-HT is found in the following 3 main areas of the body: the intestinal wall (where it causes increased gastrointestinal motility), blood vessels (where it causes constriction of large vessels), and the central nervous system. Several lines of evidence suggest that 5-HT regulates cardiovascular function during embryogenesis and adulthood. 5-HT is secreted from enterochromaffin cells into the blood and stored in the platelets. Circulating 5-HT can also be taken up by sympathetic neurons and vascular endothelial cells and can be co-released. The effects of 5-HT in the cardiovascular system are complex: for example, 5-HT has been associated with bradycardia or tachycardia, hypotension or hypertension, and vasodilatation or vasoconstriction. Recent pharmacological studies suggested that compounds acting on 5-HT receptors could be of therapeutic use in the treatment of migraine, hypertension, and heart and vascular diseases.1,2

The various biological actions of 5-HT are mediated by numerous cognate receptors. It now appears that there are at least 15 receptor subtypes that belong to the following 4 classes of receptors: 5-HT1A, 5-HT2, 5-HT3, and 5-HT4/6/7.3 Binding of 5-HT to the Gq/11-coupled, 5-HT2A,B,C receptors activates phospholipase C, which initiates a rapid release of inositol triphosphate and increases intracellular calcium levels. The 5-HT2B receptor (5-HT2B) is expressed in the adult cardiovascular system, as well as in the gut and brain. 5-HT2B mediates 5-HT–induced mitogenesis in transfected fibroblasts by recruiting c-Src for cell cycle progression via the mitogen-activated protein kinase (MAPK ERK1/2) pathway.4 Stimulation of the 5-HT2B receptor in cross talk with the 5-HT1B/D receptor subtype via activation of phospholipase A2 and NO synthesis via a PSD-95, DLG, Zo-1 (PDZ) recognition motif.5

In clinical disorders associated with increased 5-HT plasma levels such as carcinoid tumors, valvular heart disease has been commonly observed. This valvulopathy is characterized by hyperplastic valvular and endocardial lesions with increased extracellular matrix. The 5-HT mitogenic signaling has been proposed to trigger the valvular hyperplasia observed in carcinoid patients.6 Antidepressant drugs that selectively inhibit the membrane 5-HT transporter (increasing the availability of 5-HT) have also been shown to produce arrhythmias, including atrial fibrillation, bradycardia, and heart block.7 Antidepressants might contribute to cardiac damage in patients with coronary heart disease by amplifying the platelet aggregation, thus continuing vasocostriction through increasing 5-HT levels. The prevalence of major depression in individuals with coronary artery disease is estimated to range from 15% to 23%.8 Another drug that causes the efflux of 5-HT, 3,4-methylenedioxyamphetamine, can produce significant cardiovascular toxicity.9 Some patients taking appetite suppressants such as fenfluramine or ergot derivatives also experience valvular hyperplasia.10 Fenfluramine is a potent 5-HT releaser acting at the 5-HT transporter.

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902
However, its main metabolite, norfenfluramine, has preferentially high affinity for human 5-HT2Rs, acting as an agonist. Norfenfluramine-mediated valvular disease was recently reported to be mediated predominantly by 5-HT2Rs via ERK1/2 activation through both a protein kinase C (PKC) and an Src stimulation. In addition, use of fenfluramine resulted in a recent outbreak of pulmonary hypertension in humans. It has also been reported that activation by 5-HT or fenfluramine of the 5-HT2R is a limiting step that controls lung vascular proliferation and remodeling, including the elastase activity and transforming growth factor-β release associated with pulmonary hypertension.

The diversity of 5-HT receptors and the lack of 5-HT receptor isotype-specific pharmacological agents have complicated attempts to identify the specific receptors involved in 5-HT-induced cardiac functions. As an alternative to classical pharmacological approaches, mice lacking or overexpressing 5-HT receptors are useful tools for defining the specific 5-HT receptor subtypes involved in 5-HT responses.

5-HT2bR Is Required for Myocardial Trabeculation During Embryogenesis

We have created 5-HT2bR gene knockout (KO) mice to address the roles of 5-HT2bR during development and in the adult. Genetic ablation of 5-HT2bR induces trabeculation defects in the developing heart, causing partial lethality at midgestation. KO mice undergo 2 periods of lethality, one before embryonic day 11.5 and the other shortly after birth. Histological analysis of hearts from 5-HT2bR KO embryos revealed defects of the subepicardial layer and lack of trabeculation of the ventricular myocardium. The myocardial abnormalities of the 5-HT2bR embryo mice correlate with 5-HT2bR expression in the compact zone and in the myocardial trabeculae. Because the Gq-coupled 5-HT2bR transduces mitogenic signals in fibroblasts, impaired differentiation and proliferation in the heart of 5-HT2bR KO embryos probably accounts for the midgestation lethality. Interestingly, analysis of the mutant mice for Gq/G11 protein demonstrated a strict dependence on Gq/G11 dosage. Mice lacking both G proteins Gq/11 and G11-C lost embryonic day 11 as a result of ventricular hypoplasia. In addition, Gq+/−/G11+/− newborn mutants exhibit craniofacial defects. Thus, 2 active Gq and G11 alleles are necessary for postnatal life, and at least 1 intact Gq or G11 allele is required to bring the embryo to term. G11 seems to be preferentially required for 5-HT2bR-dependent heart developmental events, given that the skeletal abnormalities observed in Gq+/−/G11+/− embryos could not be detected in the 5-HT2bR KO mice.

5-HT2bR Mutations Alter Cardiomyocyte Function and Structure

Newborn 5-HT2bR KO mice developed cardiac dilation at 100% penetrance. The thinning of the ventricular wall and the reduction in ventricular mass observed in the 5-HT2bR KO mice result from both a reduction in the number of myocardial cells and a decrease in cell size. The decrease in cardiomyocyte size could be due to impaired growth during postnatal development. Cardiomyocytes from KO mice also exhibit impaired contractility and beating rates in response to dobutamine (a β-adrenergic receptor agonist) in the absence of sympathetic innervation, indicating cell autonomous defects. The impaired contractility and myofibrillar degeneration could be related to the altered intercalated disc structures observed ultrastructurally in 5-HT2bR KO hearts. Myofibrillar loss is the most obvious structural change in human cardiomyopathy, and sarcomeric disarray is characteristic of failing hearts. Interestingly, most mutations leading to dilated cardiomyopathy in humans affect structural proteins involved in cytoskeleton–extracellular matrix interactions at the Z stripe. Z line–associated structures are responsible for the lateral alignment of myofibrils and their anchorage to N-cadherin–vinculin-containing costameres along the cell membrane. N-cadherin plays an important role in maintaining myofibril integrity, in cardiomyocyte interaction, and in myofibrilogenesis. The 5-HT2bR KO mice exhibit decreased N-cadherin levels. Downregulation of N-cadherin and disruption of intercellular adhesion have also been reported in failing guinea pig hearts. Myofibrillar organization and intercellular junction structures are impaired in the absence of 5-HT2bR, suggesting that its activation plays a crucial and specific role in the organization and expression of cytoskeletal structures in cardiomyocytes.

The 5-HT2bR KO Heart Phenotype Is Reminiscent of the Natural History of Patients With Dilated Cardiomyopathy

All 5-HT2bR KO mice that survived until the first postnatal week reached adulthood and exhibited dilated cardiomyopathy-like symptoms. Dilated cardiomyopathy in human is diagnosed with 2 typical features, left ventricular (LV) dilatation and depressed LV systolic performance. Both features were observed in adult 5-HT2bR KO mouse hearts. Echographic analysis showed that the LV end-diastolic diameter and the LV end-systolic diameter were significantly increased in 5-HT2bR KO male mice. Moreover, serum biochemical indicators of myocardial infarction (creatinine kinase MB mass and troponin I-C) are increased in the 5-HT2bR KO mice. 5-HT2bR KO mice therefore provide a novel model of mouse cardiomyopathy, characterized by a phenotype of dilation with a “failed” hypertrophic response (Figure 1).

Heart-Specific Overexpression of 5-HT2bR Leads to Cardiomyopathy

Overexpression of 5-HT2bR in the heart using a myosin heavy chain (MHC) promoter containing the transgene also leads to specific defects. Transgenic (TG) mice overexpressing the Gq-coupled 5-HT2bR exhibit hypertrophy that is due to increased number and growth of cardiomyocytes. The overexpression of 5-HT2bR raises the expression of hypertrophic genes such as atrial natriuretic factor and β-MHC as evidence of hypertrophic response in the TG heart. This hypertrophic response is a direct effect of overexpression of 5-HT2bR in the myocardium, because hypertrophy was observed without evidence of hemodynamic overload. Cardiac fibrosis was not observed in TG hearts, indicating that cardiomyocyte-specific
overexpression of 5-HT_{2B}R does not alter remodeling in nonmyocyte cells through paracrine mechanisms.\textsuperscript{20}

Several factors might be responsible for the development of compensated hypertrophy after overexpression of 5-HT_{2B}R. A first possibility to explain the development of hypertrophy is the change in signaling pathways and Gq-protein repertoire coupling. Overexpression of Gq-downstream signaling molecules has been associated with the induction of a cardiomyopathy characterized by a ventricular hypertrophy, as follows: cardiac-specific overexpression of constitutively active δ-PKC and e-PKC isoforms caused identical, nonpathological hypertrophic phenotypes\textsuperscript{21,22}; TG mice expressing an activated MEK1 cDNA in the heart also demonstrated concentric hypertrophy without signs of cardiomyopathy.\textsuperscript{23}

Another possible cause of hypertrophy after overexpression of 5-HT_{2B}R could be secondary to compensation for the early apoptosis and increased proliferation of cardiomyocytes. 5-HT_{2B}R KO newborn mice exhibit ventricular hyperplasia due to impaired cardiomyocyte proliferation.\textsuperscript{13} It is possible that overexpression of 5-HT_{2B}R in the heart activates the mitogenic pathway(s) before birth and then inhibits apoptosis in terminally differentiated and nonproliferative cardiomyocytes after birth.

The involvement of Gq-coupled receptors in regulating cardiomyocyte growth has not yet been fully understood despite the use of both loss-of-function and gain-of-function experiments to a given receptor in vivo. For example, TG mice overexpressing the angiotensin AT_{1} receptor in the myocardium develop cardiac hypertrophy,\textsuperscript{24} but pressure overload and stretch-induced hypertrophy still occur in AT_{1} KO mice; cardiac-specific overexpression of constitutively active α-1B adrenergic receptor in TG mice results in mild cardiac hypertrophy,\textsuperscript{26} but no hypertrophy developed in TG mice overexpressing the wild-type α-1B adrenergic receptor.\textsuperscript{27} Mice with selective Gq and G11 ablation in cardiomyocytes showed no detectable ventricular hypertrophy in response to pressure overload induced by aortic constriction.\textsuperscript{28}

**Mitochondrial Defects Are Observed in the 5-HT_{2B}R KO and TG Hearts**

Mitochondrial dysfunction has been reported in human cardiac diseases including ischemic and nonischemic heart failure, myocardial infarction, arrhythmia, myocarditis, and dilated cardiomyopathy.\textsuperscript{29,30} Although damage in mitochondria is a key step leading to programmed cell death, no typical apoptotic bodies were observed in the heart of 5-HT_{2B}R KO mice.\textsuperscript{15} Altered mitochondrial membrane integrity was observed, however, in the cardiomyocytes of 5-HT_{2B}R KO mice that presented dilated cardiomopathy (Figure 2). Furthermore, reduced succinate dehydrogenase and cytochrome C (cytoC) oxidase (COX) indicated altered functions of electron transport complexes II and IV, respectively.\textsuperscript{31} Increased lactate plasma levels in KO mice confirmed these observations.\textsuperscript{31} Decreased oxidative phosphorylation and respiration that led to lactate production have also been observed in human mitochondrial myopathies and animal models for dilated cardiomyopathy.\textsuperscript{32} 5-HT_{2B}R KO cardiomyocytes may have been in the preapoptotic stage long before nuclear events became morphologically manifested in vivo. Accordingly, evidence of cytoC redistribution from mitochondria to cytoplasm and caspase activation without nuclear morphology of apoptosis has also been observed in idiopathic dilated cardiomyopathy in the human heart.\textsuperscript{33} These data raise the issue of how cardiomyocytes seemingly tolerate some cytosolic cytoC. The balance between nuclear fragmentation and protein cleavage is variable in cardiomyocytes.\textsuperscript{34} Other factors might explain the presence of processed caspase-3 in cells that are not undergoing apoptosis.

Overexpression of 5-HT_{2B}R in the mouse heart leads to abnormally high mitochondrial numbers as observed by transmission electron microscopic analysis and red ragged fiber staining. Moreover, mitochondrial enzyme activities such as COX and SDH are increased in TG mouse hearts. This increase in oxidative phosphorylation activity is also suggestive of an accumulation of mitochondria in the TG heart.\textsuperscript{20}
Mitochondria Are Targets in 5-HT<sub>2B</sub>R Survival Signals in Isolated Cardiomyocytes

Mitochondria represent an essential component of many apoptotic pathways by controlling the release of cytoC into the cytosol.<sup>33,35</sup> Released cytoC from mitochondria forms an activation complex with proapoptotic protein-activating factor-1 and caspase-9, which activates downstream caspases to execute final morphological and biochemical alterations.<sup>36</sup> This pathway is tightly regulated by a group of antiapoptotic proteins, such as Bcl-2, and proapoptotic proteins, such as Bax.<sup>37</sup> Further downstream regulation occurs through various inhibitors of caspases.<sup>38</sup> Cardiomyocytes also use a mitochondria-dependent apoptotic pathway.<sup>39</sup> In isolated cardiomyocytes, serum withdrawal is a classical inducer of apoptosis. Our work has shown that 5-HT via the 5-HT<sub>2B</sub>R acts as a survival factor, by inhibiting serum withdrawal-induced apoptosis as manifested by DNA fragmentation, nuclear chromatin condensation, and terminal deoxynucleotidyl transferase UTP nick end-labeling (TUNEL).<sup>31</sup> 5-HT prevents cytoC release and caspase-9 and -3 activation after serum deprivation via cross talk between phosphatidylinositol-3 kinase (PI3K)/Akt and ERK1/2 signaling pathways. On activation of Akt by 5-HT, phosphorylation of IkB-α triggers its degradation to release nuclear factor (NF)-κB. This activation of NF-κB inhibits serum deprivation-induced adenine nucleotide translocator (ANT) expression to maintain mitochondrial permeability.<sup>31</sup> Parallel to this pathway, ERK activation by 5-HT inhibits elevation of Bax expression induced by serum deprivation. Defects in the survival pathway in the 5-HT<sub>2B</sub>R KO heart are not secondary to the cardiomyopathy, because defective cardiomyocyte survival can be reversed by transfection of 5-HT<sub>2B</sub>R cDNA and leukemia inhibiting factor (LIF) survival signaling is intact. In addition, 5-HT did not induce hypertrophy of cultured cardiomyocytes (unpublished observation).

5-HT via 5-HT<sub>2B</sub>R Regulates the Expression of ANT-1 in the Heart

Although alternative mechanisms of mitochondrial membrane permeabilization may exist, ANT-1 emerges as a major player in the regulation of cell death.<sup>40</sup> ANT-1 combines mitochondrial energy-producing and cytosolic energy-consuming processes. Impaired ANT-1 functions have been observed in heart tissue from patients with dilated cardiomyopathy.<sup>41</sup> A shift in the ANT isoform transcription profile was found in heart tissue from patients with dilated cardiomyopathy, but not in that from such patients with ischemic or valvular cardiomyopathy. The shift is characterized by an
increase in ANT-1, a decrease in ANT-2, and an unchanged ANT-3 proportion. This alteration in the ANT isoform pattern is not a general phenomenon of end-stage heart failure, and it clearly occurs already before the heart is terminally damaged. Therefore, an altered ANT isoform expression appears to be a feature of a dilated cardiomyopathy-specific gene program. ANT-1 KO mice exhibited severe cardiomyopathy, and point mutations in the ANT-1 gene have been reported in cases of human mitochondrial diseases. ANT-1 overexpression leads to phenotypic alterations typical of apoptosis, ie, collapsed mitochondrial membrane potential, cytoC release, caspase activation, and DNA degradation. In the 5-HT2B R–overexpressing TG hearts, elevated expression level of ANT-1 was detected. In cardiomyocytes, ANT-1 is a main target of PI3K/Akt signaling that controls mitochondrial permeability. Moreover, ANT-1 downregulation was observed in 5-HT2B R–overexpressing TG hearts (Figure 3). Interestingly, histological and ultrastructural examination of muscle from ANT1–null KO mice revealed red ragged fibers, COX and SDH activation, and cardiac hypertrophy with mitochondrial proliferation similar to those of 5-HT2B R TG mice.

5-HT via 5-HT2B R Regulates Bax Expression in the Heart

The proto-oncogenes Bcl-2 (an inhibitor of apoptosis) and Bax (an inducer of apoptosis) play critical roles in the molecular circuit controlling apoptosis in cardiac muscle. The ratio of Bax to Bcl-2 determines survival or death after an apoptotic stimulus. Patients with mild heart failure show significantly higher Bax/Bcl-2 ratios than patients with advanced heart failure. The susceptibility of myocytes to apoptosis is significantly increased in the early phase of heart failure but decreases with worsening of the disease due to depressed expression of the Bax oncoprotein. This increased susceptibility to apoptosis may have a role in the transition from mild to severe heart failure in patients with idiopathic dilated cardiomyopathy.

In cardiomyocyte culture, the effect of 5-HT via 5-HT2B R was to downregulate Bax expression that was completely inhibited by the ERK1/2 inhibitor PD-09858. In neonatal cardiomyocytes, Bax is necessary, but not sufficient, to control cytoC release; cytoC diffusion is controlled by both ERK1/2 and PI3K/Akt. Although the Bcl-2 family of proteins, at least in part, controls the mitochondrial apoptosis, only ERK1/2 inhibition can overturn 5-HT–induced downregulation of Bax in cardiomyocytes. Bax forms membrane pores that control mitochondrial permeability and release cytoC. Bcl-2 and Bcl-XL inhibit formation of these pores; however, no alteration in the expression of these genes could be detected in 5-HT2B R KO heart mRNA. In vivo analysis in hearts of KO mice showed that the Bax expression level was increased. Our data indicate that 5-HT/5-HT2B R cytoprotective signaling targets mitochondria by regulating Bax and ANT-1 expression in the heart.

A Proposed Model for Transition From Hypertrophic to Dilated Cardiomyopathy

Hypertrophy is viewed, as compensatory and the transition to heart failure occurs via the constitutive activation of proapo-
Trophic signals due to an extensive hypertrophic stimulus. In cardiac tissue, apoptosis is a form of programmed cell death distinct from necrotic cell death. It has been proposed that ventricular dilatation and neurohumoral activation during heart failure lead to upregulation of transcriptional factors induced during cardiomyocyte hypertrophy that prepared the cells for entry in the cell cycle. However, terminally differentiated cardiomyocytes cannot divide; instead, they undergo apoptosis. Initiation of apoptosis is associated with activation of upstream cascades, including the release of cytoC from mitochondria to cytoplasm and processing of proteolytic caspases. Persistent aerobic conditioning induces a compensated hypertrophy that is thought to be beneficial to the heart. These functional changes may increase the mitochondria proliferation rate. Failing mitochondrial functions may lead to decompensation due to induction of apoptotic signaling. Intrinsic determinants of mitochondrial apoptosis have recently been elucidated that modify or abort decompensation; cardiac hypertrophy induced by the Gq pathway upregulates Nix expression, whereas a generalized increase in apoptotic mediators did not occur. Recent data on the 5-HT₂B signaling pathway indicate that 5-HT can control expression of the nuclear genes Bax and ANT-1, which regulate mitochondrial function. It is becoming clear that 5-HT signaling via 5-HT₂B converges onto mitochondrial major cellular compartments, which can modify cardiac hypertrophy or decompensation (Figure 4). These findings promise to have important implications for the understanding of congenital heart disease and the development of potential therapeutic interventions for cardiovascular disease.

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Functional Consequence of Serotonin/5-HT₂B Receptor Signaling in Heart: Role of Mitochondria in Transition Between Hypertrophy and Heart Failure?
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