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The serotonin 5-HT3 receptor: a novel neurodevelopmental target

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The serotonin (5-hydroxytryptamine, 5-HT) receptor belongs, together with the nicotinergic acetylcholine, the GABAergic, and the glycine receptor, to the Cys-loop family of ligand-gated ion channels (Barnes and Sharp, 1999; Chameau and van Hooft, 2006; Walstab et al., 2010; Lummis, 2012). To date, two subunits (5-HT3A and 5-HT3B) have been identified in rodents (Martin et al., 1991; Davies et al., 1999), and additional three subunits (δ, ν, θ) have been identified in humans (Niesler et al., 2007). Functional 5-HT3 receptors can be built from the same (only 5-HT3A) or different subunits (5-HT3A and 5-HT3B receptor subunits). The receptor composition is crucial for its function (Chameau and van Hooft, 2006; Vitalis et al., 2004; Bonnin et al., 2006). However, recent evidence suggests that the 5-HT3 receptor is involved in several mechanisms which determine the formation of neuronal circuits from embryonic stages onward. In this review, we summarize those recent findings which suggest that 5-HT3 receptors emerge as a novel target during the development of the CNS.

EXPRESSION OF 5-HT3 RECEPTORS DURING DEVELOPMENT

The 5-HT3 receptor belongs, together with the nicotinergic acetylcholine, the GABAergic, and the glycine receptor, to the Cys-loop family of ligand-gated ion channels (Barnes and Sharp, 1999; Chameau and van Hooft, 2006; Waalst et al., 2010; Lummis, 2012). To date, two subunits (5-HT3A and 5-HT3B) have been identified in rodents (Martin et al., 1991; Davies et al., 1999), and additional three subunits (δ, ν, θ) have been identified in humans (Niesler et al., 2007). Functional 5-HT3 receptors can be built from the same (only 5-HT3A) or different subunits (5-HT3A and 5-HT3B receptor subunits). The receptor composition is crucial for its function (Chameau and van Hooft, 2006; Vitalis et al., 2004; Bonnin et al., 2006). However, recent evidence suggests that the 5-HT3 receptor is involved in several mechanisms which determine the formation of neuronal circuits from embryonic stages onward. In this review, we summarize those recent findings which suggest that 5-HT3 receptors emerge as a novel target during the development of the CNS.
Thompson and Lumsden, 2007), in such a way that incorporation of 5-HT_{3A} leads to an increase in single channel conductance and decrease in Ca^{2+} permeability (Davis et al., 1999; Noam et al., 2008). Whether the 5-HT_{3A} subunit is a major determinant of 5-HT_{3} receptor function in the CNS is still a subject of debate (van Hooft and Yaker, 2003; Chameau and van Hooft, 2006; Jensen et al., 2008) and appears to, at least in part, depend on species-specific expression patterns. Yet, the putative expression of 5-HT_{3A} subunits as part of a heteromeric 5-HT_{3} receptor complex in the CNS remains of interest, especially in view of the profound effects on Ca^{2+} permeability and associated downstream effectors. Most studies of 5-HT_{3} receptor expression and function in the CNS in rodents focus on 5-HT_{3A} receptors and the terms 5-HT_{3} and 5-HT_{3A} are used as equivalent here.

**5-HT_{3} RECEPTORS ARE EXPRESSED IN CAUDAL EMINENCE-DERIVED IMMATURE AND MATURE INTERNEURONS DURING CORTICOGENESIS**

In the CNS, the 5-HT_{3} receptor is first observed in the subpallial ganglionic eminence (GE), the major source of interneurons in the basal telencephalon, at E12.5 (Johnson and Heinemann, 1995; Mäuel et al., 1995; Tecott et al., 1995). The rostral GE generates later neocortical GABAergic interneurons which migrate tangentially into the cortical plate. In contrast, neocortical glutamatergic neurons originate in the pallial ventricular zone (VZ) and migrate radially into the cortex (Corbin et al., 2001; Nadarajah and Parnavelas, 2002). Different areas of the GE give rise to various subpopulations of GABAergic interneurons which can be subclassified by their morphology and neuropeptide expression (Flames and Marin, 2005; Rudy et al., 2011; Vitalis and Rissler, 2011).

5-HT_{3} receptor-positive interneurons compromise ∼30% of the superficial GABAergic interneurons in the somatosensory cortex (Lee et al., 2010). They comprise cholecystokinin (CCK), vasoactive intestinal peptide (VIP), and/or neuropeptide Y (NPT) and, at smaller fractions, calretinin (CR) and/or reelin, but not vasoactive intestinal peptide (VIP), and/or neuropeptide Y (NPY). This might be true as well for the 5-HT_{3} receptor-positive interneurons. Therefore, 5-HT_{3} receptor-expressing CGE-derived neocortical interneurons might form a group of cells with very specific, yet unknown, characteristics and might follow different migration- and integration cues than other major groups of interneurons like PV-positive interneurons (Lee et al., 2010; Miyoshi et al., 2010).

In grafting experiments, Vucurovic et al. (2010) found that CGE-derived cells also populated several limbic structures including the bed nucleus, hippocampus, and amygdala. These were derived earlier from the CGE than the neocortical cells, which is in line with earlier genesis of interneurons in these regions (Vucurovic et al., 2010).

Furthermore, next to the CGE, embryonic 5-HT_{3} receptor expression was also observed in cells of the entopeduncular area (AEP) and perirubic area (POA; Lee et al., 2010; Vucurovic et al., 2010). The further development of these cells has not been characterized yet. Cells from the POA might contribute to interneurons in the neocortex (Gelman et al., 2009, 2011) and thus it was proposed that the POA might also give rise to 5-HT_{3} receptor-positive interneurons of the neocortex (Rudy et al., 2011). However, Vucurovic et al. (2010) found no evidence of POA cells migrating into neocortical regions but the cells rather contributed,
depended on their birthdate, to cells of the dentate gyrus (DG), amygdala, endopiriform nucleus, and the claustrum.

**5-HT3 RECEPTORS ARE EXPRESSED IN POSTNATAL IMMATURE NEURONS**

5-HT3 receptors are expressed in migrating neuroblasts in several migratory streams derived from the SVZ in the early postnatal brain (Inta et al., 2008; Vucurovic et al., 2010). The SVZ, and therefore these neuroblasts, are not derived from the CGE but from the lateral GE (LGE). Migratory streams in the early postnatal rodent brain are part of the ongoing neurogenesis and migration of neurons after birth. These migratory streams include the rostral migratory stream (RMS) populating mainly the olfactory bulb (OB), the dorsal migratory pathway (DMP) above the hippocampus directed toward the occipital cortex, the ventral migratory pathway (VMP) heading toward the striatum and nucleus accumbens, and the external migratory pathway (EMP) aiming toward lateral-dorsal brain regions (Inta et al., 2008). Neuroblasts of the RMS do not only migrate into and mature within the OB but also integrate into the cortex (Le Magueresse et al., 2011). Next to cortical interneurons derived from embryonic interneuron genesis, these neuroblasts mature into a novel, recently described subclass of CR-positive interneurons with unique firing pattern (“small axonless neurons”) which are uniquely generated in the early postnatal period and mainly integrate into deeper layers of olfactory and orbital cortices (Le Magueresse et al., 2011). Additionally, 5-HT3 receptor-positive postnatal SVZ-derived neuroblasts, so-called immature white matter interstitial cells, were recently described to populate the corpus callosum (von Engelhardt et al., 2011).

Of the several postnatal migratory streams harboring 5-HT3 receptor-positive neuroblasts, only the RMS persists into adulthood as an area of secondary neurogenesis (Alvarez-Buylla and Garcia-Verdugo, 2002; Abrous et al., 2005) containing 5-HT3 receptor-positive neuroblasts (Inta et al., 2008; Chen et al., 2012). Similar to early postnatal RMS neuroblasts, they migrate and integrate into the OB, where they mature to CR- and VIP-positive but calbindin- (CB) negative interneurons. Interestingly, and in contrast to cortical interneurons derived from the CGE, about one-third and one-tenth of the 5-HT3 receptor-expressing interneurons in the OB are PV- and SST-positive, respectively (Chen et al., 2012). Adult SVZ neurogenesis is of particular clinical interest because SVZ-derived neuroblasts can migrate into the cortex upon traumatic events or in neurodegenerative diseases to replace cortical neurons. Indeed, upon stroke in adult mice 5-HT3 receptor-positive neuroblasts integrate into the cortex and mature to CR-positive interneurons (Kreuzberg et al., 2010). However, the majority of these cells loses 5-HT3 receptor expression upon maturation (Kreuzberg et al., 2010).

To conclude, 5-HT3 receptor-expressing neuroblasts are present in several locations in the early postnatal and adult brain. Nevertheless, both the regulation of migration and maturation of embryonic CGE- and adult SVZ-derived neuroblasts as well as the functional role of 5-HT3 receptors during these processes are yet unresolved. Only little is known about downstream signaling upon activation of 5-HT3 receptors and subsequent Ca2+ tonic influx. Investigating a potential function of 5-HT3 receptors in regulating neuroblast migration and maturation therefore would be promising. Some recent studies proposed regulation of cytoskeletal remodeling in neurons by 5-HT3 receptors. For example, 5-HT3 receptor agonists were found to promote neurite elongation of GABAergic cortical interneurons (Vitalis and Parnavelas, 2003). Activation of 5-HT3 receptors further promotes dendrite formation in primary thalamic neurons in vitro (Persico et al., 2006; note contradictory: Lotto et al., 1999). In growth cones, cohesion spots, and dendrites of hippocampal neurons and in human embryonic kidney (HEK) cells, 5-HT3 receptors were found to form clusters with the light chain (LC1) of microtubule-associated protein 1B (MAP1B) and the tubulin cytoskeleton (Sun et al., 2008) and these clusters lead to the formation of F-actin-rich lamellipodia (Emrert et al., 2002). 5-HT3 receptors follow the tubulin and F-actin networks for receptor routing and precise tuning at the neuronal membrane surface (Giralte et al., 2004; Llegems et al., 2004). Furthermore, LC1 might regulate the receptor function in these cells (Sun et al., 2008). Therefore, 5-HT3 receptors and the cytoskeleton are highly interactive, which might not only lead to the specific transport of 5-HT3 receptors into synaptic sites and regulation of receptor function, but also 5-HT3 receptors might evoke signaling involved in cytoskeletal remodeling. 5-HT3 receptor activity in immature and mature interneurons might be crucial for their activity as well as development.

Interestingly, it was recently reported that electrophysiological activity is essential for the postnatal correct migration and axonal and dendritic integration of CGE-derived reelin- and CR-, but not VIP-positive neurons (Garcia et al., 2011). Whereas this activity is glutamate-dependent after P3, the source of activity before P3 is yet unclear. Serotonergic input via 5-HT3 receptors might be a candidate source of such perinatal activity.

**CONCLUSION I: 5-HT3 RECEPTORS ARE A POTENTIAL CENTRAL PART OF MATURATING INTERNEURONS DURING PRE- AND POSTNATAL CORTICAL DEVELOPMENT**

5-HT3 receptors are expressed on embryonic immature CGE-derived GABAergic interneurons as well as neuroblasts in early postnatal migratory streams and the adult SVZ. Therefore, they might be involved in (fine)regulation of neuronal excitability and thus migration, maturation, and network formation of inhibitory networks from early embryonic to adult stages (Figure 1).

**EXPRESSION OF 5-HT3 RECEPTORS ON CEREBELLAR GRANULE AND CORTICAL CAJAL–REITZIUS CELLS**

Next to the pre- and postnatal central expression of 5-HT3 receptors on mature and immature interneurons, recent evidence showed also expression on two specific types of glutamatergic cells: cerebellar granule cells and cortical Cajal–Reitzius cells. First, ubiquitous post- and presynaptic expression of 5-HT3 receptors was recently observed in glutamatergic granule cells of the cerebellum within the first three postnatal weeks in rodents (Oostland et al., 2011, 2013). 5-HT3 receptors are important for the serotonergic regulation of short-term synaptic plasticity at parallel fiber–Purkinje cell synapses during the early postnatal sensitive period and regulate the maturation state of these synapses (Oostland et al., 2011). They further regulate the...
FIGURE 1 | Summary of (A) 5-HT3 receptor expression on GABAergic interneurons during pre- and postnatal brain development and (B) recently described mechanisms of 5-HT3 receptor-mediated regulation of maturation of cortical pyramidal cells and cerebellar Purkinje cells in the early postnatal brain.

The time course of early postnatal morphological maturation of Purkinje cells as indicated by higher dendritic length and complexity in 5-HT3 receptor knock-out mice and in vitro after treatment with a 5-HT3 receptor antagonist (Oostland et al., 2013). 5-HT3 receptor knock-out animals further show delayed climbing-fiber elimination (Oostland et al., 2013). However, morphology and physiology of Purkinje cells in 5-HT3 receptor knock-out mice appears normal in adult mice, thus indicating a narrow postnatal time window of serotonergic, 5-HT3 receptor-mediated regulation of cerebellar maturation and connectivity (Oostland et al., 2013). Further research might explore a function of 5-HT3 receptors in the development of early life motor coordination and learning.
Second, glutamatergic Cajal–Retzius cells were recently described to express 5-HT3 receptors upon birth (Chameau et al., 2009, Lee et al., 2010). Cajal–Retzius cells are transient neurons located in the marginal zones of the neocortex and hippocampus during CNS development (Marin-Padilla, 1998). In the cortex, they are strategically located in layer I, the area where the apical dendrites of pyramidal neurons terminate and secrete the extracellular matrix glycoprotein reelin. Reelin plays a major role as guidance factor for cell migration, cell positioning, and neuronal process outgrowth (Frotscher, 1997). Cajal–Retzius cells in mice are innervated by serotonergic fibers as early as E16. Disruption of the serotonergic system during embryonic development results in lower levels of reelin and a disturbed corticogenesis with disrupted formation of cortical columns (Juncos et al., 2005; Juncos and Chugani, 2002). The data presented in this review highlights the 5-HT3 receptor as a crucial regulator of brain development. This also makes it interesting as novel candidate to be involved brain development pathologies such as ASD. Indeed, several studies present evidence that ASD might be caused by disruptions of the serotonergic system during brain development. Common ASD animal models are based on alterations of prenatal 5-HT levels (Whitaker-Azmitia, 2005; Boylan et al., 2007; Hohmann et al., 2007). Likewise, clinical data from ASD patients points toward a causal relationship of distortion of the serotonergic system and ASD pathology (Anderson et al., 1987; Naffah-Mazzacoratti et al., 1993; Chugani, 2002).

Investigating a potential role of 5-HT3 receptors in the development of ASD, it is apparent that 5-HT3 receptor knock-out mice display some features similar to ASD symptoms including impaired social behavior (Smit-Rigter et al., 2010) and a reduction in basal anxiety-related behavior (Kelley et al., 2003; Bhatnagar et al., 2004; Smit-Rigter et al., 2010). Further, in line with the potential role of the 5-HT3 receptor outlined earlier in this review, these animals display some alterations in neocortical development, especially in the balance between excitatory and inhibitory circuits, but also consequently for the processing of information within the circuit. As a potential consequence of this disturbed cortical wiring and function, 5-HT3 receptor knockout mice display reduced anxiety-like behavior (Kelley et al., 2003; Bhatnagar et al., 2004) and impaired social behavior (Smit-Rigter et al., 2010), although a direct link between the cortical abnormalities and the behavioral phenotypes remains to be established.

CONCLUSION II: 5-HT3 RECEPTORS REGULATE MATURATION AND DENDRITE COMPLEXITY OF NON-INTERNEURON CELLS

5-HT3 receptors regulate the wiring of the local microcircuit in the cortex and the cerebellum by yet unknown direct or indirect mechanisms via Cajal–Retzius cells and granule cells, respectively. Therefore, 5-HT3 receptors may be crucially involved in the formation of higher-level neuronal structures (Figure 1).

PUTATIVE IMPLICATIONS FOR NEURODEVELOPMENTAL DISORDERS

5-HT3 receptors are associated with several psychiatric disorders in humans. Single nucleotide polymorphism, especially the C178T polymorphism in the 5′ UTR region of the 5-HT3 receptor, were found to be associated with bipolar disorder (Niebler et al., 2001), schizophrenia (Niebler et al., 2001; Thompson et al., 2006), lowered harm avoidance in women (Melke and Westberg, 2003), alcohol and drug dependence (Engel et al., 2009), lowered activity of amygdala and prefrontal cortex (Iidaka et al., 2005), prefrontal and hippocampal gray matter loss, and early life quality-dependent elevated depressed mood (Gaut et al., 2010a,b). These variants are associated with changes in 5-HT3 receptor function and expression (Krzysikowski et al., 2007). However, it has to be noted that 5-HT3 receptor genetics is fundamentally different between humans and rodents: 5-HT3 receptor expression in humans is much more complicated including additional splice variants of 5-HT3α, the possible expression of heteromeric receptors in the CNS, and three additional receptor genes (5-HT3C,5-HT3D,5-HT3E), whose function and expression in the CNS have yet to be investigated.

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and increased cortical volume (Bailey et al., 1998; Casanova et al., 2002; Carper and Courchesne, 2005). Further, reelin signaling was proposed to be impaired in ASD by Bruneau et al. (2007). Indeed, 5-HT3 gene polymorphisms were recently found to be associated with ASD (Anderson et al., 2009; Rehnström et al., 2009). However, there is yet no evidence of a role of 5-HT3 receptors in the pathology of ASD.

Finally, recent literature draws attention to the potential risk of disturbing serotonergic circuits during fetal brain development via exposure of fetuses to selective serotonin reuptake inhibitors (SSRIs). The use of SSRIs by pregnant women, especially during the first trimester, may increase the risk of ASD in the offspring (Cronen et al., 2011). In mice, early postnatal exposure to SSRIS leads to increased anxiety-like behavior (Ansorge et al., 2004). In addition, in utero exposure to fluoxetine leads to life-long abnormalities of cortical cytoarchitecture and increased anxiety-like behavior (Simon-Rigter et al., 2012). These effects are initiated in 5-HT3 receptor knockout mice suggesting that the adverse effect of fluoxetine-exposure during brain development might be 5-HT3 receptor-dependent (Simon-Rigter et al., 2012).

We conclude that, although current data is still limited, 5-HT3 receptors are important for proper brain development. The 5-HT3 receptor knockout mouse has proven to be a valuable tool to elucidate some of the roles of 5-HT3 receptors in neuronal development. However, the availability of more advanced tools to knock-out or knock-down 5-HT3 receptors in a more spatially and temporally controlled manner is eagerly anticipated.

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