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The serotonin 5-HT3 receptor: a novel neurodevelopmental target

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INTRODUCTION

In addition to its role as a classical neurotransmitter, it is now well established that serotonin (5-hydroxytryptamine, 5-HT) plays a pivotal role in the development of the mammalian central nervous system (CNS). 5-HT is one of the first neurotransmitters to appear during development (E13 in the rat, Lauder, 1990; and E11 in the mouse, Piaar et al., 2002) and acts a neurotrophic factor in early embryonic CNS development and thus even before synapse formation of cortical neurons is completed. Therefore, it aids to establish CNS organization, supporting as well serotonergic synapse formation and function in the CNS, which could have a major impact on our understanding of neurodevelopmental disorders in which 5-HT plays a role.

The myriad of functions of 5-HT in developmental processes corresponds to the expression of a vast amount of receptors, each with its spatial and temporal expression patterns. Seven receptor families for 5-HT have been identified, including the G protein-coupled receptors 5-HT1, 5-HT2, and 5-HT4, and the only ligand-gated ion channel 5-HT3. Thus far, 5-HT1 and 5-HT2 receptors have received the most attention as effectors of the actions of 5-HT during CNS development (Borella et al., 1997; Armita, 2001; Whitaker-Azmitia, 2001; Gaspar et al., 2003; Puig 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 these 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; Walstab et al., 2010; Lummis, 2012). To date, two subunits (5-HT3A and 5-HT3B) have been identified in rodents (Martin et al., 1995; Davies et al., 1999), and additional three subunits (α3–α5) 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., 2007).
Thompson and Lummis, 2007), in such a way that incorporation of 5-HT₃ₐ leads to an increase in single channel conductance and decrease in Ca²⁺ permeability (Davis et al., 1999; Noam et al., 2008). Whether the 5-HT₃ₐ subunit is a major determinant of 5-HT₃ receptor function in the CNS is still a subject of debate (van Hooff and Yäkel, 2003; Chameau and van Hooff, 2006; Jensen et al., 2008) and appears to, at least in part, depend on species-specific expression patterns. Yet, the putative expression of 5-HT₃ subunits as part of a heteromeric 5-HT₃ receptor complex in the CNS remains of interest, especially in view of the profound effects on Ca²⁺ permeability and associated downstream effectors. Most studies of 5-HT receptor expression and function in the CNS in rodents focus on 5-HT₃ receptors and the terms 5-HT₃ and 5-HT₃ₐ are used as equivalent here.

**5-HT<sub>3</sub> Receptors are Expressed in Caudal Eminent-Derived Immature and Mature Interneurons During Corticogenesis**

In the CNS, the 5-HT<sub>3</sub> receptor is first observed in the subpial ganglionic eminence (GE), the major source of interneurons in the basal telencephalon, at E12.5 (Johnson and Heinemann, 1995; Mäder et al., 1995; Tecott et al., 1995). The rodent GE generates later neocortical GABAergic interneurons which migrate tangentially into the cortical plate. In contrast, neocortical gluatamatergic 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 Rossier, 2011).

5-HT<sub>3</sub>-receptor-positive interneurons compromise ~30% of the superficial GABAergic interneurons in the somatosensory cortex (Lee et al., 2010). They express cholecystokinin (CCK), vasoactive intestinal peptide (VIP), and/or neuropeptide Y (NPY) and, at smaller fractions, calretinin (CR) and/or reelin, but not vasoactive intestinal peptide (VIP), and/or neuropeptide Y (NPY) and, at smaller fractions, calretinin (CR) and/or reelin, but not.

**Further expression several morphological and electrophysiological properties, 5-HT<sub>3</sub>-receptor-positive interneurons form a rather heterogeneous group of cells, whose potential common properties remain to be fully characterized (for a recent review, see Rudy et al., 2011). 5-HT<sub>3</sub>-receptor-expressing neocortical interneurons are not only excited by 5-HT but also acetylcholine via nicotinic receptors (Lee et al., 2010). At least a subset of 5-HT<sub>3</sub>-receptor-positive cells receives monosynaptic thalamocortical input leading to strong depolarization of these cells (Lee et al., 2010). Therefore, 5-HT<sub>3</sub>-receptor-expressing cells might be part of potential feedforward inhibitory thalamocortical networks whose sensitivity is potentially regulated by serotonergic and/or cholinergic input (Lee et al., 2010; Rudy et al., 2011). Further discussion of potential functional significance of 5-HT<sub>3</sub>-receptors on these interneurons was published recently (Rudy et al., 2011).

The major source of 5-HT<sub>3</sub>-receptor-expressing neocortical interneurons is the caudal part of the GE (CGE; Lee et al., 2010; Vucurovic et al., 2010). Based on recent publications, there is no expression of 5-HT<sub>3</sub>-receptor in the medial GE (MGE; Lee et al., 2010; Vucurovic et al., 2010), which is the area PV-and SST-expressing cortical interneurons are derived exclusively from (Miyoshi et al., 2007). Note that embryonic 5-HT<sub>3</sub>-receptor expression was mistakenly described in the MGE in earlier publications (Tecott et al., 1995).

Recently, the generation of enhanced green fluorescent protein (EGFP)-expressing 5-HT<sub>3</sub> reporter mice by Inta et al. (2008) and the GENSAT (Gene Expression Nervous System Atlas) project allowed for detailed analysis and fate mapping of 5-HT<sub>3</sub>-receptor-positive cells during embryonic corticogenesis (Lee et al., 2010; Vucurovic et al., 2010). 5-HT<sub>3</sub>-receptor-positive superficial neocortical interneurons were found to be generated in the CGE around E13.5–14.5 (Vucurovic et al., 2010). Similar, Miyoshi et al. (2010) described the genesis of cortical interneurons in the CGE to begin at E12.5 and peak at E16.5. Therefore, CGE-derived interneurons are some of the latest cells to integrate into neocortical layers, which by this time point are already populated by other interneurons including MGE-derived interneurons (Butt et al., 2005; Miyoshi et al., 2007); peak of MGE-derived cortical interneuron genesis at E14.5 (Vucurovic et al., 2010). 5-HT<sub>3</sub>-receptor-positive neuroblasts thereby migrate at least partly through the neocortical subventricular zone (SVZ) and intermediate zone (IZ; Tanaka and Nakajima, 2012). Further, unlike MGE-derived interneurons, 5-HT<sub>3</sub>-receptor-expressing interneurons do occupy preferentially superficial cortical layers I–III (Miyoshi et al., 2007; Lee et al., 2010; Vucurovic et al., 2010). Additionally, they migrate into the neocortical layers in an “outside-in” (Vucurovic et al., 2010) rather than the “inside-out” integration manner of PV- and SST-expressing interneurons. Such “outside-in” neurogenesis was previously described as a feature of CR interneurons (Rymar and Sadikot, 2007).

Interestingly, in contrast to PV-interneurons, the birthdate of these CR-expressing interneurons does not match that of neighboring projection neurons in the corresponding layer (Vucurovic et al., 2009). This might be true as well for the 5-HT<sub>3</sub>-receptor-positive interneurons. Therefore, 5-HT<sub>3</sub>-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<sub>3</sub>-receptor expression was also observed in cells of the entopeduncular area (AEP) and perirhinal 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<sub>3</sub>-receptor-positive interneurons of the neocortex (Robert et al., 2011). However, Vucurovic et al. (2010) found no evidence of POA cells migrating into neocortical regions but the cells rather contributed,
the majority of these cells loses 5-HT3 receptor expression upon replace cortical neurons. Indeed, upon stroke in adult mice 5-HT3 cal interest because SVZ-derived neuroblasts can migrate into the (Chen et al., 2012). Adult SVZ neurogenesis is of particular clini-
interneurons in the OB are PV- and SST-positive, respectively
brain (Inta et al., 2008; Vucurovic et al., 2010). The SVZ, and there-
latero-dorsal brain regions (Inta et al., 2008). Neuroblasts of the
pus directed toward the occipital cortex, the ventral migratory
tral migratory stream (RMS) populating mainly the olfactory bulb
of neurons after birth. These migratory streams include the ros-
rodent brain are part of the ongoing neurogenesis and migration
receptor-positive neuroblasts integrate into the cortex and matu-
activation of 5-HT3 receptors and subsequent Ca2+
flux. Some recent studies proposed regulation of cytoskeletal
function, but also 5-HT3 receptors might evoke signal-
ing involved in cytoskeletal remodelling. 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 (García et al., 2013). 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 excitabil-
ity 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–RETZIUS CELLS

Next to the pre- and postnatal central expression of 5-HT3 recep-
tors on mature and immature interneurons, recent evidence
showed also expression on two specific types of glutamatergic
cells: cerebellar granule cells and cortical Cajal–Retzius cells.
First, ubiquitous post-/extra- 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
neuroblast migration and maturation therefore would be promis-
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 forma-
tion in primary balanonic 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 (Emerit
et al., 2002). 5-HT3 receptors follow the tubulin and F-actin net-
works for receptor routing and precise tuning at the neuronal
membrane surface (Grailhe et al., 2004; Llegems et al., 2004). Fur-
then, LC1 might regulate the receptor function in these cells (Sun
et al., 2008). Therefore, 5-HT3 receptors and the cytoskeleton
are highly interacting, 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 signal-
neurons of the dentate gyrus (DG), amygdala, endopineal 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 there-
fore these neuroblasts, are not derived from the CGE but from the
lateral GE (LGE). Migratory streams in the early postnatal
roden brain are part of the ongoing neurogenesis and migration
of neurons after birth. These migratory streams include the ros-
tral migratory stream (RMS) populating mainly the olfactory bulb
(OB), the dorsal migratory pathway (DMP) above the hippocamp-
pus directed toward the occipital cortex, the ventral migratory
pathway (VMP) heading toward the striatum and nucleus accum-
bens, 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 interneu-
ron genesis, these neuroblasts mature into a novel, recently
described subclass of CR-positive interneurons with unique firing
pattern (“small axonless neurons”) which are uniquely gener-
atated in the early postnatal period and mainly integrate into
deep 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 adult-
hood as an area of secondary neurogenesis (Alvarez-Buylla and
García-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 clini-
cal 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 matu-
rate 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+
influx. Investigating a potential function of 5-HT3 receptors in regulating
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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.

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 (Marín-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 a 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 (Janusonis et al., 2009). The regulation of corticogenesis by Cajal–Retzius cells is at least partly dependent on 5-HT3 receptor signaling (Chameau et al., 2009). Chameau et al. (2009) not only reported expression of 5-HT3 receptors specifically on Cajal–Retzius cells (but not on pyramidal neurons), but further established a novel role of 5-HT3 receptors, Cajal–Retzius cells, and reelin in the postnatal maturation of cortical pyramidal neurons. Cajal–Retzius cells limit the apical dendritic outgrowth of cortical layer II/III pyramidal cells and thus complexity of cytoarchitecture and network formation. Blocking 5-HT3 receptor activity with an antagonist or reelin signaling with an anti-reelin antibody leads to hypercomplexity of the apical dendrites of layer II/III pyramidal neurons in the somatosensory cortex. A similar phenotype is also present in 5-HT3 receptor knock-out mice and can be rescued by application of recombinant reelin (Chameau et al., 2009). However, it remains to be investigated if, and how, the release of reelin from Cajal–Retzius cells is directly regulated by 5-HT3 receptor activity. Similar findings of possibly indirect regulation of migration and regulation of cytoarchitecture in cortical pyramidal neurons were shown in vitro in mixed GABA- and non-GABAergic cortical neuron cultures, where 5-HT3 receptor activation inhibited axonal and dendritic outgrowth and dendritic branching only in non-GABAergic cells (Hayashi et al., 2010).

The increased dendritic complexity of cortical layer II/III pyramidal neurons in 5-HT3 receptor knock-out mice has been associated with altered corticospinal spatial organization and connectivity with larger dendritic bundles in layer III tangential sections, whereas spine density was not affected (Smit-Rigter et al., 2011). On a functional level, the increase in dendritic complexity of cortical layer II/III pyramidal neurons in 5-HT3 receptor knock-out mice results in a different firing pattern of these cells (van der Velden et al., 2012), suggesting that 5-HT3 receptor activity during maturation of neurons is not only important for the wiring of the local microcircuitry, 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 knock-out 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 microcircuitry 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 3′UTR region of the 5-HT3 receptor, were found to be associated with bipolar disorder (Niesler et al., 2001), schizophrenia (Niesler et al., 2001; Thompson et al., 2006), lowered harm avoidance in women (Melke and Westberg, 2003), alcohol and drug dependence (Enoch et al., 2010), lowered activity of amygdala and prefrontal cortex (Lidaka 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 (Krzyszkowski 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-HT3, 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.

The data presented in this review highlights the 5-HT3 receptor as a crucial regulator of brain development. This also makes it interesting as a novel candidate to be involved in neurodevelopmental 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-Mazzocoratti 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 as hypercomplexity of apical dendrites of cortical layer II/III pyramidal neurons (Chameau et al., 2009) and increased apical dendrite bundling (Smit-Rigter et al., 2011). Disruptions of neocortical development, especially in the balance between excitatory and inhibitory circuits, might at least partially underlie autism neuroanatomy (Polleux and Lauder, 2004; Levitt, 2005).

For example, in parallel with 5-HT3 receptor knock-out animals, ASD patients display a cortical column pathology with changes in cortical minicolumn size, number and cellular distribution,
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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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