

Cholestenic acids regulate motor neuron survival via liver X receptors

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Cholestenic acids are formed as intermediates in metabolism of cholesterol to bile acids, and the biosynthetic enzymes that generate cholestenic acids are expressed in the mammalian CNS. Here, we evaluated the cholestenic acid profile of mammalian cerebrospinal fluid (CSF) and determined that specific cholestenic acids activate the liver X receptors (LXRs), enhance islet-1 expression in zebrafish, and increase the number of oculomotor neurons in the developing mouse in vitro and in vivo. While 3 β ,7 α -dihydroxycholest-5-en-26-oic acid (3 β ,7 α -diHCA) promoted motor neuron survival in an LXR-dependent manner, 3 β -hydroxy-7-oxocholest-5-en-26-oic acid (3 β H,7O-CA) promoted maturation of precursors into islet-1⁺ cells. Unlike 3 β ,7 α -diHCA and 3 β H,7O-CA, 3 β -hydroxycholest-5-en-26-oic acid (3 β -HCA) caused motor neuron cell loss in mice. Mutations in *CYP7B1* or *CYP27A1*, which encode enzymes involved in cholestenic acid metabolism, result in different neurological diseases, hereditary spastic paresis type 5 (SPG5) and cerebrotendinous xanthomatosis (CTX), respectively. SPG5 is characterized by spastic paresis, and similar symptoms may occur in CTX. Analysis of CSF and plasma from patients with SPG5 revealed an excess of the toxic LXR ligand, 3 β -HCA, while patients with CTX and SPG5 exhibited low levels of the survival-promoting LXR ligand 3 β ,7 α -diHCA. Moreover, 3 β ,7 α -diHCA prevented the loss of motor neurons induced by 3 β -HCA in the developing mouse midbrain in vivo. Our results indicate that specific cholestenic acids selectively work on motor neurons, via LXR, to regulate the balance between survival and death.

Introduction

The vertebrate CNS is composed of a wide variety of neurons that are generated following tightly regulated developmental programs. Characterization of the function and specificity of molecules working on distinct neuronal populations is thus essential in order to enhance our understanding of how such complexity is achieved in the developing brain and how it is maintained in the

adult brain. One means of developmental and adult regulation is via nuclear receptors. Examples of nuclear receptors expressed in embryonic and adult brain having both a developmental role (1) and a function in the adult brain (2) are the liver X receptors (LXR α and LXR β), which are activated by oxysterols (3, 4). Analysis of double-knockout *Lxra*^{-/-}*Lxrb*^{-/-} mice revealed that LXRs are required for neurogenesis during ventral midbrain (VM) development (1). Moreover, adult male *Lxrb*^{-/-} show progressive accumulation of lipids in the brain and loss of spinal cord motor neurons, suggestive of a neuroprotective role of LXRs and their ligands on adult motor neurons (5). Similarly, the number of islet-1⁺ oculomotor neurons is lower in the developing midbrain of *Lxra*^{-/-}*Lxrb*^{-/-} mice, indicating a role of LXRs not only in the maintenance of

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adult motor neurons, but also in their development (1). In agreement with these findings, enzymes involved in the synthesis of cholesterol and oxysterols, such as 2,3-oxidosqualene-lanosterol cyclase, are localized in islet-1⁺ oculomotor neurons in the mouse VM at E11.5 (1). In addition to the above, we recently found that oxysterols and other endogenous brain LXR ligands are sufficient to regulate neurogenesis in the developing VM (1, 6). While endogenous brain LXR ligands have been identified and found to regulate the development of midbrain dopamine neurons and red nucleus neurons (6), to date, no endogenous ligand capable of regulating the survival of motor neurons *in vivo* has been identified. In a recent study, we found that cholesterol metabolites that had the capacity to activate LXRs can be identified in human cerebrospinal fluid (CSF) (7). In order to identify novel LXR ligands that regulate motor neuron function, we delved deeper into the human CSF sterolome and examined plasma of patients with 2 different human diseases associated with upper motor neuron degeneration, hereditary spastic paresis type 5 (SPG5) and cerebrotendinous xanthomatosis (CTX). These diseases result from mutations in the cytochrome P450 (CYP) genes *CYP7B1* and *CYP27A1*, respectively (8–17). The enzymes coded by these genes are responsible for 7 α -hydroxylation of oxysterols and (25R),26-hydroxylation of sterols, respectively, reactions that generate further oxysterols and ultimately cholestenic acids (Figure 1A and ref. 18). Note that we have adopted the sterol nomenclature recommended by the lipid maps consortium: 26-hydroxycholesterol (26-HC) refers to cholest-(25R)-5-en-3 β ,26-diol; similarly, carboxylic acids that introduce 25R stereochemistry to the side-chain are at C-26 (19). We found that specific cholestenic acids with a 3 β -hydroxy-5-ene, but not a 3-oxo-4-ene, structure activated LXR α and LXR β in neuronal cells, increased expression of islet-1, a transcription factor required for the development of motor neurons (20–22), and promoted the survival of islet-1⁺ oculomotor neurons. Moreover, these effects were abolished by knockdown or knockout of the LXR-encoding genes in zebrafish or in rodent models, respectively. In addition, we showed that patients with CTX and SPG5 are unable to synthesize normal amounts of the LXR ligand 3 β ,7 α -dihydroxycholest-5-en-26-oic acid (3 β ,7 α -diHCA), a cholestenic acid that we found to promote neuronal survival. This is of interest in relation to the fact that patients with SPG5 present with motor neuron degeneration and spastic paraplegia. Patients with CTX may sometimes also present with spasticity, possibly due to upper motor neuron degeneration. Our findings may have important implications for neurological diseases leading to motor neuron degeneration, since LXR ligands, as well as inhibitors of specific biosynthetic enzymes in the cholestenic acid biosynthetic and metabolic pathways, may be useful pharmaceuticals for the treatment of motor neuron disorders.

Results

Specific cholestenic acids are abundant in human CSF. We have previously shown that cholestenic acids are abundant in human plasma (23, 24) and that human CSF also contains specific cholestenic acids (7). Surprisingly, in CSF, the levels of cholestenic acids were higher than those of oxysterols. In this study, we delved deeper into the CSF sterolome, particularly into the cholestenic acid portion, using liquid chromatography–electrospray ioniza-

tion–mass spectrometry (LC-ESI-MS) analysis. We hereby report the exact identity of 16 oxysterols and downstream metabolites, including cholestenic acids, found in human CSF (Supplemental Table 1; supplemental material available online with this article; doi:10.1172/JCI68506DS1). The most abundant of these metabolites (19.48–0.40 ng/ml; Supplemental Figure 1) were 7 α -hydroxy-3-oxocholest-4-en-26-oic acid (7 α H,3O-CA), 3 β -hydroxycholest-5-en-26-oic acid (3 β -HCA), and 2 newly identified metabolites in CSF, 3 β ,7 α -diHCA and 3 β ,7 β -dihydroxycholest-5-en-26-oic acid (3 β ,7 β -diHCA). Precursors of these acids, including 26-HC and newly identified 7 α ,26-dihydroxycholesterol (7 α ,26-diHC; cholest-5-ene-3 β ,7 α ,26-triol) and 7 α ,26-dihydroxycholest-4-en-3-one (7 α ,26-diHCO), were also found, but at lower levels (0.15–0.03 ng/ml). Our results thus identified 4 novel oxysterol metabolites in human CSF that were downstream of 26-HC (Figure 1A). 26-HC is metabolized via 7 α ,26-diHC and 7 α ,26-diHCO, or via 3 β -HCA and 3 β ,7 α -diHCA, to 7 α H,3O-CA. While 26-HC can cross the blood-brain barrier (BBB) and enter the brain from the circulation (25), 7 α H,3O-CA traverses the BBB and is exported from the brain (26). Very low levels of 24S-hydroxycholesterol (24S-HC; cholest-5-ene-3 β ,24S-diol), 25-hydroxycholesterol (25-HC; cholest-5-ene-3 β ,25-diol), and newly identified 7 α ,25-dihydroxycholesterol (7 α ,25-diHC; cholest-5-ene-3 β ,7 α ,25-triol) and 7 α ,25-dihydroxycholest-4-en-3-one (7 α ,25-diHCO) were also found in CSF (0.08–0.03 ng/ml).

Reduced levels of 7 α -hydroxylated cholestenic acids in CSF and plasma/serum of human patients with SPG5. SPG5 presents with upper motor neuron signs and results from mutations in *CYP7B1*, encoding the oxysterol 7 α -hydroxylase responsible for 7 α -hydroxylation of side-chain oxidized sterols that is required for extrahepatic synthesis of 7 α H,3O-CA and its precursor, 3 β ,7 α -diHCA (Figure 1A and ref. 18). In order to examine the pathogenic role of such mutations, we sought to identify alterations in oxysterol and cholestenic acid profiles in CSF and plasma from these patients and then examine the biological activities of the altered metabolites. We first studied the CSF from 3 patients with SPG5 (see Supplemental Table 3 for patient clinical data). Elevated levels of the *CYP7B1* substrates 25-HC ($P < 0.10$), 26-HC ($P < 0.07$), and 3 β -HCA ($P < 0.02$), as well as reduced levels of its products, 3 β ,7 α -diHCA ($P < 0.03$) and 7 α H,3O-CA ($P < 0.001$), were found compared with 18 individual control subjects; similar results were found when the SPG5 patients were compared with 2 healthy carrier heterozygotes with a single mutation in *CYP7B1* (Figure 1, F–I, and Supplemental Table 1). When plasma was analyzed from 9 SPG5 patients (8, 10, 14), significantly elevated 25-HC ($P < 0.03$), 26-HC ($P < 0.001$), and 3 β -HCA ($P < 0.02$) and reduced 3 β ,7 α -diHCA ($P < 0.001$) and 7 α H,3O-CA ($P < 0.02$) were found compared with control subjects (Figure 1, B–E, and Supplemental Table 2). Similar differences were found between patient samples and 3 healthy carriers. This indicates that for these metabolites, plasma represents a good surrogate for CSF. However, while 3 β ,7 α -diHCA and 7 α H,3O-CA in the CNS is normally derived from 26-HC, that found in the circulation can be derived via either the 26-HC or the 7 α -hydroxycholesterol (7 α -HC; cholest-5-ene-3 β ,7 α -diol) pathway (acidic and neutral, respectively) of bile acid biosynthesis (18). Thus, in SPG5 patients (*CYP7B1* mutation), the liver-specific 7 α -hydroxylase *CYP7A1* (neutral pathway) accounts for the residual content of 3 β ,7 α -diHCA and 7 α H,3O-CA found in the

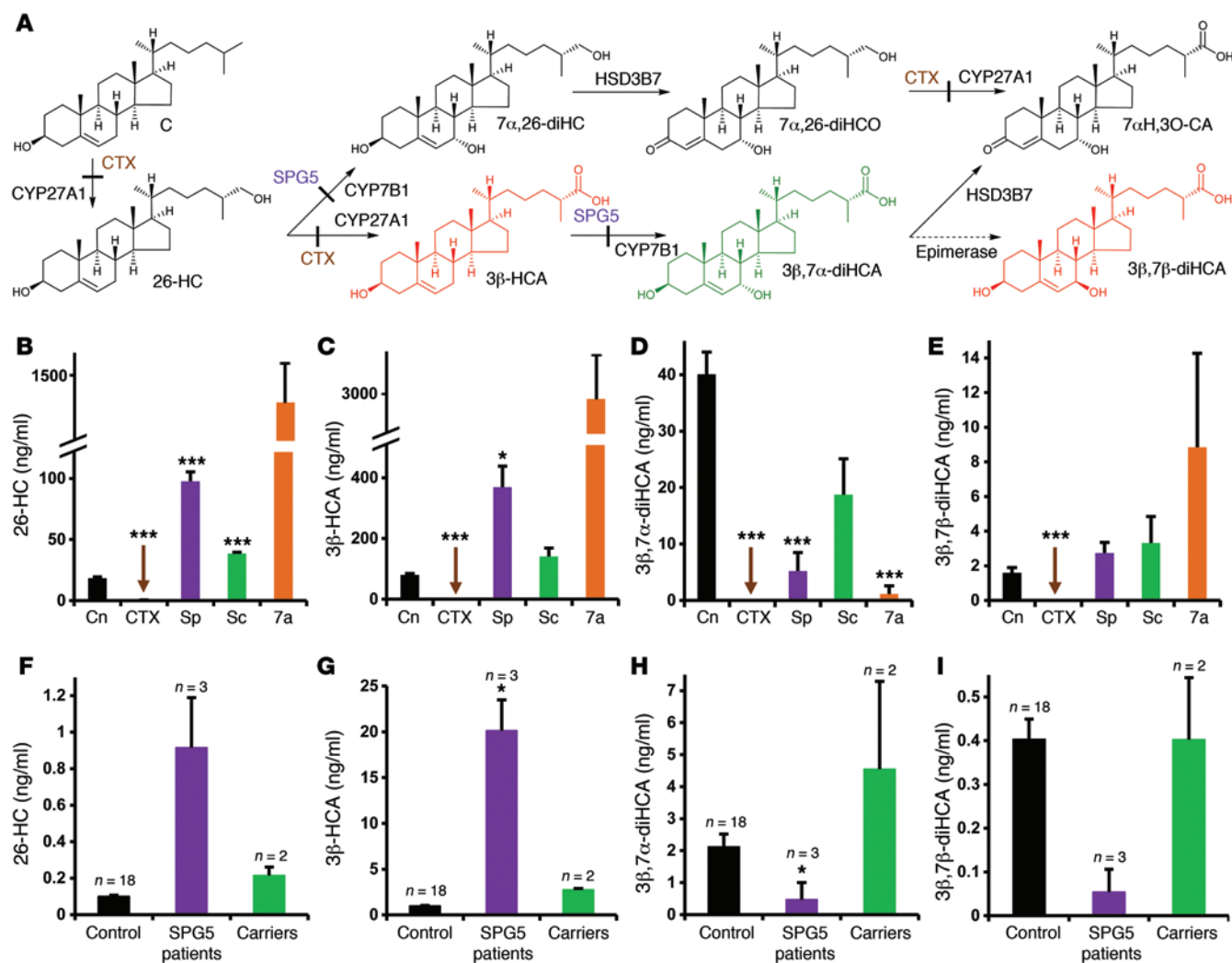


Figure 1. Biosynthesis of cholestenic acids in brain and levels of cholestenic acids in the circulation and CSF. (A) Suggested metabolic pathway for the biosynthesis of 3 β -HCA, 3 β ,7 α -diHCA, 3 β ,7 β -diHCA, and 7 α H,30-CA. Sterols are abbreviated according to cholesterol (C), cholest-4-en-3-one (CO), and cholestan-26-oic acid (CA) structures; numbers (with Greek letters) indicate the location of hydroxy (H) and oxo (O) groups. The enzymes in the pathway are indicated. With the exception of the epimerase, each enzyme is known to be expressed in brain. Enzyme defects in CTX and SPG5 are depicted by solid bars across arrows. Metabolites that are toxic toward neurons (red) or neuroprotective (green) are indicated. (B–E) Levels of (B) 26-HC, (C) 3 β -HCA, (D) 3 β ,7 α -diHCA, and (E) 3 β ,7 β -diHCA in plasma/serum from control subjects (Cn; $n = 50$), CTX patients ($n = 4$), SPG5 patients (Sp; $n = 9$), SPG5 carriers (Sc; $n = 3$) and infants with O7AHD (7a; $n = 3$). (F–I) Levels of (F) 26-HC, (G) 3 β -HCA, (H) 3 β ,7 α -diHCA, and (I) 3 β ,7 β -diHCA in CSF from control subjects ($n = 18$), SPG5 patients ($n = 3$), and SPG5 carriers ($n = 2$). Measurements were made by LC-ESI-MS (see Supplemental Tables 1 and 2). * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$ vs. control, Dunnett T3 test.

circulation. We previously investigated the plasma oxysterol and cholestenic acid profile of 3 infants with mutations in *CYP7B1* (Supplemental Table 2) resulting in oxysterol 7 α -hydroxylase deficiency (O7AHD) and neonatal liver disease (27–30), as well as SPG5 in adults (31). The first identification of *CYP7B1* mutations were found in a child with severe cholestasis (32), defining a new inborn error of bile acid biosynthesis. As expected by the absence of functional *CYP7B1* in these patients, we found very low plasma levels of 3 β ,7 α -diHCA ($P < 0.001$; Figure 1D and Supplemental Table 2), as described above for SPG5. These patients also had considerably elevated plasma levels of 24S-HC, 25-HC, and 26-HC and high levels of hepatotoxic 3 β -hydroxycholestan-5-en-24-oic acid (3 β H- Δ^5 -BA) compared with SPG5 patients and controls. These findings suggest that additional factors, including increased

levels of toxic 3 β -hydroxy-5-ene acids, may contribute to the progressive liver disease in these patients at an early age.

CTX is a second human disease that may present with signs of motor neuron loss. It is characterized by mutations in *CYP27A1*. We found that the plasma of patients with CTX was essentially devoid of 26-HC and the downstream cholestenic acids (Figure 1, B–E, and Supplemental Table 2). As reported previously (33), elevated levels of 7 α -HC plus 7 α -hydroxycholestan-4-en-3-one (7 α -HCO) and/or 7 α ,12 α -dihydroxycholesterol (7 α ,12 α -diHC; cholest-5-ene-3 β ,7 α ,12 α -triol) plus 7 α ,12 α -dihydroxycholestan-4-en-3-one (7 α ,12 α -diHCO) were observed (Supplemental Table 2). The absence of cholestenic acids in plasma indicates an inability to biosynthesize C_{27} acids in extrahepatic steroidogenic tissue, including the CNS.

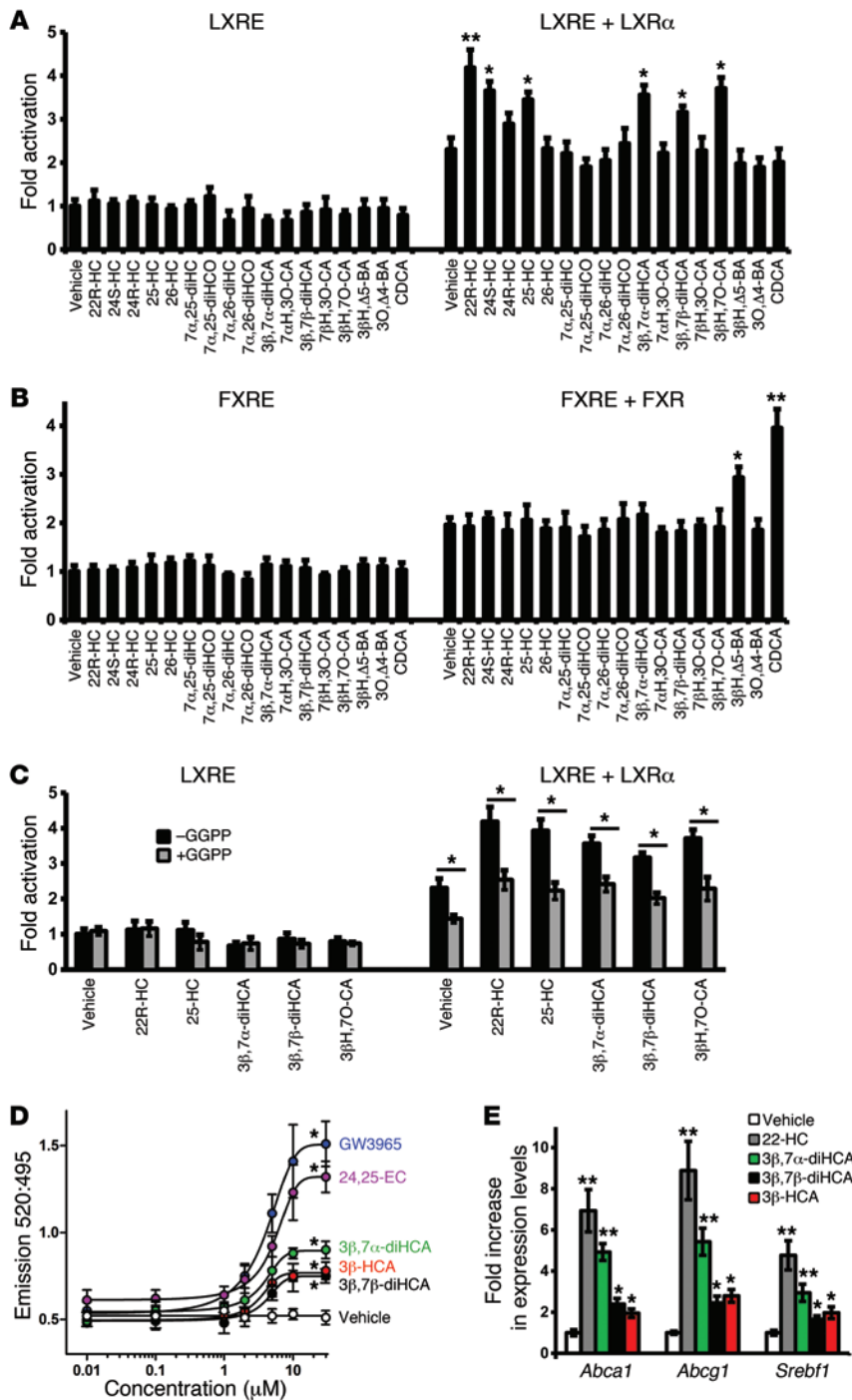


Figure 2. Analysis of the nuclear receptor activation capacity of oxysterols and cholestenic acids. (A) Luciferase activity in SN4741 neural cells transfected with an LXR-responsive luciferase reporter construct (LXRE) with or without LXR α and stimulated for 24 hours with 22R-HC (10 μ M), a known LXR α ligand (3, 4), or the compounds indicated. (B) Similar assay in cells transfected with an FXR-responsive luciferase reporter construct (FXRE) with or without FXR and stimulated for 24 hours with CDCA, a known FXR ligand, or the compounds indicated. (C) Additional luciferase assays performed as in A with or without addition of the LXR antagonist GGPP (10 μ M) along with the indicated cholesterol metabolites (10 μ M each). Values in A–C are fold activation over the basal LXRE or FXRE luciferase activity (set to 1) ($n = 3$). * $P < 0.05$, ** $P < 0.01$ vs. vehicle or as indicated by brackets, Mann-Whitney test. (D) TR-FRET LXR β coactivator assay, used to determine the binding affinity of cholestenic acids as well as the known LXR ligands GW3965 and 24,25-EC toward the LXR β -LBD ($n = 3$). The 520:495 TR-FRET ratio was determined as described in Methods. * $P < 0.05$ vs. vehicle for $\geq 10 \mu$ M 3 β ,7 α -diHCA, $\geq 10 \mu$ M 3 β ,7 β -diHCA, $\geq 10 \mu$ M 3 β -HCA, $\geq 5 \mu$ M 24,25-EC, and $\geq 5 \mu$ M GW3965, Mann-Whitney test. (E) 3 β ,7 α -diHCA, 3 β ,7 β -diHCA and 3 β -HCA induced significant increases in *Abca1*, *Abcg1*, and *Srebf1* in SN4741 cells ($n = 3$). * $P < 0.05$, ** $P < 0.01$ vs. vehicle, Mann-Whitney test.

In summary, our data showed specific changes in 7 α -hydroxylated cholestenic acids in plasma of CTX and SPG5 patients; we thus decided to examine their effect on neural function.

Specific cholestenic acids are ligands to LXR α and LXR β in neural cells. In order to gain insights into the mechanism by which alterations in cholesterol metabolism causes neurological disease, we studied whether any of the cholestenic acids present at high levels in control human CSF and deregulated in CSF or plasma of SPG5 or CTX patients work as LXR ligands. We thus focused on 26-HC, 3 β -HCA, 3 β ,7 α -diHCA, its isomer 3 β ,7 β -diHCA, and 7 α H,3O-CA (Figure 1A) and tested their capacity to activate LXR α

and LXR β in neural cells. We previously found that 3 β -HCA activates LXR (7) and here observed that 3 β ,7 α -diHCA, its isomer 3 β ,7 β -diHCA, and the necessary intermediate for the interconversion of the isomers, 3 β -hydroxy-7-oxocholest-5-en-26-oic acid (3 β H,7O-CA), had the ability to activate both LXRs and therefore act as LXR ligands in neural cells (Figure 2A and Supplemental Figure 2, A and B). 3 β ,7 α -diHCA was the most potent cholestenic acid, exhibiting 61% activity/efficacy toward LXR β activation compared with the known LXR ligand 22R-hydroxycholesterol (22R-HC; cholest-5-ene-3 β ,22R-diol), followed by 3 β -HCA and 3 β ,7 β -diHCA (Supplemental Figure 2B). However 3 β ,7 β -diHCA

had the lowest 50% effective concentration (EC_{50}), followed by $3\beta,7\alpha$ -diHCA and 3β -HCA. In addition, we confirmed in our system the capacity of 24S-HC and 25-HC to activate LXR and observed that 26-HC had no significant effect. We also tested the activational capacity of 7α H,3O-CA, its 7β -isomer, 7β -hydroxy-3-oxocholest-4-en-26-oic acid (7β H,3O-CA), and the precursors $7\alpha,26$ -diHC and $7\alpha,26$ -diHCO, none of which showed significant activity (Figure 2A and Supplemental Figure 2A). Moreover, in order to examine whether the identified acidic ligands exert their effect by binding to LXR, we used the LXR antagonist geranylgeranyl pyrophosphate (GGPP; ref. 34), which blocked their activity (Figure 2C), indicating that the acids are indeed LXR ligands. The activity of the known LXR ligands 22R-HC and 25-HC was similarly blocked. In order to confirm that the cholestenic acids are indeed agonists to LXR, we tested the LXR β activational capacity of $3\beta,7\alpha$ -diHCA, $3\beta,7\beta$ -diHCA, or 3β -HCA in combination with 22R-HC. No additive effect was observed (Supplemental Figure 3A), which indicates that these cholestenic acids work, as does 22R-HC, via LXR. To further examine the specificity of the cholestenic acids described above, farnesoid X receptor (FXR) luciferase reporter assays were performed (Figure 2B). As previously described (35), chenodeoxycholic acid (CDCA; $3\alpha,7\alpha$ -dihydroxy-5 β -cholan-24-oic acid) activated FXR. Interestingly, 3β H- Δ^5 -BA (36), a cholesterol metabolite identified in plasma (Supplemental Table 2), also activated FXR, but was less potent than CDCA. However, none of the other compounds tested activated the FXR luciferase reporter or modulated the activity of CDCA in neural cells (Figure 2B and Supplemental Figure 3B). Thus, the cholestenic acids do not exert their effect via modulating the activity of the FXR nuclear receptor or its ligands. Similarly, cholestenic acids did not activate luciferase reporter assays under the control of a DR5 element (activated by Nur-related factor 1/retinoid X receptor [NURR1/RXR] heterodimers), whereas 9-cis-retinoic acid (9-cis-RA) activated this reporter (Supplemental Figure 2D). Furthermore, while lithocholic acid (LCA; 3α -hydroxy-5 β -cholan-24-oic acid) activated a vitamin D receptor (VDR) luciferase reporter, none of the cholestenic acids tested showed any significant effect on VDR activation in neural cells (Supplemental Figure 2C). Thus, our results indicate that 3β -HCA (7), $3\beta,7\alpha$ -diHCA, and $3\beta,7\beta$ -diHCA are specific LXR ligands in neural cells.

Specific cholestenic acids bind and activate LXR. In order to show that specific cholestenic acids directly interact with LXR, we performed a binding and activation fluorescence resonance energy transfer (FRET) assay, in which ligand binding to the ligand binding domain (LBD) of LXR β (referred to herein as LXR β -LBD) recruits a fluorescent coactivator. $3\beta,7\alpha$ -diHCA induced FRET, in a dose-dependent manner, to a greater extent than the other acids, but to a lesser extent than the known LXR ligands GW3965 and 24S,25-epoxycholesterol (24,25-EC; 3β -hydroxycholest-5-en-24S,25-epoxide) (Figure 2D). The respective efficacy (GW3965-normalized) and EC_{50} values were 1 and 4.04 μ M for GW3965, 0.79 and 4.94 μ M for 24,25-EC, 0.41 and 4.16 μ M for $3\beta,7\alpha$ -diHCA, 0.25 and 4.51 μ M for $3\beta,7\beta$ -diHCA, and 0.27 and 3.83 μ M for 3β -HCA. To provide further evidence that cholestenic acids are LXR ligands in neural cells, we treated neural cells with the individual acids for 3 hours and measured *Abca1*, *Abcg1*, and *Srebf1* transcript levels. $3\beta,7\alpha$ -diHCA increased transcripts levels

to a similar degree as 22R-HC, while $3\beta,7\beta$ -diHCA and 3β -HCA induced transcription, but to a lesser extent (Figure 2E). These results provide further proof that 3β -HCA, $3\beta,7\alpha$ -diHCA, and $3\beta,7\beta$ -diHCA are specific LXR ligands in neural cells.

$3\beta,7\alpha$ -diHCA and 3β H,7O-CA increase *islet-1* expression in *islet-1-GFP* zebrafish embryos. Having established that cholestenic acids that are altered in CTX or SPG5 can activate LXRs in vitro, we next sought to identify their effect in vivo. In particular, we focused on the expression of *islet-1*, a transcription factor expressed in all postmitotic motor neurons (20, 37) and required for multiple aspects of motor neuron development, including motor neuron specification, motor column formation, axonal growth, and maintenance of spinal motor neuron identity (38). We used transgenic zebrafish embryos expressing GFP driven by the *is1l* gene promoter/enhancer sequences (Tg[*is1l*:GFP]) (39, 40) to screen for biologically active compounds in vivo. Previous studies have indicated that *islet-1* protein is required for the formation of zebrafish primary motor neurons and is conserved throughout vertebrate evolution (21). Treatment of Tg[*is1l*:GFP] embryos with the weak LXR ligands 3β -HCA and $3\beta,7\beta$ -diHCA, as well as CDCA, the most potent FXR ligand, had a deleterious toxic effect that impaired survival and precluded further in vivo analysis. Interestingly, we found that 2 LXR agonists, $3\beta,7\alpha$ -diHCA and 3β H,7O-CA, increased *islet-1-GFP* expression, but had no significant effect on the number of *islet-1*⁺ cells, in the different cranial nerves examined (loci III, IV, V, VII, and X; Figure 3, A and B). These effects were specific, as 7α H,3O-CA, which is not an LXR ligand, failed to regulate *islet-1-GFP* expression (Figure 3B). Notably, the increase in *islet-1-GFP* expression observed in response to the specific acidic compounds was evident in all cranial nerves studied (Figure 3B). Importantly, the increased *islet-1-GFP* expression in response to $3\beta,7\alpha$ -diHCA and 3β H,7O-CA was also accompanied by an increased level of *is1l* mRNA, as assessed by quantitative PCR (Figure 3C). To further verify our results, we examined whether these cholestenic acids regulated the in vivo expression of endogenous LXR target genes, such as *abca1*. Our results showed enhanced expression of *abca1* by both $3\beta,7\alpha$ -diHCA and 3β H,7O-CA, but not by 7α H,3O-CA (Figure 3D). Finally, in order to determine whether these effects are actually mediated by LXRs, we performed *lxx* morpholino (MO) injections in Tg[*is1l*:GFP] zebrafish. Interestingly, we found that *lxx* MO injections abolished the in vivo increase in *islet-1-GFP* levels by $3\beta,7\alpha$ -diHCA and 3β H,7O-CA, compared with control scrambled MO (Supplemental Figure 4). Thus, our data showed that cholestenic acids are capable of activating endogenous LXR target genes in vivo and regulate the in vivo expression of *islet-1* in brain motor neurons via LXR.

$3\beta,7\alpha$ -diHCA and 3β H,7O-CA increase, whereas $3\beta,7\beta$ -diHCA and 3β -HCA decrease, the number of rodent oculomotor neurons in vitro. In order to determine the functional relevance of our findings in mammalian cells, we examined whether any of the cholestenic acids present in human CSF and implicated in motor neuron loss are also capable of regulating *islet-1* expression in mouse primary brain progenitor cultures. We first performed dose-response analysis of the cholestenic acids of interest, using a wide range of concentrations; whereas $3\beta,7\beta$ -diHCA and 3β -HCA caused loss of *islet-1*⁺ cells in the cultures, equimolar concentra-

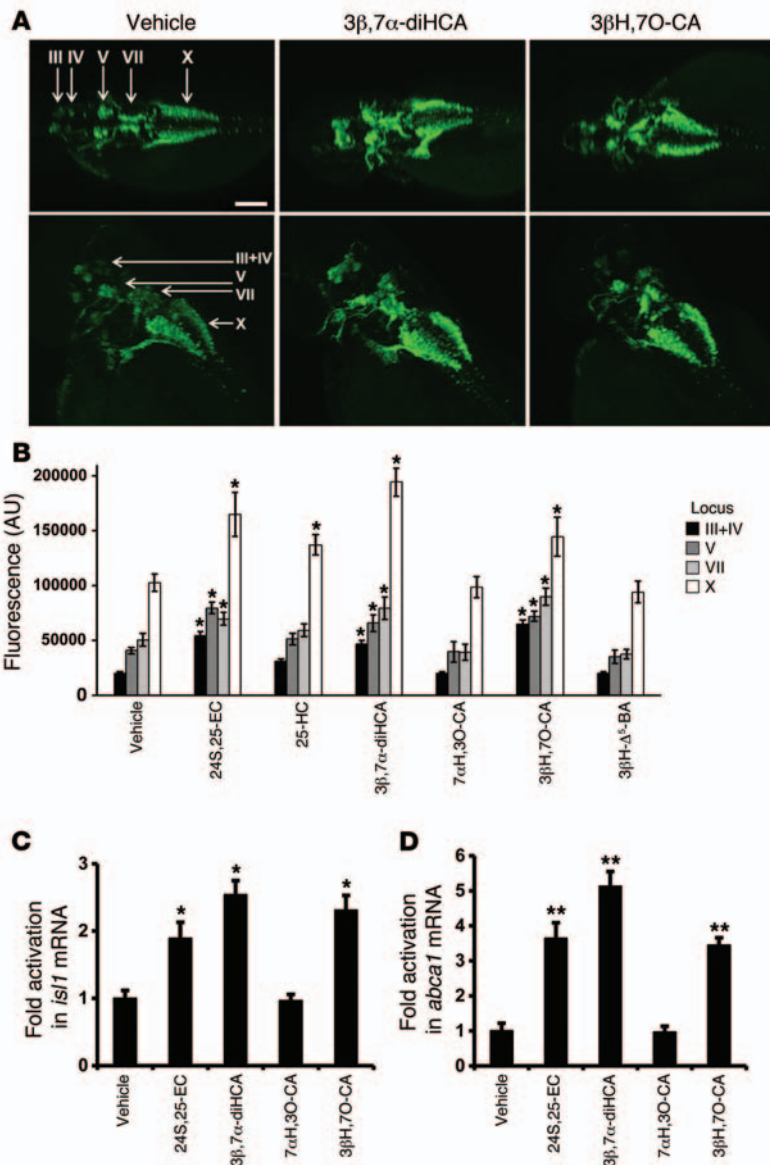


Figure 3. Effects of cholestenic acids on zebrafish motor neurons. Tg[islet1:GFP] embryos were incubated with 10 μM test compound or vehicle added to medium, and the medium was replaced every 12 hours with fresh solution (containing test compound or vehicle). Immunocytochemistry was performed using an anti-GFP antibody at 48 hpf. (A) Dorsal (top) and dorsolateral (bottom) views of the head/upper back region of embryos treated with vehicle, 3β,7α-diHCA, or 3βH,7O-CA. Arrows indicate loci III, IV, V, VII, and X (37), which are evolutionarily homologous to the cranial nerves in humans (40). Locus III contains the oculomotor neurons, locus IV the trochlear neurons, locus V the trigeminal motor neurons, locus VII the facial motor neurons, and locus X the cell bodies of the vagus nerve. Scale bar: 50 μm. (B) Quantification of islet1-GFP signal intensity in the different loci (n = 4). 24,25-EC was used as a positive control. (C and D) mRNA levels of (C) *islet1* and (D) *abca1* after treatment with the indicated compounds. Data are mean ± SEM (n = 3). *P < 0.05, **P < 0.01 vs. respective vehicle, Mann-Whitney test.

not affect the number of other midbrain neurons, such as tyrosine hydroxylase-positive (TH⁺) dopamine neurons, GABAergic neurons, or red nucleus neurons in the cultures (data not shown). In order to examine whether the effects of 3β,7α-diHCA and 3βH,7O-CA were specifically mediated by LXR receptors in the rodent brain, we performed progenitor brain cultures from *Lxra*^{-/-}*Lxrb*^{-/-} mice. Remarkably, the effects of 3β,7α-diHCA and 3βH,7O-CA (at their most efficient concentration) on islet-1⁺ neurons were eliminated (Figure 4C), confirming that they regulate the number of islet-1⁺ cells in the rodent brain through LXRs. Moreover, the effects of these acids were blocked by GGPP (Figure 4D), further suggesting that the observed effects were mediated by LXR receptors.

Interestingly, 26-HC, a precursor of cholestenic acids in the acidic pathway of bile acid biosynthesis (18) that had no LXR activation effect in luciferase assays in neural cells (Figure 2 and ref. 6), also exhibited no effect on the number of islet-1⁺ cells (data not shown). Furthermore, the effects of 3β,7α-diHCA, 3β,7β-diHCA, and 3β-HCA on islet-1⁺ cells were not altered by the known LXR ligand 22R-HC (Supplemental Figure 3C), which does not show an effect toward islet-1⁺ cells (6). These findings are very exciting, as none of the previously known endogenous brain LXR ligands regulates the function of motor neurons. We recently reported that brain endogenous LXR ligands selectively regulate neurogenesis and/or survival of other cell populations in the developing mid-brain (6). We thus sought to examine the mechanism by which 3β,7α-diHCA and 3βH,7O-CA increase the number of islet-1⁺ cells and studied their role in neurogenesis, proliferation, and motor neuron survival in the developing brain.

3β,7α-diHCA promotes rodent oculomotor neuron survival in vitro, whereas 3β,7β-diHCA and 3β-HCA are toxic. Neurogenesis was examined in BrdU pulse-chase experiments, in which neuronal progenitors in primary cultures are labeled with a pulse of BrdU at the beginning of the experiment and then are examined for their differentiation into motor neurons, as assessed by the acquisition

tions of 3β,7α-diHCA and 3βH,7O-CA increased islet-1⁺ oculomotor cell numbers (Figure 4A). EC₅₀ values were 5.21 μM for 3β,7α-diHCA and 3.58 μM for 3βH,7O-CA, and IC₅₀ values were 4.44 μM for 3β,7β-diHCA and 2.63 μM for 3β-HCA. Moreover, islet-1⁺ cells coexpressed the transcription factor NKX6.1 as well as choline acetyltransferase (ChAT) (Figure 4B and data not shown), which indicates that they are bona fide oculomotor neurons. Time-course analysis confirmed the stimulatory effect of 3β,7α-diHCA and 3βH,7O-CA, as well as the toxic effect of 3β,7β-diHCA and 3β-HCA, over a range of incubation times (Supplemental Figure 5A). The number of oculomotor neurons peaked after 2 days in culture and leveled thereafter. These results confirmed in rodent cells the dual effects of cholestenic acids first observed in zebrafish, where 3β,7β-diHCA and 3β-HCA caused death, whereas 3β,7α-diHCA and 3βH,7O-CA regulated islet-1 expression. Thus, our data provide further evidence of the differential effect of cholestenic acids on islet-1⁺ oculomotor neurons. Interestingly, the effects of 3β,7α-diHCA and 3βH,7O-CA were specific, as they did

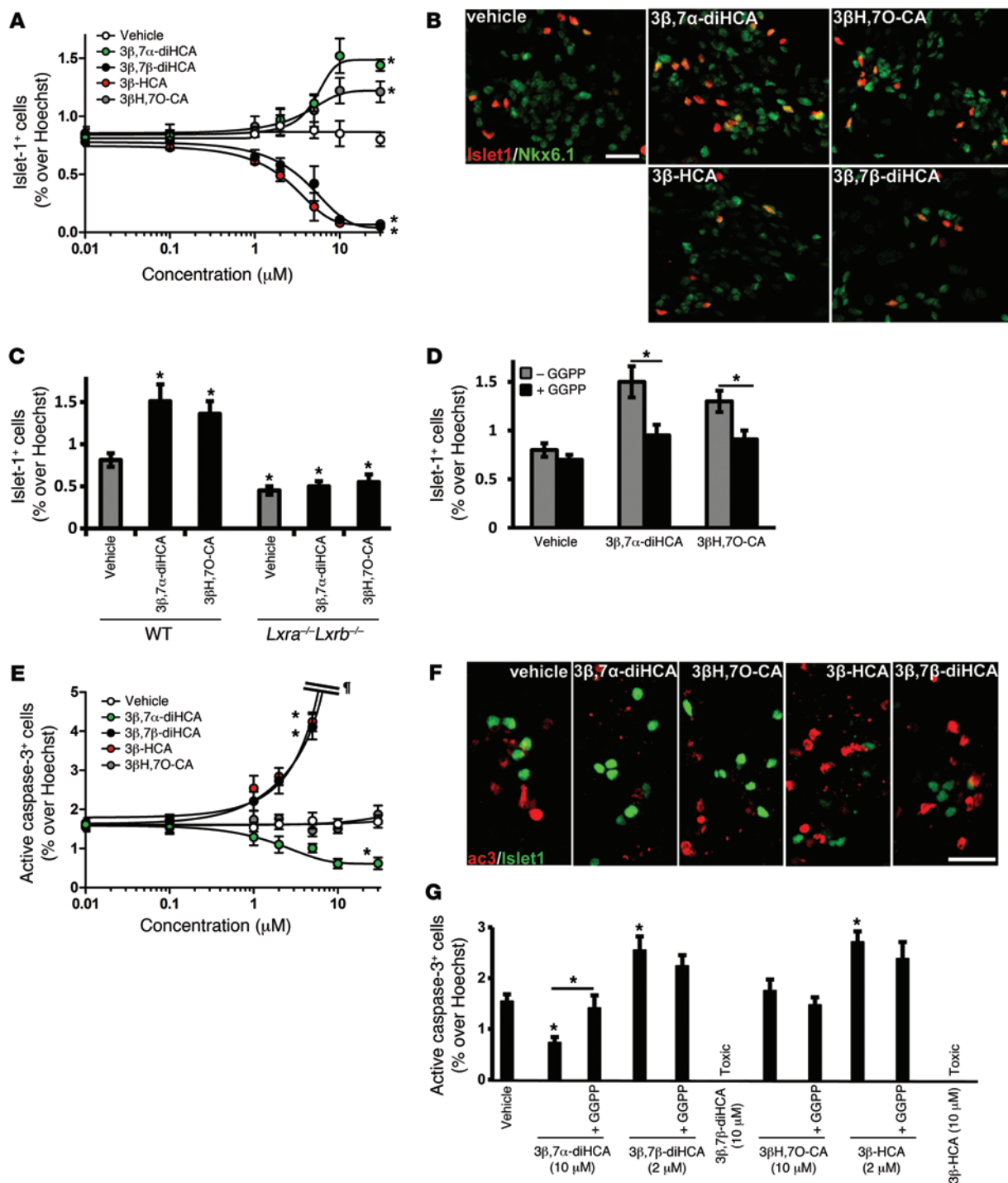


Figure 4. Specific cholesteric acids increase the number of islet-1⁺ oculomotor neurons, promote neuronal survival, or are toxic in mouse E11.5 brain primary cultures. (A) Dose-response curves for quantification of islet-1⁺ cells in mouse E11.5 brain primary cultures from WT embryos treated with the indicated compounds. **P* < 0.05 vs. vehicle for ≥5 μM 3β,7α-diHCA, ≥10 μM 3βH,7O-CA, ≥2 μM 3β,7β-diHCA, and ≥2 μM 3β-HCA, Mann-Whitney test. (B) Representative islet-1- and NKX6.1-stained cell nuclei treated with 3β,7α-diHCA (10 μM), 3βH,7O-CA (10 μM), 3β,7β-diHCA (2 μM), or 3β-HCA (2 μM). (C) Quantification of islet-1⁺ cells in primary cultures from WT or *Lxra*^{-/-}*Lxrb*^{-/-} embryos treated with 3β,7α-diHCA or 3βH,7O-CA (10 μM). **P* < 0.05 vs. vehicle, Mann-Whitney test. (D) Effect of 10 μM GGPP on treatment in the WT group. **P* < 0.05, Mann-Whitney test. (E) Dose-response curves for quantification of active caspase-3⁺ cells in mouse E11.5 brain primary cultures. Very high cell death in the cultures is denoted by †. **P* < 0.05 vs. vehicle for ≥10 μM 3β,7α-diHCA, ≥2 μM 3β,7β-diHCA, and ≥2 μM 3β-HCA, Mann-Whitney test. (F) Representative active caspase-3- and islet-1-stained cell nuclei treated as in B. (G) Quantification of active caspase-3⁺ cells in primary cultures (WT group) treated as indicated, with or without 10 μM GGPP. **P* < 0.05 vs. vehicle or as indicated by brackets, Mann-Whitney test. All data are mean ± SEM (*n* = 3). Scale bars: 20 μm.

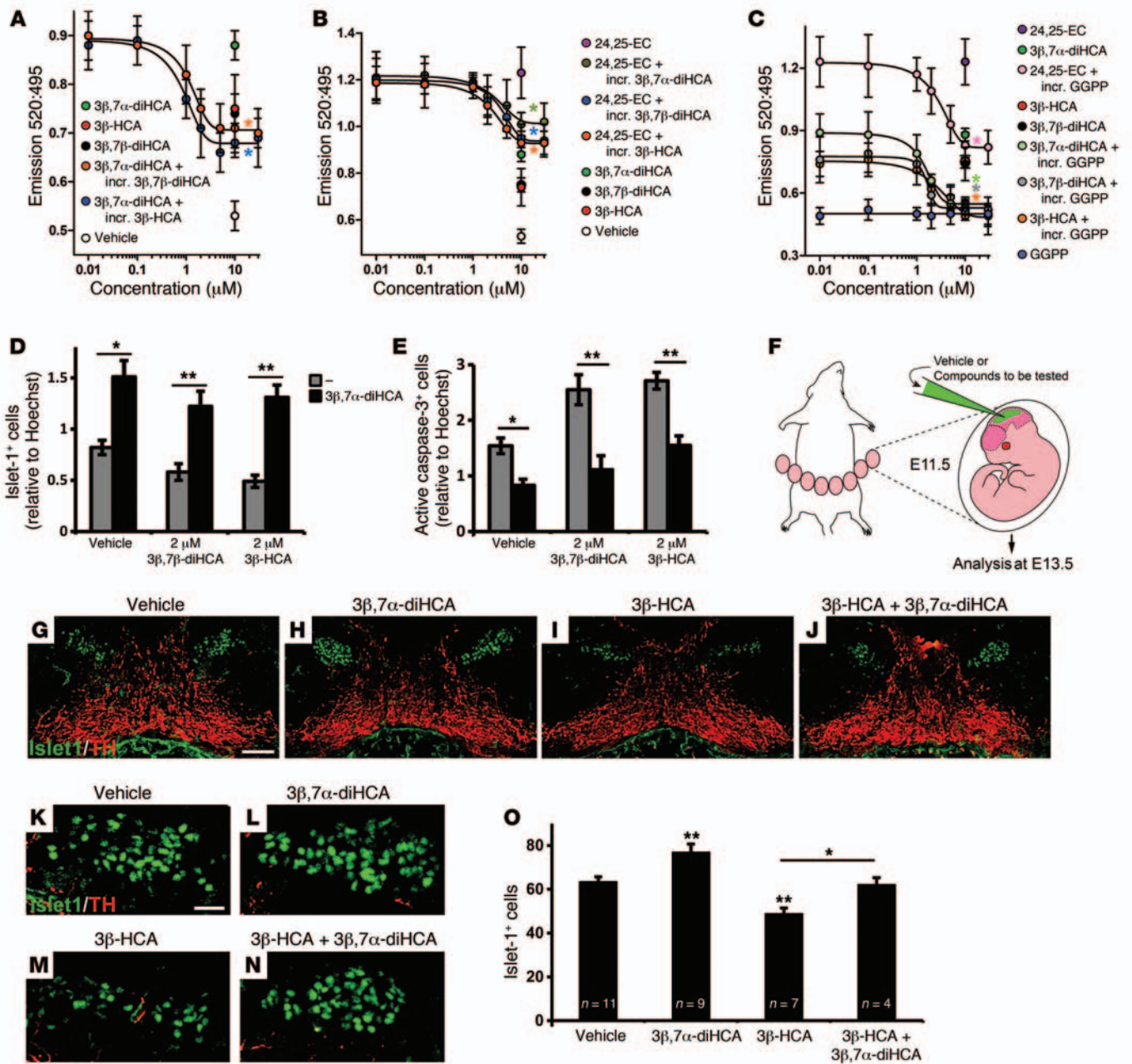


Figure 5. Competition between cholestenic acid effects, and 3β,7α-diHCA promotes motor neuron survival in vivo. (A–C) TR-FRET LXRβ coactivator assays. (A) The effect of 10 μM 3β,7α-diHCA was dose-dependently competed by increasing concentrations (incr.) of 3β,7β-diHCA and 3β-HCA (both *P < 0.05 for ≥ 2 μM). Similarly, (B) the effect of 10 μM 24,25-EC was dose-dependently competed by 3β,7α-diHCA (*P < 0.05 for ≥ 10 μM), 3β,7β-diHCA (*P < 0.05 for ≥ 10 μM), and 3β-HCA (*P < 0.05 for ≥ 5 μM), and (C) the effects of 3β,7α-diHCA, 3β-HCA, 3β,7β-diHCA, and 24,25-EC (all 10 μM) were dose-dependently competed by GGPP (all *P < 0.05 vs. respective no-GGPP group). Data were analyzed by Mann-Whitney test. (D and E) 10 μM 3β,7α-diHCA rescued the toxic effect of 2 μM 3β,7β-diHCA or 3β-HCA on islet-1⁺ cells and reduced neuronal cell death induced by these acids, as indicated by the number of active caspase-3⁺ cells, in mouse E11.5 brain primary cultures. *P < 0.05, **P < 0.01, Mann-Whitney test. (F) Mouse embryos were injected with vehicle or cholestenic acid into the mesencephalic ventricle in utero at E11.5 and collected at E13.5. (G–J) Midbrain coronal sections showing islet-1⁺ motor neurons (green) and neighboring TH⁺ neurons (red) (G–J), and higher magnification of islet-1⁺ cells (K–N), for embryos injected with vehicle (G and K), 5 μM 3β,7α-diHCA (H and L), 1 μM 3β-HCA (I and M), and 1 μM 3β-HCA plus 5 μM 3β,7α-diHCA (J and N). (O) Quantification of islet-1⁺ cell number in each group. *P < 0.05, **P < 0.01, 1-way ANOVA with LSD post-hoc test. Scale bars: 100 μm (G–J); 20 μm (K–N). All data are mean ± SEM (n = 3).

of islet-1 expression, a marker for motor neuron fate (41). Surprisingly, none of the cholestenic acids studied affected the number of double-positive BrdU⁺islet-1⁺ cells (Supplemental Figure 6A), which indicates that they do not promote motor neuron neurogenesis. Similarly, none of the cholestenic acids affected the total num-

ber of BrdU⁺ cells in the cultures (Supplemental Figure 6B), which suggests that they do not modulate proliferation. Finally, we tested whether cholestenic acids regulate neuronal survival, as assessed by active caspase-3 staining to detect the number of cells undergoing apoptosis in the cultures. Interestingly, treatment with 3β,7α-

diHCA over a wide range of concentrations decreased the number of active caspase-3⁺ cells, whereas 3 β H,7O-CA had no effect (Figure 4, E and F). Since proliferation, neurogenesis, and cell death were not affected by 3 β H,7O-CA, we attribute the increase in islet-1⁺ cells to an increase in differentiation, given the known role of islet-1 in this process (20). Cholestenic acids that reduced the number of islet-1⁺ cells were also examined for their capacity to induce cell death in oculomotor neuron cultures. Interestingly, low concentrations of either 3 β ,7 β -diHCA or 3 β -HCA increased the number of active caspase-3⁺ cells (Figure 4, E and F), with toxicity starting at 1 μ M. No surviving cells were detected when cultures were treated with concentrations of 3 β ,7 β -diHCA or 3 β -HCA higher than 5 μ M. Time-course experiments showed that toxicity was evident after 2 days of incubation (Supplemental Figure 5B).

The survival-promoting effect of 3 β ,7 α -diHCA was completely blocked by coincubation with GGPP (Figure 4G), which indicated that this effect was mediated by LXR. Conversely, the cell death effects of 3 β ,7 β -diHCA or 3 β -HCA (at 2 μ M) were not blocked by GGPP (Figure 4G), which suggested that the survival-promoting effects of 3 β ,7 α -diHCA, but not the toxic effects of 3 β ,7 β -diHCA or 3 β -HCA, were mediated by LXR.

We next examined whether the toxic effects of 3 β ,7 β -diHCA or 3 β -HCA could be mediated by receptor blockade or competition. We first performed a binding and activation FRET assay using 3 β ,7 α -diHCA at its most effective concentration and increasing concentrations of 3 β ,7 β -diHCA or 3 β -HCA. We found that 3 β ,7 β -diHCA and 3 β -HCA reduced the binding of 3 β ,7 α -diHCA in a dose-dependent manner (Figure 5A), which indicates that these toxic cholestenic acids compete with the neuroprotective 3 β ,7 α -diHCA for binding to the LXR β -LBD. K_i values were 0.91 μ M for 3 β -HCA and 1.22 μ M for 3 β ,7 β -diHCA.

Furthermore, we performed competition experiments using the known LXR ligand 24,25-EC (at its most effective concentration) and increasing concentrations of each of the cholestenic acids studied. 3 β ,7 α -diHCA, 3 β -HCA, and 3 β ,7 β -diHCA each reduced the binding of 24,25-EC to the LXR β -LBD in a dose-dependent manner (Figure 5B), which suggests that each of these cholestenic acids competes with 24,25-EC for binding to the LXR β -LBD. 3 β -HCA had the lowest K_i value (3 β ,7 α -diHCA, 3.56 μ M; 3 β ,7 β -diHCA, 3.45 μ M; 3 β -HCA, 2.43 μ M).

In order to further prove that 3 β ,7 α -diHCA, 3 β -HCA, and 3 β ,7 β -diHCA are specific LXR ligands in neural cells, we incubated the acids with GGPP (6). This antagonized and inhibited the ligand-dependent induction of FRET by 3 β ,7 α -diHCA, 3 β -HCA, and 3 β ,7 β -diHCA as well as by the known LXR ligand 24,25-EC (Figure 5C), which indicates that 3 β ,7 α -diHCA, 3 β -HCA, and 3 β ,7 β -diHCA bind to LXRs. The K_i values for the compounds of interest when incubated with GGPP were 3.96 μ M for 24,25-EC, 1.95 μ M for 3 β ,7 α -diHCA, 2.51 μ M for 3 β ,7 β -diHCA, and 2.02 μ M for 3 β -HCA.

We next tested whether 3 β ,7 α -diHCA could also compete and reduce the toxic effect of 3 β ,7 β -diHCA or 3 β -HCA. Treatment with 10 μ M 3 β ,7 α -diHCA reversed the loss of islet-1⁺ cells and the increased number of activated caspase-3⁺ cells induced by 2 μ M of 3 β ,7 β -diHCA or 3 β -HCA (Figure 5, D and E). These observations reinforce the notion of balance between the survival- and death-inducing effects of cholestenic acids and suggest a new avenue for therapeutic intervention.

3 β ,7 α -diHCA promotes survival of rodent motor neurons in vivo and prevents toxicity by 3 β -HCA. In order to examine whether the observed effects of cholestenic acids on motor neuron survival could also be detected in the mammalian brain in vivo, we performed cholestenic acid injections into the cerebral aqueduct of E11.5 mice in utero and analyzed brain sections at the midbrain level at E13.5 (Figure 5F). While only occasional double-positive islet-1⁺ activate caspase-3⁺ cells remained at the end of the experiment (Supplemental Figure 7), reliable cell counts could be performed for islet-1 and TH (Figure 5, G–O). 3 β ,7 α -diHCA did not affect the number of TH⁺ neurons, but increased the number of islet-1⁺ oculomotor neurons, indicative of a selective survival effect of 3 β ,7 α -diHCA on oculomotor neurons in vivo. Upon injection of 3 β -HCA, the number of islet-1⁺ oculomotor neurons was reduced, showing the toxic effect of this metabolite on motor neurons in vivo. Finally, coinjection of 3 β -HCA and 3 β ,7 α -diHCA reversed the loss of oculomotor neurons induced by 3 β -HCA, indicating that 3 β ,7 α -diHCA protects oculomotor neurons against cholestenic acids such as 3 β -HCA in vivo. These data further confirm the specificity of the neuronal survival and toxic effects of these cholestenic acids on islet-1⁺ neurons, but not TH⁺ neurons, as well as the competitive interaction between prosurvival and toxic cholestenic acids on motor neurons in vivo.

In summary, our results indicate that cholestenic acids regulate the number of islet-1⁺ motor neurons by controlling islet-1 expression (3 β H,7O-CA) and competitively regulating neuronal survival in a positive (3 β ,7 α -diHCA) or negative (3 β ,7 β -diHCA and 3 β -HCA) manner.

Discussion

The results presented herein show that cholestenic acids are not mere intermediate metabolites of bile acid biosynthesis, but rather represent a diverse family of bioactive compounds capable of regulating nuclear receptor function. Cholestenic acids were found to specifically activate LXR and elicit an exquisite array of functions, ranging from the regulation of islet-1 expression to the positive and negative regulation of motor neuron survival both in vitro and in vivo. Moreover, our findings identified cholestenic acids in human CSF to be deregulated in plasma of CTX and SPG5 patients. Importantly, an absence of neuroprotective cholestenic acids was found in CTX patient plasma, while a combination of decreased neuroprotective and increased toxic cholestenic acids was detected in SPG5 plasma. These results are consistent with cholestenic acids being key regulators of motor neuron function in development and disease.

Cholesterol is present at high levels in the CNS of vertebrates and is metabolized in brain predominantly to 24S-HC (42), which accounts for about two-thirds of brain cholesterol metabolism (43). Low levels of 26-HC have been found in human and mouse brain (Supplemental Results and Supplemental Table 4) and in human CSF, where it may be imported from the blood (25, 44–46). Conversely, 7 α H,3O-CA, a metabolic product of 26-HC, is exported from brain to blood in humans (26). In the current study, we found 4 intermediates in the biosynthesis of 7 α H,3O-CA from 26-HC via CYP27A1 and CYP7B1 to be present in normal CSF: 3 β -HCA, 3 β ,7 α -diHCA, 7 α ,26-diHC, and 7 α ,26-diHCO (Figure 1A). While 3 β -HCA and 7 α ,26-diHC were previously found in human neu-

ral tissue (46, 47), $3\beta,7\alpha$ -diHCA and $7\alpha,26$ -diHCO have not been previously found in neural tissue or CSF. Importantly, the identification of these intermediates in the biosynthesis of 7α H, $3O$ -CA lends further support to the hypothesis that 7α H, $3O$ -CA is biosynthesized in the human brain (26). This pathway is also conserved in rodents, in which 26-HC is the precursor for the synthesis of 3β -HCA in fetal neurons and of $3\beta,7\alpha$ -diHCA and 7α H, $3O$ -CA in fetal astrocytes (Figure 1A and ref. 48). There have been few studies of specific brain regions for cholestenic acids; however, human retina has been found to contain 3β -HCA at a level of up to 130 pmol/mg protein, about 10% of the level of 24S-HC in brain gray matter (47), whereas in chronic subdural hematoma, 7α H, $3O$ -CA has been found at a level of 1.5 μ M (49). Future studies will be directed at profiling cholestenic acids in distinct brain regions. Surprisingly, *Cyp7b1*^{-/-} and *Cyp27a1*^{-/-} mice, unlike human SPG5 patients and some CTX patients, do not suffer from motor neuron disease, despite an absence of $3\beta,7\alpha$ -diHCA in brain and plasma (Supplemental Table 4). These findings suggest that other LXR ligands may compensate for the accumulative effect of altered levels of cholestenic acids in *Cyp7b1*^{-/-} and *Cyp27a1*^{-/-} mice.

Classic studies by Lehmann et al. (4) and Janowski et al. (3) defined the general structural requirements of steroidal LXR ligands to be a 3β -hydroxy-5-ene function in the ring system and a hydroxy, oxo, or epoxide function on the C-17 side-chain (3, 4). The side-chain functions have more recently been extended to include a carboxylic acid group (7, 50), a functional group that is also present in the synthetic nonsteroidal LXR ligand GW3965. In the current study, we confirmed the LXR-activational capacity of cholestenic acids with a 3β -hydroxy-5-ene structure in neural cells and showed that despite the introduction of a 7α -hydroxy, 7β -hydroxy, or 7-oxo group, LXR activity was maintained. On the contrary, the 3-oxo-4-ene equivalents of these acids were not LXR ligands. Thus, 3β -HCA, $3\beta,7\alpha$ -diHCA, its 7β -isomer ($3\beta,7\beta$ -diHCA), and the necessary 7-oxo intermediate in the epimerization reaction (3β H, $7O$ -CA) are all LXR ligands effective at micromolar concentrations. Moreover, none of these acids were found to activate FXR, VDR, or NURR1 in neural cells, thereby confirming the specificity of their effect on LXR.

Numerous studies in recent years have linked LXR to neuronal degeneration (2, 5, 51–53). These studies have used *Lxrb*^{-/-} and *Lxra*^{-/-}*Lxrb*^{-/-} mice. Indeed, both LXR isoforms are expressed in brain (1, 54), and the knockout mice show progressive lipid accumulation in brain, abnormal BBB, increased reactive microglia, astrogliosis, and degeneration of adult spinal cord motor neurons (2, 5). Interestingly, a decrease in the number of oculomotor neurons was also detected during development in *Lxra*^{-/-}*Lxrb*^{-/-} mice at E11.5 (1). However, the identity of endogenous brain LXR ligands that regulate motor neuron function was unknown. Here we used zebrafish to study the in vivo function of acidic LXR ligands newly identified in human CSF (i.e., $3\beta,7\alpha$ -diHCA and $3\beta,7\beta$ -diHCA), and the 7-oxo intermediate in their epimerization, to study the effect of these molecules on islet-1⁺ cranial motor neurons. While metabolites that did not activate LXR, such as 7α H, $3O$ -CA, did not regulate islet-1 expression, the LXR ligands $3\beta,7\alpha$ -diHCA and 3β H, $7O$ -CA enhanced *isl1* transcript expression in zebrafish embryos (Figure 3), effects that were abolished by injection of *lxr* MO (Supplemental Figure 4). These effects were confirmed in rodent primary oculo-

motor neuron cultures, which showed that only $3\beta,7\alpha$ -diHCA and 3β H, $7O$ -CA increased the number of islet-1⁺ neurons (Figure 4, A–D). Importantly, their activity was specific to and mediated by LXR, as their biological activities were eliminated in cultures from *Lxra*^{-/-}*Lxrb*^{-/-} mice or by the LXR inhibitor GGPP. The effect of $3\beta,7\alpha$ -diHCA on WT cultures was accompanied by a decrease in the number of active caspase-3⁺ cells (Figure 4E), but no change in neurogenesis or proliferation was detected (Supplemental Figure 6), which indicates that the mechanism by which it increased the number of motor neurons was by promoting neuronal survival. In vivo experiments performed on embryonic brain in utero confirmed this neuroprotective effect of $3\beta,7\alpha$ -diHCA on oculomotor neurons (Figure 5, G–O). In contrast, 3β H, $7O$ -CA had no effect on cell death, neurogenesis, or survival in WT cultures, but increased the expression of islet-1, which suggested that it promoted the maturation of precursor cells into islet-1⁺ neurons. Analysis of the function of $3\beta,7\beta$ -diHCA and 3β -HCA revealed a toxic effect, manifested by an increase in the number of active caspase-3⁺ cells at low concentrations (Figure 4E). Thus, our results indicated that only some of the cholestenic acids capable of activating LXR promote motor neuron development. Intriguingly, our findings also suggested that cholestenic acids regulate motor neuron number by distinct mechanisms regulating differentiation and survival. Moreover, we found that the regulation of motor neuron survival could be either positive, as shown by the neuroprotective effect of $3\beta,7\alpha$ -diHCA, or negative, as shown by the toxic effect of $3\beta,7\beta$ -diHCA and 3β -HCA (Figures 4 and 5). These results were quite unexpected, but correlated very well with the cholestenic acid profiles in patients with the human diseases CTX and SPG5 (characterized by mutations in *CYP27A1* and *CYP7B1*, respectively) that may present with signs of motor neuron loss. Indeed, we found that 3β -HCA, one of the LXR ligands identified to have a toxic effect, was present at higher levels in SPG5 patients in both plasma and CSF (Figure 1, C and G, and Supplemental Tables 1 and 2). At the same time, the LXR ligand found to be neuroprotective, $3\beta,7\alpha$ -diHCA, was present at lower levels in SPG5 patients and absent in CTX patients (Figure 1, D and H). These observations suggest a double-hit model for SPG5, in which loss of motor neurons is effected by both mechanisms, whereas for CTX we propose that the predominant mechanism would be loss of neuroprotection. Moreover, our finding that the neuroprotective cholestenic acid $3\beta,7\alpha$ -diHCA prevented the loss of oculomotor neurons induced by 3β -HCA, both in vitro and in vivo, suggests a possible application of $3\beta,7\alpha$ -diHCA in the treatment of both SPG5 and CTX. The fact that deletion of LXRs results in early developmental motor neuron loss (1), while the onset of disease in SPG5 or CTX is usually in adolescent or adults, indicates that additional endogenous LXR ligands may partially compensate for the loss of $3\beta,7\alpha$ -diHCA in SPG5 and CTX patients. Future studies should examine whether $3\beta,7\alpha$ -diHCA and other yet-unidentified LXR ligands represent useful therapeutic tools to treat these and perhaps other devastating diseases affecting motor neurons.

In summary, we identified $3\beta,7\alpha$ -diHCA and $3\beta,7\beta$ -diHCA as LXR ligands present in human CSF. Of these, $3\beta,7\beta$ -diHCA and the previously identified LXR ligand 3β -HCA were found to cause cell death, and the latter was present at high levels in patients with SPG5. Instead, $3\beta,7\alpha$ -diHCA, which was found at low levels in

SPG5 and absent in CTX patients, promoted motor neuron survival, while β H,7O-CA regulated islet-1 expression levels. Thus, our results uncovered several novel functions of cholestenic acids and identified them as LXR ligands and key regulators of motor neuron function in development and disease. We suggest that factors with neuroprotective function, such as β ,7 α -diHCA, may thus find a therapeutic application to prevent motor neuron loss. This suggestion is supported by our finding that β ,7 α -diHCA, a cholestenic acid that decreased in SPG5, prevented cell loss by β -HCA, a cholestenic acid that accumulates in SPG5.

Methods

Extraction of sterols. Sterols were extracted from CSF, plasma, or mouse brain into ethanol and fractionated by reversed phase solid phase extraction (SPE) to give a cholestenic acid- and oxysterol-rich fraction devoid of cholesterol (7, 55, 56).

Charge-tagging of sterols. The sterols were charge-tagged with the GP-hydrazine as described previously (7, 55, 56). This greatly enhances their response when analyzed by LC-ESI-MS and tandem mass spectrometry (MSⁿ).

Reagents. HPLC-grade water and solvents were from Fisher Scientific or Sigma-Aldrich. Authentic sterols, steroids, cholestenic acids, bile acids, and their precursors were from Avanti Polar Lipids, Steraloids, Sigma-Aldrich, or from previous studies in our laboratories. Girard P (GP) reagent [1-(carboxymethyl)pyridinium chloride hydrazide] was from TCI Europe or synthesized in earlier studies, and cholesterol oxidase from *Streptomyces* sp. was from Sigma-Aldrich. Certified Sep-Pak C₁₈ 200 mg SPE cartridges were from Waters. Luer-lock syringes were from BD Biosciences.

LC-ESI-MSⁿ on the LTQ-Orbitrap. LC-ESI-MS and LC-ESI-MSⁿ were performed using an Ultimate 3000 HPLC system (Dionex) linked to the ESI source of a LTQ-Orbitrap XL or LTQ-Orbitrap Velos (Thermo Fisher) mass spectrometer as described previously (7, 55, 56).

Luciferase reporter assay. The ability of oxysterols and their acidic metabolites to activate several nuclear receptors (i.e., LXR α , LXR β , FXR, VDR, and NURR1) was tested in luciferase assays. Transient transfection studies were performed in the mouse neuronal cell line SN4741. This cell line was selected because the oxysterols and acidic metabolites tested were initially identified in CSF. Cells were plated in 24-well plates (5×10^5 cells/well) 24 hours before transfection and transfected with 1 μ g plasmid DNA/well complexed with 2 μ l Lipofectamine 2000 (Invitrogen). Cells were transfected with 400 ng of a LXR-, FXR-, VDR-, or NURR1-responsive luciferase reporter construct and 200 ng LXR α , LXR β , FXR, VDR, or NURR1. A reporter gene expressing the Renilla luciferase (pRL-TK; Promega) was cotransfected in all experiments as an internal control for normalization of transfection efficiency. After a 12-hour incubation, the lipid/DNA mix was replaced with fresh 2.5% serum medium containing vehicle or appropriate ligand (10 μ M), as specified in each experiment. The ability of cholestenic acids to activate LXR was confirmed in experiments with or without the LXR inhibitor GGPP (10 μ M) also added to the medium. Luciferase activities were assayed 24 hours later using the Dual-Luciferase Reporter Assay System (Promega), following the manufacturer's protocol.

LXR β ligand binding assay. For LXR β ligand binding activity measurement, we used the Lanthascreen TR-FRET LXR β Coactivator Assay (Invitrogen). The assay uses a terbium-labeled anti-GST

antibody, a fluorescein-labeled coactivator peptide, and the LXR β -LBD tagged with glutathione-S-transferase (GST). Binding of the agonist/ligand to the LXR β -LBD causes a conformational change that increases the affinity of LXR β for the coactivator peptide. Close proximity of the fluorescently labeled coactivator peptide to the terbium-labeled antibody increases the TR-FRET signal intensity. The 520:495 TR-FRET ratio was calculated using a Victor multilabel reader with an excitation wavelength of 340 nm and emission wavelengths of 520 nm and 495 nm. The activation capacity of potential ligands was tested in a 382-well polypropylene plate following the manufacturer's protocol.

Zebrafish experiments. Zebrafish were raised on a 14-hour day/10-hour night cycle and kept at 28.5°C. Tg[*isl1*:GFP] embryos were obtained via natural spawning and staged in hours postfertilization (hpf) or days post fertilization, according to Kimmel et al. (57). Embryos older than 24 hpf were treated with 0.03% phenylthiourea (PTU) to inhibit pigmentation. MO injections were performed using splice site-specific zebrafish *lxr* MO, as previously reported (58). MO-injected embryos were immediately dechorionated, transferred to a 96-well plate, and exposed to DMSO- or ligand-treated medium. Tg[*isl1*:GFP] embryos were collected by natural mating, immediately dechorionated (at the 1-cell stage), and transferred to a 96-well plate. Each compound tested was obtained as 10 mM stock and diluted in embryo medium to a final concentration of 10 μ M, and 200 μ l was added to each well. DMSO- or propan-2-ol-treated embryo medium was used as control. Ligand solutions were replaced every 12 hours with fresh ligand solution prepared in PTU-treated embryo medium. Embryos were collected at 48 hpf, fixed for 4 hours at room temperature with 4% paraformaldehyde (PFA), and then washed and kept in PBST. Immunocytochemistry was performed using an anti-GFP antibody, and fluorescence was viewed and photographed using a Zeiss Axioplan compound microscope and a Zeiss Axiocam digital camera.

Quantitative PCR. Total RNA was extracted from SN4741 cells and from zebrafish treated with the compounds of interest using the RNeasy Mini Kit (Qiagen); 1 μ g was treated with RQ1 RNase-free DNase (Promega) and reverse transcribed using SuperScript II Reverse Transcriptase (Invitrogen) and random primers (Invitrogen) (RT+ reaction). Parallel reactions without reverse transcriptase enzyme were performed as a control (RT- reaction), and Sybergreen real-time quantitative PCR assays were carried out. Expression levels were obtained by normalization to the value of the housekeeping gene encoding actin or 18S, obtained for every sample in parallel assays.

Mice. Mice were housed, bred, and treated according to the guidelines of the European Communities Council (directive 86/609/EEC) and the Society for Neuroscience. *Lxra*^{-/-}*Lxrb*^{-/-} mouse cell cultures were from the colony at the Department of Biosciences and Nutrition at Novum, Karolinska Institutet. Male and female WT and *Lxra*^{-/-}*Lxrb*^{-/-} mice were generated as previously described (59, 60). Mice were backcrossed onto a C57BL/6 background for 10 generations. Male *Cyp7b1*^{-/-} mouse brain and plasma were from animals generated at the University of Edinburgh. Male mice homozygous for targeted disruption of the *Cyp7b1* gene (61) congenic on the C57BL/6 genetic background (>15 generations backcrossed to C57BL/6) and WT littermate controls were generated from *Cyp7b1*^{+/-} crosses. Male *Cyp27a1*^{-/-} mouse tissue and plasma was purchased from The Jackson Laboratory (strain B6.129-Cyp27a1^{tm1Elt}/J; ref. 62). The *Cyp27a1*^{-/-} colony was backcrossed to C57BL/6J inbred mice for approximately

12 generations by the donating investigator (62) prior to sending to The Jackson Laboratory Repository. Upon arrival, mice were bred to C57BL/6J inbred mice for at least 1 generation to establish the colony. WT animals from the colony were used as controls. Tissue and blood sampling from these mice was performed under the aegis of the UK Scientific Procedures (Animals) Act, 1986.

Primary midbrain cultures. Brains from E11.5 mice were obtained, and the midbrain region was dissected, mechanically dissociated, plated on poly-D-lysine (150,000 cells/cm²), and grown in serum-free N2 media consisting of F12/DMEM (1:1 mixture) with 10 ng/ml insulin, 100 µg/ml apo-transferrin, 100 µM putrescine, 20 nM progesterone, 30 nM selenium, 6 mg/ml glucose, and 1 mg/ml BSA. Cells were treated for 3 days *in vitro* with the compounds of interest, fixed with 4% PFA, and processed for staining using appropriate antibodies.

For BrdU analysis, cells were treated with BrdU 1 hour after plating, and media was replaced with fresh medium after 16 hours. After a further 2 days in culture, cells were treated for 30 minutes with 2N HCl, and immunocytochemistry was performed to evaluate the number of double-positive BrdU⁺islet-1⁺ cells (a measure of motor neuron neurogenesis). Hoechst staining was performed by permeabilizing cells with a 0.3% Triton-X 100/PBS solution for 5 minutes followed by incubation with Hoechst 33258 (Sigma-Aldrich) for 10 minutes.

Immunocytochemistry. Cells were fixed in 4% PFA, washed in PBS, and blocked in 5% normal goat serum/PBS for 1 hour at room temperature. Primary antibodies were diluted in PBS (pH 7.4), 0.3% Triton X-100, and 1% BSA, and incubations were carried out overnight at 4°C or at room temperature for 2 hours. The antibodies used were anti-BrdU (diluted 1:400; Abcam), anti-islet-1 (1:100; Developmental Studies Hybridoma Bank), anti-cleaved caspase-3 (Asp175) (1:100; Cell Signaling Technology), anti-TH (1:1,000; Pel-Freeze), anti-GABA (1:1,000; Sigma-Aldrich), anti-BRN3A (1:250; Millipore), anti-NKX6.1 (1:200; Novus Biologicals), anti-ChAT (1:500; Millipore), and appropriate secondary antibodies (Jackson ImmunoResearch or Alexa). Cells positive for the corresponding marker were counted directly at the microscope at ×20 magnification. Cells were counted in every well — in 8 consecutive fields (from one side of the well to the other, passing through the center) — in 3 different wells per experiment and 3 different experiments per condition. Random images of the wells were taken for every condition to document the result, and representative images were subsequently selected to represent the quantitative data. Photos were acquired with a Zeiss Axioplan microscope and a Hamamatsu camera C4742-95 using Openlab software.

Intraventricular injections *in utero*. Female WT CD-1 mice (25–35 g; Charles River Breeding Laboratories) were used for these experiments. For embryo analyses, WT CD-1 mice were mated overnight, and noon of the day the plug was considered E0.5. E11.5 pregnant females were deeply anesthetized using isoflurane (IsoFlo; Abbott Labs), and the uterine horns were accessed through an abdominal incision. 1 µl 3β,7α-diHCA (5 µM) or 3β-HCA (1 µM) or vehicle solution (isopropanol; 50% v/v) was injected into the cerebral aqueduct. The uterine horns were replaced into the abdominal cavity, which was then closed with sutures. Embryos were analyzed 48 hours later.

Immunohistochemical analysis of rodent embryos. Embryos were dissected out of the uterine horns in ice-cold PBS, fixed in 4% PFA for 4 hours to overnight, cryoprotected in 15%–30% sucrose, frozen in Tissue-Tek OCT compound (Sakura Finetek) on dry ice, and stored at –80°C until use. Serial coronal 14-µm sections of the brain

were obtained on a cryostat. 14-µm serial coronal sections through the midbrain region were cut on a cryostat and placed serially on 10 slides. Slides 1 and 6 were subjected to immunohistochemistry. Sections were preincubated for 1 hour in blocking solution followed by incubation at 4°C overnight with the following primary antibodies: anti-TH (1:750, Pel-Freeze), anti-islet-1 (1:100; Developmental Studies Hybridoma Bank), and anti-cleaved caspase-3 (Asp175) (1:100; Cell Signaling Technology). After washing, slides were incubated for 1–2 hours at room temperature with the appropriate fluorophore-conjugated (Cy2, Cy3, and Cy5, 1:300, Jackson Laboratories; Alexa Fluor 488, Alexa Fluor 555, and Alexa Fluor 647, 1:1,000, Invitrogen) secondary antibodies. Confocal images were taken with a Zeiss LSM5 Exciter or LSM700 microscope.

Statistics. Statistical analyses (Mann-Whitney test, Dunnett T3 test, and 1-way ANOVA with LSD post-hoc test) were performed using Prism 4 (GraphPad Software). All data represent mean ± SEM. A *P* value less than 0.05 was considered significant.

Study approval. Human samples, collected according to the principles of the Declaration of Helsinki, were provided to University Hospital Basel, Barts Health NHS Trust, St. Mary's Hospital, Institute of Child Health, Conegliano Research Centre, Federico II University, University of Tübingen, Kurume University School of Medicine, and University Hospital "Attikon" with written informed consent and IRB and ethical approval. Ethical approval was granted by Stockholm Norra Djurförsöksetisks Nämnd for zebrafish experimentation (nos. N293/09 and N338/10), mouse experimentation (nos. N154/06, N145/09, N370/09, and N273/11), and *in utero* experimentation (no. N486/12).

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