Transporters MCT8 and OATP1C1 maintain murine brain thyroid hormone homeostasis

Steffen Mayerl,1 Julia Müller,1 Reinhard Bauer,2 Sarah Richert,3 Celia M. Kassmann,3 Veerle M. Darras,4 Katrin Buder,1 Anita Boelen,5 Theo J. Visser,8 and Heike Heuer1,7

1Leibniz Institute for Age Research/Fritz Lipmann Institute, Jena, Germany. 2Institute of Molecular Cell Biology and Integrated Research and Treatment Center, Center for Sepsis Control and Care (CSCC), Jena University Hospital, Friedrich Schiller University, Jena, Germany. 3Max-Planck-Institute of Experimental Medicine, Göttingen, Germany. 4Laboratory of Comparative Endocrinology, Katholieke Universiteit Leuven, Leuven, Belgium. 5Academica Medical Center, Amsterdam, The Netherlands. 6Erasmus Medical Center, Rotterdam, The Netherlands. 7Leibniz Research Institute for Environmental Medicine, Düsseldorf, Germany.

Allan-Herndon-Dudley syndrome (AHDS), a severe form of psychomotor retardation with abnormal thyroid hormone (TH) parameters, is linked to mutations in the TH-specific monocarboxylate transporter MCT8. In mice, deletion of Mct8 (Mct8 KO) faithfully replicates AHDS-associated endocrine abnormalities; however, unlike patients, these animals do not exhibit neurological impairments. While transport of the active form of TH (T3) across the blood-brain barrier is strongly diminished in Mct8 KO animals, prohormone (T4) can still enter the brain, possibly due to the presence of T4-selective organic anion transporting polypeptide (OATP1C1). Here, we characterized mice deficient for both TH transporters, MCT8 and OATP1C1 (Mct8/Oatp1c1 DKO). Mct8/Oatp1c1 DKO mice exhibited alterations in peripheral TH homeostasis that were similar to those in Mct8 KO mice; however, uptake of both T3 and T4 into the brains of Mct8/Oatp1c1 DKO mice was strongly reduced. Evidence of TH deprivation in the CNS of Mct8/Oatp1c1 DKO mice included highly decreased brain TH content as well as altered deiodinase activities and TH target gene expression. Consistent with delayed cerebellar development and reduced myelination, Mct8/Oatp1c1 DKO mice displayed pronounced locomotor abnormalities. Intriguingly, differentiation of GABAergic interneurons in the cerebral cortex was highly compromised. Our findings underscore the importance of TH transporters for proper brain development and provide a basis to study the pathogenic mechanisms underlying AHDS.

Introduction

Monocarboxylate transporter 8 (MCT8) is a specific thyroid hormone (TH) transporter that facilitates the passage of the prohormone 3,3′,5′-triiodothyronine (T4; also known as thyroxine) and the receptor active form, 3,3′,5′-triiodothyronine (T3), across the plasma membrane (1). MCT8 is encoded by SLC16A2 (hereafter MCT8) located on human chromosome Xq13.2. Inactivating mutations and deletions in MCT8 result in a distinct clinical picture known as Allan-Herndon-Dudley syndrome (AHDS) (2–5).

All affected patients manifest a severe form of psychomotor retardation composed of central hypotonia, spastic tetraplegia, lack of speech development, severe intellectual deficits, and global developmental delays. In addition to the pronounced neurological symptoms, patients exhibit characteristic changes in the serum TH profile, with highly elevated T3 and lowered T4 concentrations. Since 2004, more than 45 families with 125 affected individuals have been reported in the literature, and 1% of cases with the diagnosis of X-linked mental retardation have been estimated to be associated with mutations in MCT8 (6). However, by which pathogenic mechanisms MCT8 deficiency causes AHDS remains largely unknown.

MCT8 is present in many organs, such as liver, kidneys, pituitary, and thyroid gland, and is also widely expressed in the CNS. Studies in mouse and human brain tissues revealed MCT8 expression in distinct neuronal populations, with the highest mRNA levels in neo- and allocortical structures (e.g., cerebral cortex, hippocampus, and amygdala) as well as in hypothalamic neuroendocrine nuclei (e.g., paraventricular nucleus [PVN]). In addition, MCT8 is found in tanyctyes, in choroid plexus structures, and in capillary endothelial cells of the blood-brain barrier (BBB) (7–10). In light of its localization, it has been speculated that MCT8 deficiency compromises the uptake of TH into brain cells, thereby interfering with proper neural migration and differentiation processes during critical stages of brain development.

To get further insight into the pathophysiological role of MCT8, mice with deletion of Mct8 have been generated and extensively studied (9, 11, 12). These Mct8 KO animals fully replicated the abnormalities in circulating TH concentrations in AHDS patients and showed a thyrotoxic situation in the liver and kidneys (13). In contrast to AHDS patients, Mct8 KO mice did not exhibit any overt neurological symptoms. This observation was rather unexpected, as in vivo transport studies have revealed highly diminished T3 uptake into the brains of Mct8 KO mice (12, 14). However, T4 transport into the CNS was only partially compromised in these animals. Likewise, Mct8 KO mice displayed only a moderate reduction in brain T3 content, a consequence of a rise in astrocytic type 2 deiodinase (D2) activities, and thus enhanced local T4-to-T3 conversion. It would therefore appear that mice express another T4-specific transporter that maintains almost normal passage of T4 across the BBB and/or the blood-CSF barrier (BCSFB) in the absence of MCT8. The mouse brain would consequently be much less affected by MCT8 deficiency than the human CNS, in which such an alternative route for T4 may not exist.

Which transporter can replace MCT8 in the mouse brain? Organic anion transporting polypeptide 1c1 (OATP1C1; also known as OATP14 or OATP-F), encoded by Slco1c1 (hereafter Oatp1c1), is an intriguing candidate. This transporter accepts preferentially T4 as well as reverse T3 as substrates (15). In mice, OATP1C1 expres-
MCT8 and OATP1C1 deficiency leads to deranged development of the HPT axis by early postnatal time points. Consequently, pituitary thyrotropin-releasing hormone (TRH) expression, which was previously observed in Mct8 KO animals (12). In fact, in situ hybridization (ISH) analysis of P21 animals revealed even higher TRH-specific signal intensities in Mct8/Oatp1c1 DKO PVN than in Mct8 KO PVN (Figure 2A and B).

In order to study the postnatal differentiation process of the HPT axis in more detail, we examined hypothalamic TRH as well as pituitary Tshb and D2 transcript levels at P6, P12, P21, and P33 by ISH. Significantly elevated TRH transcript levels were already detected in Mct8/Oatp1c1 DKO animals at P6 (Figure 2B), which indicated that in the absence of both TH transporters, TRH-expressing neurons are already in a pronounced hypothyroid state during early stages of postnatal development. Surprisingly, pituitary Tshb expression was significantly reduced in Mct8/Oatp1c1 DKO mice at P6, but significantly elevated at later time points. Moreover, compared with the single-mutant and WT animals, D2 expression was slightly elevated in Mct8/Oatp1c1 DKO mice at P6, whereas at P21, no significant differences between Mct8 KO and Mct8/Oatp1c1 DKO mice were noted by ISH or by activity measurements (Supplemental Figure 2A and Supplemental Figure 3A). These results indicated that combined MCT8 and OATP1C1 deficiency leads to deranged development of the HPT axis by early postnatal time points.

Since Mct8/Oatp1c1 DKO mice were growth retarded, we speculated that the somatotropic axis may also be affected in Mct8/Oatp1c1 KO and Mct8/Oatp1c1 DKO animals (Supplemental Figure 1A; supplemental material available online with this article; doi:10.1172/JCI70324DS1). WT, single-mutant, and double-mutant mice were born with the expected Mendelian frequency and were indistinguishable from each other during the first 2 weeks of postnatal development. Daily recording of body weight revealed significantly reduced body weight in Mct8/Oatp1c1 DKO mice starting from P17 (Supplemental Figure 1B). The growth delay persisted after weaning and resulted in a 15%–20% decrease in body weight of adult Mct8/Oatp1c1 DKO mice compared with WT and single-mutant animals (Supplemental Figure 1C). The growth retardation, however, did not compromise the animals’ fertility. Female and male Mct8/Oatp1c1 DKO mice reproduced normally with a regular litter size.

Analysis of the hypothalamus-pituitary-thyroid (HPT) and somatotropic axes. Determination of serum TH concentrations in P21 animals revealed similarly elevated serum T3 and decreased T4 values in Mct8 KO and Mct8/Oatp1c1 DKO mice (Figure 1), which indicated that Mct8/Oatp1c1 DKO animals show the same abnormalities in the serum thyroid state as do Mct8 KO mice. Moreover, concentrations of serum thyroid-stimulating hormone (TSH; encoded by Tshb) tended to be even more increased in Mct8/Oatp1c1 DKO mice than in Mct8 KO mice (Figure 1), although Tshb transcript levels were similarly elevated in both mouse models (Figure 2B). These changes may be due to a rise in hypothalamic thyrotropin-releasing hormone (TRH) expression, which was previously observed in Mct8 KO animals (12).

Results

Generation of Mct8/Oatp1c1 DKO mice. For the generation of mouse mutants deficient in MCT8 and OATP1C1, Mct8 KO mice (12) were mated with Oatp1c1 KO animals (19). Heterozygous offspring of the first generation were intercrossed, producing WT, Mct8 KO,
In vitro T3 transport studies. We previously demonstrated by in vivo transport studies that the uptake of i.p. $[^{125}\text{I}]$T3 into the mouse brain was strongly diminished in the absence of MCT8, whereas the transport of $[^{125}\text{I}]$T4 was only mildly affected (12). Here, we repeated the transport studies by injecting at least 3 adult animals per time point and genotype with 1.2 μCi $[^{125}\text{I}]$T4 i.p. At given time points, the amount of radioactivity in the brain, liver, kidneys, and blood samples was determined by γ counter and expressed as percentage of the injected dose per gram tissue. No differences among the 4 genotypes were detected in blood and liver samples (Figure 3A), which indicates that neither the absence of MCT8 nor the lack of OATP1C1 affected T4 transport in the blood and into the liver. In the kidneys, Mct8 KO and Mct8/Oatp1c1 DKO mice showed a significantly increased accumulation of radioactivity, thereby confirming previous findings in Mct8 KO animals (13). In both Mct8 KO and Oatp1c1 KO mice, accumulation of radioactivity in the CNS was reduced to approximately 50% of WT levels, which suggested that both transporters contribute equally to the passage of T4 into the brain. Most interestingly, uptake of T4 into the brain was strongly reduced in Mct8/Oatp1c1 DKO mice. Thus, these animals would consequently be expected to display a severe state of hypothyroidism specifically in the CNS.

Analysis of TH content and metabolism in the brain. In order to determine brain TH content, we intracerebrally perfused P21 animals with PBS, after which forebrains and cerebella were collected and processed as described previously (19). In agreement with Oatp1c1 DKO mice.
previous observations, Mct8 KO and Oatp1c1 KO mice exhibited an approximately 50% reduction in forebrain T4 levels compared with WT animals, whereas forebrain T3 concentrations were only mildly decreased in Mct8 KO mice and not altered in Oatp1c1 KO animals. However, forebrain T4 and T3 values were strongly reduced in Mct8/Oatp1c1 DKO mice, accounting for only 10% of WT levels (Figure 3B).

The highly reduced TH concentration in Mct8/Oatp1c1 DKO brains should lead to pronounced alterations in D2 and type 3 deiodinase (D3) activities, as these are negatively and positively regulated, respectively, by TH. Indeed, evaluation of D2 activities in forebrain and cerebellum of P21 animals revealed the highest activities in cortical and hippocampal regions of WT animals, whereas endothelial expression of Aldh1a1 remained unaltered in all mutant animals. In contrast, D2 ISH signals were visibly elevated throughout the brain only in the absence of both TH transporters. Even expression of Crym — which is highly enriched in distinct neurons of the hippocampus, cortex, and striatum — appeared to be increased in Mct8/Oatp1c1 DKO animals (Figure 5A), which suggested that this TH-binding protein is negatively regulated by T3.

In order to validate these ISH findings, we performed qPCR analysis using whole forebrain samples of P21 animals. In addition to Mct8 KO, Oatp1c1 KO, Mct8/Oatp1c1 DKO, and WT animals, we again included Pax8 KO mice in our analysis. Inactivation of MCT8 and/or OATP1C1 led to significantly reduced renal radioactivity at all analyzed time points. Most importantly, transport of radiolabeled T4 into the brain was strongly diminished in Mct8/Oatp1c1 DKO mice, whereas in the single-mutant animals, T4 uptake was reduced to approximately 50% of the respective WT levels. 

In conclusion, the knockouts of MCT8 and/or OATP1C1 resulted in a decreased TH concentration in the brain and a pronounced decrease in D2 activities in mice. This TH metabolism defect should lead to pronounced alterations in D2 and type 3 deiodinase activities, as these are negatively and positively regulated by T3 (21, 22). In addition, we included D2 in our analysis as a prominent example of a negatively regulated gene. Finally, we examined the transcript levels of mu-crystallin (Crym), which encodes an established intracellular TH-binding protein (23, 24).

Expression analysis of T3-regulated target genes in the CNS. For monitoring cell-specific changes in T3 concentrations, extensive ISH studies were performed in order to determine the expression levels of well-established T3 target genes. Frontal brain sections of P21 animals were hybridized with radioactively labeled cRNA probes specific for hairless (Hr), neurogranin (RC3), and aldehyde dehydrogenase 1a1 (Aldh1a1), all of which are known to be positively regulated by T3 (21, 22). In addition, we included Aldh1a1-specific ISH signals were very low in cortical areas of Mct8 KO animals and strongly decreased in the cerebral cortex of Mct8/Oatp1c1 DKO animals (Figure 5A). Expression of Aldh1a1 remained unaltered in all mutant animals. In contrast, D2 ISH signals were visibly elevated throughout the brain only in the absence of both TH transporters. Even expression of Crym — which is highly enriched in distinct neurons of the hippocampus, cortex, and striatum — appeared to be increased in Mct8/Oatp1c1 DKO animals (Figure 5A), which suggested that this TH-binding protein is negatively regulated by T3.

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Figure 3

Strongly diminished uptake of T4 into the brain in the absence of MCT8 and OATP1C1. (A) For in vivo transport studies, adult animals (n = 3 per genotype and time point) were injected i.p. with 1.2 μCi [125I]T4. A blood sample was obtained, after which animals were perfused with PBS, and brains, livers, and kidneys were collected. The amount of radioactivity was expressed as percentage of the injected dose per gram of tissue. Whereas the amount of radioactivity in blood and liver samples did not differ among mutant groups, Mct8 KO and Mct8/Oatp1c1 DKO mice showed increased renal radioactivity at all analyzed time points. Most importantly, transport of radiolabeled T4 into the brain was strongly diminished in Mct8/Oatp1c1 DKO mice, whereas in the single-mutant animals, T4 uptake was reduced to approximately 50% of the respective WT levels. *P < 0.05, Mct8 KO vs. WT; †P < 0.05, Mct8/Oatp1c1 DKO vs. WT; ‡P < 0.05, Oatp1c1 KO vs. WT.

(B) Animals at P21 (n = 8 per genotype) were perfused with PBS before forebrains were collected for determining tissue TH concentrations. The concomitant inactivation of both TH transporters resulted in a pronounced decline of both T3 and T4 to approximately 10% of the levels in WT animals, which indicated that only Mct8/Oatp1c1 DKO mice exhibit a severe hypothyroid state in the CNS. ***P < 0.001 vs. WT, or as otherwise indicated (brackets).

Figure 5

Strongly diminished TH concentration in the brain of Mct8/Oatp1c1 DKO mice (Figure 5A). Expression analysis of MCT8 and/or OATP1C1 led to significantly reduced renal radioactivity at all analyzed time points. Most importantly, transport of radiolabeled T4 into the brain was strongly diminished in Mct8/Oatp1c1 DKO mice, whereas in the single-mutant animals, T4 uptake was reduced to approximately 50% of the respective WT levels. *P < 0.05, Mct8 KO vs. WT; †P < 0.05, Mct8/Oatp1c1 DKO vs. WT; ‡P < 0.05, Oatp1c1 KO vs. WT. (B) Animals at P21 (n = 8 per genotype) were perfused with PBS before forebrains were collected for determining tissue TH concentrations. The concomitant inactivation of both TH transporters resulted in a pronounced decline of both T3 and T4 to approximately 10% of the levels in WT animals, which indicated that only Mct8/Oatp1c1 DKO mice exhibit a severe hypothyroid state in the CNS. ***P < 0.001 vs. WT, or as otherwise indicated (brackets).
KO animals (Figure 5B), a finding that under-

Delayed cerebellar development in Mct8/Oatp1c1 DKO mice. To study the effect of combined MCT8 and OATP1C1 deficiency on neural development, we histochemically monitored the maturation of different brain areas during postnatal development. Sagittal vibratome sections through the cerebellar vermis were immunostained with an antibody against calbindin D28 (CB), which allows for visualization of Purkinje cells (PCs). PC dendritogenesis, a differentiation process whose dependence on proper TH supply has been well established (25), takes place in rodents within the first 3 postnatal weeks. PCs displayed poor arborization and reduced dendritic growth in sections derived from P12 Mct8/Oatp1c1 DKO mice, whereas the morphology of PCs derived from Mct8 KO and Oatp1c1 KO animals was not altered (Supplemental Figure 4A). However, at P33 and P120, differences in PC morphology were no longer observed in Mct8/Oatp1c1 DKO mice. Quantification of the thickness of the molecular layer that is primarily determined by the dimension of the PC dendritic tree confirmed the immunohistochemical observations: only at P12 was significantly reduced thickness of the molecular layer noted in Mct8/Oatp1c1 DKO animals.

Myelination is permanently compromised in Mct8/Oatp1c1 DKO mice. Formation of myelin is another maturation process in the CNS that is compromised under hypothyroid conditions (26). TH has been shown to promote myelination by inducing the expression of proteins such as myelin basic protein (MBP) (27). In order to assess the effect of combined MCT8 and OATP1C1 deficiency on the development of white matter tracts, coronal vibratome fore-

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In order to elucidate the myelination status in closer detail, ultrathin brain sections of P21 WT, Mct8/Oatp1c1 DKO, and Pax8 KO mice were processed for transmission EM, and the white matter area comprising the cc at the level of the cingulum bundle was analyzed. WT animals exhibited ubiquitous myelination, whereas Mct8/Oatp1c1 DKO and Pax8 KO mice showed a patchy myelination pattern, with many axons remaining unmyelinated (Figure 6B). However, higher magnification revealed a normal ultrastructure of the myelin sheaths of those axons that were myelinated (Figure 6B). The reduced number of myelinated axons may affect the thickness of white matter regions. In order to address this possibility, we performed myelin Gallyas silver impregnation as well as axonal Biel- schowsky silver stainings on coronal paraffin sections at P21 and P180 and quantified cc thickness at the level of the cingulum bundle (Figure 6C and Supplemental Figure 4B). At both time points, the width of the cc was significantly reduced in Mct8/Oatp1c1 DKO mice by both staining methods, which indicated that overall myelin content is permanently reduced in the absence of both TH transporters. Similarly, the size of another major brain white matter tract, the anterior commissure, was reduced in Mct8/Oatp1c1 DKO animals, albeit to a lesser extent than in the cc (data not shown).

Neuronal differentiation is impaired in the cerebral cortex of Mct8/Oatp1c1 DKO mice. Formation and maintenance of not only the cer-
ebellar cortex, but also the cerebral cortex, depends on proper TH supply during pre- and postnatal stages. In particular, the differentiation of GABAergic interneurons has been shown to be delayed in hypothyroid rats, as evidenced by reduced parvalbumin (PV) immunoreactivity (28, 29). We therefore wondered whether similar alterations also occur in Mct8/Oatp1c1 DKO mice and performed immunohistochemical staining for the calcium-binding proteins PV, calretinin (CR), and CB, which serve as distinct markers for specific subgroups of cortical interneurons. In addition, we included antibodies against glutamate decarboxylase 67 (GAD67) in our studies, which allows for visualization of all GABAergic interneurons. NeuN immunoreactivity was used to label all mature neurons. Similar results were obtained in the somatosensory cortex (Figure 7) as well as the motor and the cingulate cortex (data not shown).

Quantification of the immunohistochemical stainings at P33 revealed a significantly reduced number of PV-positive neurons in the somatosensory cortex of Mct8/Oatp1c1 DKO mice at all analyzed time points (Figure 7A). Moreover, GAD67 immunoreactivity was found to be significantly decreased in Mct8/Oatp1c1 DKO mice as well (Figure 7B). The reduction in GAD67 immunoreactivity was detected with 2 different antibodies, thereby excluding epitope-specific effects. This observation was surprising, since previous studies in hypothyroid animals as well as in TRα1-mutant animals have not revealed alterations in cortical GAD67 expression (29, 30). In contrast, CB immunoreactivity was decreased in Mct8/Oatp1c1 DKO mice only at P12; no alterations were ascertained among genotypes at P33 and P120 (Supplemental Figure 5A). A significantly increased abundance of CR-positive neurons...
was observed in Mct8/Oatp1c1 DKO mice only at P120, although a tendency toward higher numbers was already detectable at P12 and P33 (Figure 7B). NeuN-labeled brain sections were used to quantify the thickness of the different cortical layers (Supplemental Figure 5B). Whereas layers V–VI exhibited similar thicknesses in animals of all genotypes (Supplemental Figure 5A), layers I–IV were significantly thinner in Mct8/Oatp1c1 DKO animals at all time points (Figure 7B). In summary, our immunohistochemical data pointed to persistent alterations in neuronal differentiation and cortical circuit formation in the absence of MCT8 and OATP1C1.

Mct8/Oatp1c1 DKO mice exhibit pronounced locomotor dysfunctions. As a first approach to assessing the neuromotor performance of TH transporter–mutant mice, we studied the gait of the animals by footprint analysis. Stride length was significantly reduced, and hind paw angle approximately 10° larger, in Mct8/Oatp1c1 DKO versus WT mice; conversely, Mct8 KO and Oatp1c1 KO animals exhibited gait parameters similar to those of WT controls (Figure 8, A and B). These alterations in stride length and hind paw angle were characteristic of cerebellar impairments and have also been found in other hypothyroid animal models (30).

To further examine locomotor behavior, we subjected 4-month-old mice (6–8 per genotype) to an accelerating rotarod test. After an initial training period under constant velocity, animals were tested on 5 consecutive days for their ability to stay on the rotating rod. With every day of testing, WT, Mct8 KO, and Oatp1c1 KO mice learned to stay for a longer time period on the rotating rod. In contrast, Mct8/Oatp1c1 DKO mice did not improve their motor capabilities during the test period and fell down significantly earlier (Figure 8C).
Since the lower body weight of Mct8/Oatp1c1 DKO mice may contribute to the poor rotarod performance, we repeated the experiments in order to compare 5-month-old Mct8/Oatp1c1 DKO and Mct8 KO littermates with 2-month-old Mct8 KO mice, whose body weight was similar to that of the Mct8/Oatp1c1 DKO mice examined. Mct8 KO animals displayed similar rotarod performance, independent of age and body weight, whereas Mct8/Oatp1c1 DKO mice again fell off the rotating wheel very quickly (Supplemental Figure 7).
Abnormal gait and severe locomotor deficiencies in Mct8/Oatp1c1 DKO mice. Mct8/Oatp1c1 DKO animals exhibited abnormal gait, as demonstrated by significantly reduced stride length (A), and a strongly elevated hind paw angle (B) based on footprint analysis. (C) Locomotor deficiencies were monitored by a rotarod test using 4-month-old male mice (n = 6–8 per genotype). In contrast to WT, Mct8 KO, and Oatp1c1 KO animals, Mct8/Oatp1c1 DKO mice performed poorly on the rod and did not show a learning curve. *P < 0.001 vs. WT. (D) In order to assess balance and coordination, mice were monitored while running on a beam 1 cm wide and 100 cm long. Recording the hind limb slips revealed a significantly higher number of errors only in Mct8/Oatp1c1 DKO mice. (E) Mice were further subjected to a hanging wire test in order to determine neuromuscular abnormalities. Only Mct8/Oatp1c1 DKO mice were not able to cling on a metal wire for 60 seconds. (F) As these findings point to reduced muscle performance, forepaw muscle strength was quantified using a grip strength meter, revealing an approximately 35% reduction in Mct8/Oatp1c1 DKO animals. *P < 0.05, **P < 0.01, ***P < 0.001 vs. WT, or as otherwise indicated (brackets).
least in the mouse CNS, MCT8 and OATP1C1 mediate the access of TH to the brain.

Although brain TH content was drastically reduced, 10% of WT T3 and T4 levels were still detected in brain homogenates of Mct8/Oatp1c1 DKO mice (Figure 4). Since animals were perfused with PBS before tissue collection, it is not likely that the TH concentrations found in these brain homogenates only reflect blood contaminations. As one possible explanation, combined MCT8 and OATP1C1 deficiency may not primarily affect the import of TH into capillary endothelial cells, but rather compromise the efflux of TH from endothelial cells into the brain parenchyme and/or astrocytes. Notably, the L-type amino acid transporter LAT1 (encoded by Slc7a5) is highly expressed in endothelial cells of the BBB, where it localizes to the luminal site (34). Since LAT1 efficiently transports not only large neutral amino acids, but also TH (35), capillary endothelial cells may still contain significant amounts of TH, even in the absence of MCT8 and OATP1C1. Future studies combining LAT1-mutant mice with animals lacking both MCT8 and OATP1C1 should provide further information in this regard.

We demonstrated by several experimental approaches that astrocytes and neurons of Mct8/Oatp1c1 DKO mice were clearly deficient in TH. Expression of the astrocytic enzyme D2, which is negatively regulated by TH at the posttranslational level and even more so by T4 at the posttranslational level, was highly increased in the brains of Mct8/Oatp1c1 DKO animals, indicative of a pronounced hypothyroid state of astrocytes. Moreover, the transcript levels of several genes known to be positively regulated by TH in distinct subsets of neurons were strongly reduced, to an extent similar to the TH transporter–deficient mice is rather unique. Congenital hypothyroidism in rodents is linked to various morphological alterations in neuronal maturation, of which retarded cerebellar development is a prominent and well-studied example (37–40). During TH deficiency, the differentiation of basically all cerebellar cell types is delayed. Consequently, the formation of synaptic contacts, which requires a highly synchronized pattern of dendritic and axonal growth, is persistently diminished. A striking hallmark of a congenitally hypothyroid cerebellum is a poorly developed Purkinje cell with stunted dendrites, a feature that was also observed in Mct8/Oatp1c1 DKO animals (Supplemental Figure 4A). As the cerebellum represents an important brain area for fine motor control, cerebellar dysfunction is linked to pronounced locomotor deficits, such as ataxia, poor coordination, and incorrectly timed movement. In agreement with disturbed cerebellar development, Mct8/Oatp1c1 DKO mice exhibited abnormal gait and poor coordination (Figure 8, A–D). Even reduced grip strength, which was a prominent feature of the Mct8/Oatp1c1 DKO mice (Figure 8F), may be related to cerebellar dysfunction, although abnormalities in neuromuscular transmission cannot be ruled out.

Impaired myelination is another hallmark of TH deficiency. TH controls the timing of oligodendrocyte development, as it induces oligodendrocyte precursor cells to initiate differentiation processes (41, 42). Moreover, the expression of several myelin-associated proteins, such as MBP, proteolipid protein, or myelin-associated glycoprotein, are directly regulated by TH (43, 44). Therefore, it is not too surprising that, as a result of low TH levels in the CNS, Mct8/Oatp1c1 DKO mice exhibited reduced myelination caused by reduced white matter tract size, as illustrated by silver stainings (Figure 6 and Supplemental Figure 4B). Such a myelination defect is expected to compromise neuronal conductance and may also contribute to the locomotor impairments and neuromuscular deficits observed in Mct8/Oatp1c1 DKO animals.

In addition to these findings, Mct8/Oatp1c1 DKO mice exhibited rather surprising abnormalities in the cerebral cortex, where immunohistochemical analysis revealed a pronounced and persistent reduction in GAD67 immunoreactivity (Figure 7, A and B), which indicated that the inhibitory cortical GABAergic system is strongly affected. These changes were not restricted to the somatosensory area, but were also observed in other cortical regions, such as the motor and the retrosplenial cortex. In previous studies, TH insufficiency during brain development has been demonstrated to reduce PV immunoreactivity in the cerebral cortex of rats (28, 29), which suggests that only a subgroup of inhibitory interneurons characterized by PV expression — so-called basket and chandelier cells — is sensitive to TH deprivation. Likewise, mouse mutants expressing a dominant-negative TRα1 protein show only a transient reduction in cortical PV immunoreactivity that normalizes after weaning (30). In contrast, PV expression in adult Mct8/Oatp1c1 DKO mice remained low compared with the respective controls. Moreover, unlike TRα1-mutant animals, Mct8/Oatp1c1 DKO mice displayed alterations in GAD67 immunoreactivity. Decreased cortical GAD expression has only been reported once for hypothyroid rats (45), which suggests that the phenotype of our TH transporter–deficient mice is rather unique.
and Oatp1c1 may greatly interfere with their differentiation. Such cell-specific effects of combined MCT8 and OATP1C1 deficiency might eventually explain, at least in part, the CNS-specific differences between Mct8/Oatp1c1 DKO mice and TRex1-mutant animals and may also answer the question of why Mct8/Oatp1c1 DKO mice exhibited reduced thickness of the outer cortical layers (Figure 7B). Future studies using conditional MCT8 and OATP1C1–mutant mice crossed with a tamoxifen-inducible cre line driven by the Oatp1c1 promoter should reveal to what extent the simultaneous inactivation of MCT8 and OATP1C1, either at prenatal or at postnatal stages, impairs brain development.

In summary, the Mct8/Oatp1c1 DKO mouse represents the first animal model showing pronounced TH deficiency in the CNS despite highly elevated T3 concentrations in the circulation, thereby underscoring the physiological importance of TH transporters in providing the brain with sufficient amounts of TH. Unlike single-mutant Mst8 KO and Oatp1c1 KO animals, Mct8/Oatp1c1 DKO mice displayed CNS-specific deficits, such as myelin defects and pronounced locomotor impairments, that have also been observed in patients. To what extent the Mct8/Oatp1c1 DKO mouse fully replicates the clinical picture of human MCT8 deficiency cannot presently be assessed, as a biochemical and histopathological analysis of postmortem brain samples of patients has not been reported yet, and even functional MRI data are scarce. Still, Mct8/Oatp1c1 DKO mice can be considered as the animal model most closely reflecting human MCT8 deficiency. Consequently, we expect detailed studies of pre- and postnatal brain development in these mice to provide further insights on the molecular mechanisms by which TH influences early events in neuronal differentiation or regulates neuromuscular performance. Moreover, Mct8/Oatp1c1 DKO mice can serve as a valuable tool for testing the efficacy of putative therapeutic interventions in preventing brain damage, since TH treatment is not a useful option for patients with MCT8 deficiency.

Methods

Animals. Mst8 KO mice were obtained from Deltagen and have been described previously (12). Oatp1c1+/– mice were generated at TaconicArtemis and mated with a germline deleter cre mouse line in order to obtain Oatp1c1 KO mice. The targeting strategy, generation, and analysis of Oatp1c1 KO animals has been published recently (19). Mst8+/–/Oatp1c1+/– breeding pairs (C57BL/6 background) were used to generate Mst8/Oatp1c1 DKO and Mst8 KO mice. Oatp1c1+/– matings (C57BL/6 background) were set up to obtain Oatp1c1 KO mice and WT littersmates. Pax8 KO mice (mixed background) were generated by breeding Pax8+/– animals (20). All mice were provided with standard laboratory chow and tap water ad libitum and were kept at constant temperature (22°C) and controlled light cycle (12-hour light/12-hour dark).

The body weight of 16 litters (5–8 newborn per litter) was monitored daily for the first 3 postnatal weeks. Female and male mice at P21 were killed by isoflurane and perfused intracardially with PBS. Forebrains were rapidly frozen on dry ice and stored at −80°C. Male mice at P12, P33, and P120 destined for immunohistochemical analysis (n = 3 per genotype and time point) were deeply anesthetized with isoflurane and subjected to intracardial perfusion fixation using a solution of 4% PFA in PBS. Whole brains were removed and postfixd for 24 hours with 4% PFA in PBS. Thereafter, brains were washed 3 times in PBS and stored in PBS containing 0.4% sodium azide at 4°C until further processing. See Supplemental Methods for details on animal genotyping.

ISH histochemistry. cDNA fragments corresponding to nt 1,380–1,941 of mouse Aldh1a1 (GenBank accession no. NM_013467.3), nt 489–1,005 of mouse Crym (NM_016669), nt 40–1,055 of mouse D1 (NM_007860), nt 131–1,045 of mouse D2 (NM_010050.2), nt 248–445 of mouse Gfb (NM_008117.2), nt 125–402 of mouse Ghrh (NM_010285.2), nt 902–1,598 of mouse Hr (NM_021877.2), nt 137–629 of mouse Igf1 (NM_010512), nt 498–1,005 of mouse RC3 (NM_020292.9), nt 42–557 of mouse Sit (NM_009215), nt 1,251–1,876 of mouse Trb (NM_009426.2), and nt 190–445 of mouse Tubb (NM_009432.2) were generated by PCR and subcloned into the pGEM-T Easy Vector (Promega). Radiolabeled riboprobes were generated by in vitro transcription using [35S]UTP as labeled substrate (Hartmann Analytik). ISH was carried out as described previously (51). In brief, frozen sections were air-dried, followed by a 1-hour fixation in a 4% phosphate-buffered PFA solution (pH 7.4), and then permeabilized by incubation in PBS containing 0.4% Triton X-100 for 10 minutes. Acetylation was carried out in 0.1 M triethanolamine (pH 8.0) containing 0.25% (v/v) acetic anhydride. Sections were dehydrated, then covered with hybridization mix containing cRNA probes diluted in hybridization buffer (50% formamide, 10% dextran sulfate, 0.6 M NaCl, 10 mM Tris-HCl pH 7.5, 51). In brief, frozen sections were air-dried, followed by a 1-hour fixation in 4% PFA solution (pH 7.4), and then permeabilized by incubation in PBS containing 0.4% Triton X-100 for 10 minutes. Acetylation was carried out in 0.1 M triethanolamine (pH 8.0) containing 0.25% (v/v) acetic anhydride. Sections were dehydrated, then covered with hybridization mix containing cRNA probes diluted in hybridization buffer (50% formamide, 10% dextran sulfate, 0.6 M NaCl, 10 mM Tris-HCl pH 7.5, 1x Denhardt’s solution, 100 μg/ml sonicated salmon sperm DNA, 1 mM EDTA, and 0.5 mg/ml t-RNA). [35S]-labeled riboprobes were diluted in hybridization buffer to a final concentration of 1 × 104 cpm/μl. Prior to application, radioactive riboprobes for Gb, Trb, and Tubb were diluted with unlabeled riboprobes (5 ng/μl in hybridization buffer) at ratios of 1:10, 1:10, and 1:3, respectively. Hybridization was performed overnight at 58°C. Slides were rinsed in 2× standard saline citrate (0.3 M NaCl and 0.03 M sodium citrate, pH 7.0) and subsequently treated with ribonuclease A/T1 at 37°C for 30 minutes. Final washes were carried out in 0.2x standard saline citrate at 65°C for 1 hour. For detection of radioactive ISH signals, sections were dehydrated and then exposed to X-ray films (BioMax MR, Eastman Kodak Co.) for 24 hours. Subsequently, sections were dipped in Kodak NTB nuclear emulsion (Kodak) and stored at 4°C for 8 (Aldh1a1, D2, and Hr), 5 (Crym and Ghrh), 4 (D1), 3 (Gb, Sit, TH, and Tubb), or 2 (RC3) days. Autoradiograms were developed and analyzed under darkfield illumination. Experiments carried out using the respective sense probes did not produce any ISH signals.

TH, TSH, D2, and D3 activity. Serum T4 and T3 were determined by RIA in P21 animals (n = 8 per genotype) as reported previously (52). Brain T4 and T3 content was measured after extraction of the tissues, as described in detail by Reyns et al. (53). D2 and D3 activities in cerebella and forebrains, as well as D2 activities in pituitary extracts, were assessed as reported previously (52). Briefly, tissues were homogenized in PED10 buffer, and protein concentration was determined by the Bradford method. For D2 activity analysis, homogenate dilutions were incubated with 2 × 105 cpm [125I]T4 in the presence of unlabeled T3. D3 activities were assessed by incubating homogenate dilutions with 2 × 105 cpm [125I]T3. After 30 minutes at 37°C, reactions were stopped by adding ice-cold ethanol. After centrifugation, supernatants were mixed with 0.02 M ammonium acetate (pH 4) and subjected to HPLC analysis. Radioactivity was monitored using a
flow scintillation detector (Radiomatic A-500; Packard). TSH serum levels were determined using a double-antibody precipitation RIA as previously described (54, 55). Briefly, 25 μl mouse serum, 25 μl PBS containing 0.1% azide, and 100 μl (final dilution, 1:25,000) rabbit anti-rat TSH serum (anti-rat TSH RIA-6; NIDDK) were incubated for 4 hours at RT. Subsequently, 100 μl [125I]TSH tracer (approximately 15,000 cpm; MP Biomedicals) was added, and the mixture was incubated overnight at RT to allow equilibration. Next, 500 μl donkey anti-rabbit secondary antibody coated onto magnetizable polymer beads (Amerlex M; GE Healthcare) was added, mixed, and incubated at RT for 15 minutes. Samples were centrifuged for 15 minutes at 756 g at RT, and the pellets were counted and calculated using Wizard γ counter and BioSmart software (Perkin Elmer). Mouse standards were prepared by serial dilution of serum pool with high murine TSH (mTSH) with mTSH-0 serum, as described previously (54), and samples were assayed in duplicate.

In vivo transport studies. Uptake analysis was carried out by injecting 2.5- to 4.5-month-old male animals (n ≥ 3 per genotype and time point) i.p. with 1.2 μCi [125I]T4 (PerkinElmer) in PBS. For injection as well as perfusion, mice were deeply anesthetized with isoflurane. After collecting heart blood, mice were intracardially perfused with PBS, after which brains, livers, and kidneys were collected. To determine the amount of radioactivity taken up by different tissues, organs and blood samples were weighed, and radioactivity was measured in an automatic γ counter.

qPCR. Total tissue RNA was isolated using the NucleoSpin RNA II Kit (Macherey-Nagel). Synthesis of cDNA was performed using the Transcripter High Fidelity cDNA Synthesis Kit (Roche). To exclude the presence of genomic DNA, 1 sample without reverse transcriptase was included as well. qPCR was performed using iQ SYBR Green Supermix and Multicolor Real-Time PCR Detection System (Bio-Rad). At least 5 samples per genotype were subjected to analysis. As a housekeeping gene for normalization, cyclophilin D (CycD) was used. See Supplemental Methods for primer sequences.

Immunohistochemistry. Perfusion-fixed 50 μm forebrain (frontal) and cerebellum (sagittal) sections of P12, P33, and P120 male mice were cut on a vibratome (Microm). Sections were blocked and permeabilized with 10% normal goat serum in PBS containing 0.2% Triton X-100. After blocking the respective antibodies (all from Millipore): rabbit anti-CB (1:500), rabbit anti-CR (1:500), mouse anti-GAD67 (1:200), mouse anti-neuN (1:500), and mouse anti-PV (1:1,000). In addition, a goat anti-human MBP (1:200), mouse anti-GAD67 (1:200), rat anti-MBP (1:200), mouse anti-NeuN (1:500), and mouse anti-PV (1:1,000). In addition, a goat anti-human


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Address correspondence to: Heike Heuer, Leibniz Institute for Age Research/Fritz Lipmann Institute, Beutenbergstr. 11, D-07745 Jena, Germany. Phone: 49.3641.65.6021; Fax: 49.3641.65.6335; E-mail: hheuer@fl-leibniz.de.
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