Oxysterols decrease apical-to-basolateral transport of Aß peptides via an ABCB1-mediated process in an in vitro Blood-brain barrier model constituted of bovine brain capillary endothelial cells

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Keywords: blood-brain barrier, ABCA1, Aß peptides, cholesterol, oxysterols, ABCB1

Abstract:

It is known that activation of the liver X receptors (LXRs) by natural or synthetic agonists decreases the amyloid burden and enhances cognitive function in transgenic murine models of Alzheimer's disease (AD). Recent evidence suggests that LXR activation may affect the transport of amyloid ß (Aß) peptides across the blood-brain barrier (the BBB, which isolates the brain from the peripheral circulation). By using a well-characterized in vitro BBB model, we demonstrated that LXR agonists (24S-hydroxycholesterol, 27-hydroxycholesterol and T0901317) modulated the expression of target genes involved in cholesterol homeostasis (such as ATP-binding cassette sub-family A member 1 (ABCA1)) and promoted cellular cholesterol efflux to apolipoprotein A-I and high density lipoproteins. Interestingly, we also observed a decrease in Aß peptide influx across brain capillary endothelial cells, although ABCA1 did not appear to be directly involved in this process. By focusing on others receptors and transporters that are thought to have major roles in Aß peptide entry into the brain, we then demonstrated that LXR stimulation provoked an increase in expression of the ABCB1 transporter (also named P-glycoprotein (P-gp)). Further investigations confirmed ABCB1's involvement in the restriction of Aß peptide influx. Taken as a whole, our results not only reinforce the BBB's key role in cerebral cholesterol homeostasis but also demonstrate the importance of the LXR/ABCB1 axis in Aß peptide influx - highlighting an attractive new therapeutic approach whereby the brain could be protected from peripheral Aß peptide entry.

Abbreviations:

24S-OH-chol: 24S-hydroxycholesterol; 27-OH-chol: 27-hydroxycholesterol; ABCA1: ATP binding cassette sub-family A member 1; ABCB1: ATP binding cassette sub-family B member 1; ABCC1: ATP binding cassette sub-family C member 1; AD: Alzheimer's disease; Aß peptides: ß-amyloid peptides; Apo: apolipoprotein; BBB: blood-brain barrier; BCECs: brain capillary endothelial cells; BCRP: breast cancer resistance protein; HDL: high density lipoprotein; LXR: liver X receptor;

MRP1: multidrug resistance associated protein 1; RAGE: receptor for advanced glycation end-products; SCARB1: scavenger receptor class B member 1.

1. Introduction

The blood-brain barrier (BBB) is known to be relatively impermeable to plasma circulating molecules, xenobiotics and metabolites. This natural obstacle between blood and brain compartments is essential for maintaining brain homeostasis and protecting the central nervous system (Abbott et al., 2010). The BBB is located within the brain capillaries and its phenotype is displayed by brain capillary endothelial cells (BCECs). The BBB's properties are induced by the cellular environment around the brain capillaries, with astrocyte end-feet and pericytes, the latter sharing a basal membrane with the BCECs (Daneman et al., 2010). Transport of molecules across this barrier can occur through a limited, specific, transcellular pathway that especially involves receptor-mediated transport (Cecchelli et al., 2007).

The best known of the compounds with limited exchange across the BBB is cholesterol, a vital sterol required for cell viability, electric insulation of the axon and membrane dynamics (Saher et al., 2005). This sterol does not cross the BBB (Osono et al., 1995; Spady et al., 1987) or crosses only very slowly (Chobanian and Hollander, 1962; Wilson, 1970) - probably because transport occurs through a limited, lipoprotein-mediated pathway (Candela et al., 2008; Dehouck et al., 1997). In the body, excess cholesterol is metabolized into oxysterols like 24S-hydroxycholesterol (24S-OH-chol) and 27-hydroxycholesterol (27-OH-chol), both of which easily cross the BBB. 24S-OH-chol is exclusively produced by a set of specific neurons (Lutjohann et al., 1996) and is involved in brain cholesterol turnover and elimination (Bjorkhem et al., 1999; Pfrieger, 2003). The clearance of 24S-OH-chol into the circulation (down its natural concentration gradient) has been estimated at 6-7 mg/day (Meaney et al., 2002). 27-OH-chol synthesized by peripheral organs is the major oxysterol in plasma and enters the brain compartment through the BBB at a rate of 4 mg/day (Leoni et al., 2003). 24S-OH-chol and 27-OH-chol have been well characterized as natural agonists of liver X receptor (LXR) nuclear receptors, which are involved in cellular cholesterol homeostasis (Vaya and Schipper, 2007). Activation of LXRs leads to the upregulation of ATP-binding cassette sub-family A member 1 (ABCA1), which mediates reverse cholesterol transport to lipid-poor

apolipoprotein A-I (ApoA-I), ApoE or high density lipoproteins (HDLs) (Kim et al., 2008; Saint-Pol et al., 2012).

The LXR/ABCA1 axis is a very attractive drug target in Alzheimer's disease (AD), a neurodegenerative disorder mainly associated with amyloid-ß (Aß) peptide accumulation, aggregation and deposition in the brain (Querfurth and LaFerla, 2010). Indeed, stimulation of the LXR pathway by agonists in murine models of AD provoked an ABCA1-dependent decrease in Aß burden in the brain, which was correlating with a partial recovery of cognitive function (Burns et al., 2006; Donkin et al., 2010; Fitz et al., 2010; Koldamova et al., 2005b; Lefterov et al., 2007; Riddell et al., 2007; Terwel et al., 2011). Overexpression of ABCA1 leads to the same observations (Wahrle et al., 2008), whereas deletion of ABCA1 is associated with enhanced Aß peptide deposition in the brain (Fitz et al., 2012; Hirsch-Reinshagen et al., 2005; Koldamova et al., 2005a; Wahrle et al., 2005). Nevertheless, the cellular and molecular mechanisms that underlie these processes have yet to be described in detail. We and others have suggested that the LXR signaling pathway may affect the transport of Aß peptides across the BBB (probably via an ABCA1-dependent process). Aß peptides cross the BCECs in both apical-to-basolateral and basolateral-to-apical directions (Zlokovic, 2008). We previously investigated the apical-to-basolateral transport of Aß peptides (i.e. influx into the brain) (Candela et al., 2010) using an in vitro BBB model (Cecchelli et al., 2007; Dehouck et al., 1992). We showed that the apical-to-basolateral entry of these peptides is mediated by the receptor for advanced glycation end-products (RAGE) and is restricted by breast cancer resistance protein (BCRP, also known as ABCG2) and P-glycoprotein (P-gp or ABCB1) (Candela et al., 2010). These receptors/transporters are expressed on the luminal side of BCECs (de Vries et al., 2007; Deane et al., 2003; Gosselet et al., 2009; Tai et al., 2009b). More recently, multidrug resistance associated protein 1 (MRP1 or ABCC1) was reported to be involved in the cerebral clearance of Aß peptides (Krohn et al., 2011). Modulation of expression and/or activity of these receptors/transporters is considered to be a promising therapeutic strategy in AD, with a view to limiting Aß peptide entry into the brain. For example, Deane and collaborators

elegantly used and designed a novel, specific RAGE inhibitor (FPS-ZM1) to produce a marked reduction of Aß peptide influx across the BBB and thus a decrease in the brain's Aß burden (Deane et al., 2012). In contrast, several studies of ABCB1 or ABCC1 have clearly shown that increasing the transporter's activity or transcription levels leads to a reduction in the brain's amyloid burden (Hartz et al., 2010; Krohn et al., 2011; Qosa et al., 2012).

With these considerations in mind, and given that the BBB is constantly exposed to 24S-OH-chol, 27-OH-chol (Bjorkhem, 2006) and Aß peptide fluxes (Zlokovic, 2008), the present study involved the use of an in vitro BBB model to clarify how these two oxysterols can act as LXR agonists on Aß peptide influx across BCECs.

2. Results

2.1 24S-OH-chol and 27-OH-chol are not toxic for BCECs in vitro (up to 10 µM)

We first assessed the toxicity of different concentrations (0-10 µM) of 24S-OH-chol and 27-OH-chol in BCECs. Oxysterols were added to the compartment in which they are usually generated, i.e. the abluminal compartment (representing the brain) for 24S-OH-chol and the luminal side (representing the blood) for 27-OH-chol. After a 24-hour treatment, the endothelial permeability (Pe) of Lucifer Yellow (a BBB integrity marker) was evaluated, as previously described (Culot et al., 2008; Hallier-Vanuxeem et al., 2009). As shown in Fig. 1, there were no significant changes in Pe values for the oxysterol concentrations tested here (0-10 µM). The same results were obtained with 0-10 µM T0901317, a well-known synthetic LXR agonist (Repa et al., 2000). Hence, a concentration of 10 µM was used in subsequent experiments.

2.2 Expression of ABCA1 is upregulated by LXR agonists

We have previously demonstrated that BCECs express LXRs, ABCA1 and SCARB1 (Gosselet et al., 2009; Saint-Pol et al., 2012). In the present study, we used semi-quantitative RT-PCR to investigate the ability of 24S-OH-chol and 27-OH-chol to stimulate this pathway in BCECs (Fig. 2A). The primers are described in Table 1. The expression levels of LXR-α, LXR-β and SCARB1 were not modified by 24h of treatment with various doses of either 24S-OH-chol or 27-OH-chol. In contrast, expression levels of ABCA1 were modified (Fig. 2A). Using real-time RT-PCR, we then quantified the upregulation of ABCA1 mRNA expression (7.17-fold for 10 µM 24S-OH-chol and 4.73-fold for 10 µM 27-OH-chol, relative to control conditions) and confirmed that LXR stimulation did not modify SCARB1 expression (Fig. 2B). Immunoblot assays performed on the BCEC membrane-enriched fraction gave the same results in terms of protein levels (Fig. 2C).

2.3 Oxysterol-mediated ABCA1 expression increases cholesterol release to ApoA-I and HDL particles

To investigate the impact of ABCA1 induction on cellular cholesterol efflux, we then studied ABCA1's ability to release cholesterol to ApoA-I and HDL particles. In the absence of oxysterol treatment, BCECs loaded with radioactive cholesterol were able to efflux a small proportion to the medium (Fig. 3A) (4.86 ± 0.7%, for a bovine serum albumin (BSA)-only control condition). Addition of lipid-free ApoA-I particles did not significantly increase the extent of release (4.02 ± 0.19% versus the control condition), whereas HDL particles increased release by up to 5-fold, compared with control condition (21.46 ± 0.73%). In the absence of cholesterol acceptors, cholesterol efflux was greater after 24h of treatment with 10 µM of 24S-OH-chol or 27-OH-chol (Fig. 3B) (160.72 ± 9.17% and 131.17 ± 13.69%, respectively, compared with dimethyl sulfoxide (DMSO) only). Fig. 3C shows that both these oxysterols also increased cellular cholesterol release in the presence of ApoA-I (204.77 ± 17.65% for 24S-OH-chol and 209.03 ± 11.57% for 27-OH-chol, compared with DMSO). Oxysterol stimulation also promoted cellular cholesterol efflux in the presence of HDL particles in the medium (146.45 ± 0.68% for 24S-OH-chol and 119.45 ± 5.02% for 27-OH-chol, compared with the control) (Fig. 3D).

2.4 Apical-to-basolateral transport of soluble Aß peptides is decreased by LXR stimulation

We previously used our in vitro BBB model to investigate apical-to-basolateral (i.e. blood-to-brain) transport of Aß peptides (Candela et al., 2010). Since 24S-OH-chol and 27-OH-chol are also exchanged across BCECs, we decided to assess the impact of the two oxysterols on Aß peptides and inulin influx across BCECs. Inulin is used as a non-specific vesicular transport marker (Brillault et al., 2002; Candela et al., 2010; Saint-Pol et al., 2012). As shown in Fig. 4, both oxysterols decreased significantly the apical-to-basolateral transport of naïve forms of $Aß_{1-40}$ (diminution of 14.7 ± 1.71% for 24S-OH-chol and 15.77 ± 1.63% for 27-OH-chol, compared with untreated condition) and $Aß_{1-42}$ peptides (diminution of 26.16 ± 4.42% and 24.86 ± 5.7%, respectively) across BCECs. Transport of [^{3}H]-inulin was not significantly modified after LXR

pathway stimulation with 10 µM 24S-OH-chol (103.88 ± 3.78%, compared with DMSO) or 10 µM 27-OH-chol (103.76 ± 2.15%).

2.5 ABCA1 is not involved in Aß peptide influx across BCECs

Given that 24S-OH-chol and 27-OH-chol were found to induce significant ABCA1 expression, we then investigated the compounds' possible roles in the decrease in Aß peptide apical-to-basolateral transport across BCECs reported in Fig. 4. We used probucol (a specific ABCA1 inhibitor (Favari et al., 2004; Saint-Pol et al., 2012)) to clarify ABCA1's involvement in this process. As in previous studies (Do et al., 2011; Saint-Pol et al., 2012; Stefulj et al., 2009), probucol was used at a concentration of 10 µM and was not toxic for BCECs at this concentration (data not shown). As shown in Fig. 5, inhibition of ABCA1 did not modify the decrease in Aß peptide influx mediated by 24S-OH-chol (67.24 ± 2.41% and 67.69 ± 4.29% in the presence and absence of probucol) or 27-OH-chol (68.12 ± 4.9,% and 72.41 ± 1.84% in the presence and absence of probucol), suggesting that ABCA1 is not directly involved in Aß peptide influx across BCECs. Probucol treatment did not modify [^{3}H]-inulin influx across BCECs (data not shown).

2.6 ABCB1 expression and activity are increased after treatment with oxysterols

We have previously used the present in vitro BBB model to show that Aß peptide influx across BCECs is mediated by RAGE and is restricted by ABCB1 and ABCG2 (Candela et al., 2010). More recently, involvement of ABCC1 in Aß peptide transport across the BBB has been suggested as to be much more important than other ABC transporters (Krohn et al., 2011). Given that ABCA1 is not responsible for the decrease in Aß peptides observed after oxysterol treatment (Fig. 5), we then studied the expression of these four Aß peptide receptors/transporters after 24 hours of treatment with 10 µM of 24S-OH-chol or 27-OH-chol (Fig. 6A). An RT-qPCR analysis indicated that transcriptional expression of RAGE, ABCC1 and ABCG2 were not modulated by oxysterol treatment, whereas ABCB1 expression was 1.8-fold and 1.7-fold greater (compared with

the control condition) after treatment with 24S-OH-chol and 27-OH-chol, respectively. Therefore, the ABCB1 efflux pump is a potential target gene in the oxysterol-induced reduction of Aß peptide influx across BCECs. ABCB1 induction by oxysterols was confirmed by immunoblot experiments in BCEC membrane-enriched fractions, which revealed that ABCB1 was respectively 3-fold, 2.7-fold and 2.3-fold more abundant after treatments with 24S-OH-chol, 27-OH-chol and T0901317 (Fig. 6B). To confirm ABCB1's involvement in this oxysterol-modulated process, we investigated its post-oxysterol activity by using colchicine, a well-known substrate of ABCB1 (Decleves et al., 2006). As shown in Fig. 6C, [^{3}H]-colchicine influx across BCECs was reduced by treatment for 24h with 10 µM 24S-OH-chol and 10 µM 27-OH-chol (84.55 ± 3.03% and 83.05 ± 1.49%, respectively, relative to the untreated condition), demonstrating that both oxysterols increase ABCB1 expression and activity and thus that the transporter may be involved in the restriction of Aß peptide influx across BCECs.

2.7 ABCB1 is involved in the oxysterol-mediated reduction in Aß peptide influx across BCECs

When ABCB1 is active, it limits substrate influx across BCECs and decreases the compounds' accumulation within the cell. Hence, inhibition of this efflux pump leads to an accumulation of its substrates in BCECs and a progressive increase in influx processes (Fenart et al., 1998). To inhibit ABCB1, we used Aß peptides as competitive inhibitors (Kuhnke et al., 2007) and measured [^{3}H]-colchicine accumulation and influx across BCECs. In each condition, competition with Aß peptides led to an almost 2-fold increase in [^{3}H]-colchicine accumulation in BCECs, when compared with the same condition in the absence of Aß peptides (212.20 ± 1.3%, 201.03 ± 10.68% and 211.03 ± 21.14% for the DMSO, 24S-OH-chol and 27-OH-chol conditions, respectively) (Fig. 7A). In presence of Aß peptides, significant increases in [^{3}H]-colchicine influx across BCECs (129.96 ± 15.61%, 140.85 ± 6.92% and 132.17 ± 7.01% for the DMSO, 24S-OH-chol and 27-OH-chol conditions, respectively) (Fig. 7B) were observed. When reverse experiments were performed (Fig. 7C), increases of apical-to-basolateral transports of Aß peptides were

measured in presence of colchicine (135.42 ± 2.23%, 142.18 ± 3.39% and 115.78 ± 3.95% for the DMSO, 24S-OH-chol and 27-OH-chol conditions, respectively). Altogether, these results confirm that LXR stimulation by oxysterols restricts Aß peptide influx across BCECs via what is probably an ABCB1-mediated process.

Discussion

The results of several recent studies suggest that the LXR/ABCA1 axis is an attractive therapeutic approach in AD. Firstly, amyloid plaque load and neuro-inflammation are exacerbated in lxr knock-out mice (Zelcer et al., 2007). Furthermore, overexpression of Abca1 decreases the amyloid burden (Wahrle et al., 2008), whereas Abca1 deletion promotes the AD phenotype (Fitz et al., 2012; Hirsch-Reinshagen et al., 2005; Koldamova et al., 2005a; Wahrle et al., 2005). Lastly, stimulation of the LXR by natural or synthetic agonists increases ABCA1 expression and decreases Aß peptide accumulation, synthesis and clearance (Burns et al., 2006; Donkin et al., 2010; Fitz et al., 2010; Koldamova et al., 2005b; Lefterov et al., 2007; Riddell et al., 2007; Terwel et al., 2011). Although it is not clear how ABCA1 affects Aß peptide proteostasis, the latter results have prompted the hypothesis whereby this lipid transporter may be directly involved in bidirectional Aß peptide transport across the BBB. Brain capillary endothelial cells (BCECs) and the surrounding brain pericytes express the receptors and ABC transporters directly involved in the exchange of Aß peptides between brain and blood compartments (Zlokovic, 2008). Although previous reports state that ABCA1 was not involved in cerebral efflux of naïve form of Aß peptides (Akanuma et al., 2008b; Saint-Pol et al., 2012), the putative link between LXR/ABCA1 axis stimulation and Aß peptide influx into the brain has never (to the best of our knowledge) been investigated. This influx must not be neglected, since an elegant study by Zlokovic's group demonstrated that reducing Aß entry into the brain may be also a valid strategy for preventing amyloid burden and cognitive deficits in AD transgenic mice (Deane et al., 2012).

With these considerations in mind, we designed the present study to characterize the effect of the LXR stimulation by natural and synthetic agonists on cholesterol cellular efflux and Aß peptide influx across the BBB. The model used in this study consists of a co-culture of bovine BCECs with glial cells (Cecchelli et al., 2007; Dehouck et al., 1990) and has previously been used to investigate the process of influx of naïve forms of Aß peptides into the brain (Candela et al., 2010).

We first assessed the toxicity of natural (24S-OH-chol and 27-OH-chol) and synthetic (T0901317) LXR agonists on BBB permeability. In our culture conditions, no toxicity was observed following 24 hours of treatment with a range of concentrations (0-10 µM). This finding agrees with previous studies in porcine BCECs (Panzenboeck et al., 2006), brain pericytes (Saint-Pol et al., 2012) and others cells, in which a toxic effect beyond a concentration of 25 µM was evidenced (Kolsch et al., 2001; Riendeau and Garenc, 2009).

Our results also showed an increase in ABCA1 expression in bovine BCECs after oxysterol treatment. ABCA1 is the major LXR target gene (Whitney et al., 2002) and is known to be a key ABC transporter involved in brain cholesterol homeostasis (Hirsch-Reinshagen et al., 2005; Wong et al., 2006). This ABC transporter is widely expressed by central nervous system cells (Abildayeva et al., 2006), choroid plexus epithelial cells (Fujiyoshi et al., 2007) and BBB cells such as brain pericytes (Saint-Pol et al., 2012) and BCECs (Akanuma et al., 2008a; Gosselet et al., 2009; Panzenboeck et al., 2002). In line with previous studies, our data show that oxysterol-mediated upregulation of ABCA1 in BCECs is correlated with an increase in cholesterol efflux to ApoA-I and HDL particles (Do et al., 2011; Panzenboeck et al., 2002; Panzenboeck et al., 2006). Furthermore, our previous results on brain pericytes demonstrated that 24S-OH-chol-mediated ABCA1 expression was also associated with an increase in cholesterol efflux from pericytes to ApoA-I and HDL particles (Saint-Pol et al., 2012). Taken as a whole, these data strongly reinforce the hypothesis in which the BBB plays a major role in brain and peripheral cholesterol homeostasis (Karasinska et al., 2009).

Furthermore, our results showed that treatment with oxysterols provoked a decrease in the influx of soluble forms of Aß peptides across BCECs (in the apical-to-basolateral direction) and thus could reduce Aß entry into the brain and limit its further accumulation in this compartment. Importantly, this effect was observed using the naïve Aß peptides that are very frequently used in transport studies. It is noteworthy that Aß peptides reportedly interact with several apolipoproteins (apoE, apoA-I) and other molecules such as α-macroglobulin 2. It remains to be seen whether influx

of these complexes is also decreased. Although ABCA1 is upregulated after stimulation of the oxysterol-mediated LXR pathway, we demonstrated that this transporter was not directly involved in the decrease in Aß peptide influx across BCECs. In line with two previous reports focusing on the efflux of naïve forms of Aß peptides across the BBB, these data suggest that ABCA1 is not directly involved in Aß peptide uptake or influx. Firstly, a study of $Abca1^{-/-}$ mice found that the lack of ABCA1 did not affect the efflux of a naïve form of Aß peptides across the BBB (Akanuma et al., 2008b). Secondly, our previous study demonstrated that brain pericytes (the first cell type encountered by Aß peptides prior to their elimination from the brain across the BBB) also express ABCA1 but that transporter is not involved in Aß uptake or cellular efflux (Saint-Pol et al., 2012).

To understand how LXR stimulation by oxysterols decreases Aß peptide influx into BCECs, we then observed the oxysterols' effects on RAGE, ABCB1, ABCC1 and ABCG2 expressed by these cells. It is now accepted that RAGE mediates apical-to-basolateral transport of naïve Aß peptide across BCECs (Candela et al., 2010; Deane et al., 2003), whereas this transport is restricted by ABCB1, ABCG2 and probably ABCC1 (Candela et al., 2010; Krohn et al., 2011; Tai et al., 2009a). We found that LXR stimulation increased transcriptional and proteins levels of ABCB1 but not RAGE, ABCC1 and ABCG2. Furthermore, activity assays using the ABCB1 substrate colchicine (Balayssac et al., 2005) demonstrated that (as had been observed for Aß peptides) the influx of this molecule across BCECs was reduced by oxysterol treatment. Competition between colchicine and Aß peptides led to an accumulation of colchicine in BCECs and an increase in apical-to-basolateral transport of this molecule across BCECs, confirming that oxysterol-induced expression of ABCB1 is correlated with an increase in its activity in BCECs. Reverse experiments give the same conclusion. These results demonstrate that the ABCB1 efflux pump is involved in oxysterol-mediated restriction of naïve forms of Aß peptides across BCECs.

As mentioned above, limiting the entry of Aß peptides into the brain compartment is a pertinent therapeutic approach in AD (Deane et al., 2012). ABCB1 is a key ABC transporter involved in the restriction of Aß peptide influx across the BBB and postmortem investigations of

brain tissue have shown that ABCB1 expression levels in vessels surrounding Aß plaques (Vogelgesang et al., 2002) and hippocampal blood vessels (Wijesuriya et al., 2010) are lower in AD patients than in age-matched patients. Moreover, ABCB1 is less active in AD patients than in non-AD patients (van Assema et al., 2012). Thus, targeting ABCB1 expression and/or its activity appears to be a potentially valid way of limiting Aß peptide accumulation in the brain. Moreover, previous research has demonstrated that increasing the ABCB1 expression at the BBB level leads to a further decrease in the brain Aß burden (Hartz et al., 2010; Qosa et al., 2012). Our present data showed that the decrease in amyloid burden after LXR stimulation by oxysterols is probably due to upregulation of ABCB1 expression/activity in BCECs. Although it is not known how LXR stimulation regulates ABCB1, this process appears to be specific to the BCECs because our previous research did not observe these effects in brain pericytes (Saint-Pol et al., 2012). Upregulation of ABCB1 by LXR agonists has been observed in brain capillaries and blood monocyte (Elali and Hermann, 2012; Langmann et al., 2006) but it is not yet clear understand how LXRs contribute to this process in molecular terms. It is likely that other nuclear receptors expressed by BCECs (Akanuma et al., 2008a; Panzenboeck et al., 2006) (such as the pregnane and farnesoid X receptors) are involved in this process. Thus, LXR pathway stimulation by agonists such as oxysterols may not only be beneficial in the context AD but also represents a new potential therapeutic approach for restoring and/or optimizing the restriction of ABCB1 substrate entry into the brain.

In conclusion, the present study demonstrated the impact of LXR pathway stimulation by 24S-OH-chol and 27-OH-chol in BCECs on (i) ABCA1-mediated cholesterol homeostasis and (ii) the restriction of Aß peptide influx from the blood to brain by an ABCB1-mediated process and thus confirmed the strong relationship between LXR nuclear receptors and AD. Taken as a whole, these data reinforce previous suggestions that stimulation of LXR receptors represents a new therapeutic strategy for protecting the brain against the characteristic amyloid burden in AD.

4. Experimental Procedure

4.1. Chemicals

24S-hydroxycholesterol (24S-OH-chol), 27-hydroxycholesterol (27-OH-chol) and T0901317 were respectively purchased from Enzo Life Science (Villeurbane, France), Avanti Polar Lipids (Alabaster, AL, USA) and Sigma (St Louis, MO, USA). The compounds were dissolved in DMSO (Sigma) at concentrations of 24.8 mM, 12.4 mM and 10.4 mM, respectively. Apolipoprotein A-I (ApoA-I) and high density lipoproteins (HDLs) were purchased from VWR (Fontenay-sous-Bois, France). Bovine serum albumin (BSA), Lucifer Yellow (LY) and colchicine were also purchased from Sigma. [^{3}H]-cholesterol (43 Ci/mmol), [^{3}H]-colchicine (85.3 Ci/mmol), [^{14}C]-sucrose (630 mCi/mmol) and [^{3}H]-inulin (1.25 Ci/mmol) were purchased from PerkinElmer Life and Analytical Sciences (Waltham, MA, USA). Ultrapure forms of $A\beta_{1-40}$ and $A\beta_{1-42}$ peptides were purchased from Life Technologies SAS (Saint Aubin, France) and resuspended as previously described (Candela et al., 2010). $A\ss_{1-40}$ and $A\ss_{1-42}$ ELISA kits were also purchased from Life Technologies SAS. Fluorescein isothiocyanate (FITC)-labeled $A\ss_{1-40}$ peptide was purchased from rPeptide (Bogart, GA, USA) and was used freshly resuspended in 1% NH_4OH according to the manufacturer's instructions (Candela et al., 2010).

4.2. Cell culture

The in vitro BBB model used in the present study was based on a co-culture of bovine brain capillary endothelial cells (BCECs) and rat glial cells that induce BBB properties (Cecchelli et al., 2007). All animal experiments were performed in compliance with the French Veterinary Council's guidelines.

Briefly, glial cells were extracted from parietal cortexes of newborn rats and seeded (after the removal of meninges and mechanical dissociation) on the bottom of uncoated, six-well plates containing Dulbecco's modified Eagle's Medium (DMEM) supplemented with 10% (v/v) FCS (fetal calf serum, Life Technologies), 2 mM L-glutamine (Sigma) and 50 µg/mL gentamicin

(Biochrom A.G., Berlin, Germany). Three weeks after seeding, the cells were confluent and were used for co-culture.

Next, BCECs were extracted and isolated from bovine brain capillaries and characterized as previously described (Candela et al., 2010; Dehouck et al., 1990; Dehouck et al., 1992). For cell culture, BCECs were seeded in 60 mm gelatin-coated dishes containing DMEM supplemented with 10% (v/v) horse serum (HS, Life Technologies), 10% (v/v) calf serum (CS, Integro b.v., Zaandam, The Netherlands), 2 mM L-glutamine and 50 µg/mL gentamicin and 1 ng/mL of basic fibroblast growth factor (HS/CS). At confluence, BCECs were ready to be used for co-culture. Filters (Costar Transwell®, pore size 0.4 or 3 µm, Corning, Avon, France) were coated with rat-tail collagen and set in six-well plates containing the glial cells. Endothelial cells were seeded on the upper side of filters. The medium was changed every two days. The endothelial cells showed BBB properties after 12 days of co-culture (Cecchelli et al., 2007).

4.3. Evaluation of BCEC permeability after treatment with compounds

The integrity of tight junctions after 24h of treatment with different doses (0-10 µM) of either 24S-OH-chol (in the abluminal compartment), 27-OH-chol, T0901317 or probucol (in the luminal compartment) was checked by calculating the endothelial permeability coefficient (Pe) of LY (50 µM per filter), as previously described (Cecchelli et al., 1999). Three filters were used per condition and LY concentrations were measured with a spectrophotometer (Biotek, Colmar, France).

4.4. mRNA extraction and PCR analysis

After 12 days of co-culture, BCECs were treated for 24h with 24S-OH-chol or 27-OH-chol (0-10 µM). Next, cells were rinsed twice with cold calcium- and magnesium free phosphate buffered saline (PBS-CMF: 8 g/L NaCl, 0.2 g/L KCl, 0.2 g/L KH_2PO_4, 2.87 g/L $NA_2HPO_4(12H_2O)$, pH 7.4) and lysed with RNeasy lysis buffer (Qiagen, Valencia, CA, USA). Lysates were frozen at -

20°C prior to thawing for total RNA extraction. mRNAs were extracted according to the Qiagen RNeasy Mini Kit protocol and were assayed by measuring absorbance at 260, 280 and 320 nm with a Tek3 microplate reader protocol (Synergy™ H1, Biotek). cDNAs were obtained from 0.5 µg of mRNA using iScript™ Reverse Transcription Supermix (BioRad, Marnes-la-Coquette, France), according to the manufacturer's instructions. Semi-quantitative cDNA amplification analysis was performed by RT-PCR using custom-designed primers (reported in Table 1) and as previously described (Saint-Pol et al., 2012). Amplification (number of cycles/annealing temperature) was carried out as follows for each gene : ABCA1 (32/55°C), SCARB1 (30/55°C), LXR-α (30/55°C), LXR-β (30/50°C) and ß-actin (25/55°C). All cDNA amplification products were then sequenced using the Sanger method (GenoScreen, Lille, France). Quantitative amplification (qPCR) of cDNA was performed using Sso Fast EvaGreen Master Mix (BioRad) and custom-designed primers (Table 1). Amplification was carried out for 40 cycles with an annealing temperature of 60°C using a CFX96 thermocycler (BioRad). The efficiency was determined for each primer pair and used in the calculation method (CFX Manager, BioRad). Melting curve analysis was performed after the amplification cycles, in order to check the specificity/purity of each amplification. Gene expression levels were evaluated according to the ΔΔCt method and were normalized against ß-actin expression.

4.5. Immunoblots

Brain capillary endothelial cells were seeded on Transwell® filters coated with rat tail collagen. The filters were then set into dishes with glial cells. After 12 days of co-culture, BCECs were treated for 24h with DMSO vehicle (as a control) or 10 µM of either T0901317, 24S-OH-chol or 27-OH-chol. Cells were then rinsed twice with warm PBS at 37°C and then incubated for 5 min with 1 mg/mL of collagenase. Cells were centrifuged at 2500 rpm at 4°C for 8 min. Pellets were resuspended with a pestle in 20 mM tricine/250 mM sucrose/1 mM EDTA buffer. The plasma membrane fraction was isolated as previously described (Saint-Pol et al., 2012). Protein extracts

were assayed using the Bradford method; 8 µg of extract were then electrophoresed on 7.5% sodium dodecyl sulfate polyacrylamide gel (BioRad) and electrotransferred onto nitrocellulose membranes (GE Healthcare, Saclay, France). After a 90-min incubation in blocking buffer (25 mM Tris-HCl (pH 8.0), 125 mM NaCl, 0.1% Tween 20, and 5% skimmed milk), the membranes were incubated with primary antibody (anti-ABCA1 (2 µg/mL, Abcam, Cambridge, UK), anti-SCARB1 (0.4 µg/mL, Abcam) or anti-Pgp (5 µg/mL, GeneTex, Paris, France)) overnight at 4°C, rinsed three times with blocking buffer and incubated with appropriate horseradish peroxidase (HRP)-conjugated secondary antibody (Dako) for 1h at room temperature. The HRP was assayed with an enhanced chemiluminescence kit (GE Healthcare) and revealed on chemiluminescence-sensitive films (GE Healthcare). The bands' optical densities were measured using TotalLab TL 100 1D Gel Analysis software (Nonlinear Dynamics, Newcastle, UK).

4.6. Apical-to-basolateral transport of Aß peptides

After a 24h-treatment with either DMSO (the control condition, 1/400) or 10 µM 24S-OH-chol or 27-OH-chol, Aß peptide influx (apical-to-basolateral transport) experiments were performed as previously described (Candela et al., 2010). Firstly, filters bearing BCECs were rinsed for 10 minutes in pH 7.4 Ringer HEPES buffer (RH; HEPES 5 mM; $NaHCO_3$ 6 mM; NaCl 150 mM; KCl 5.2 mM; $CaCl_2$ 2.2 mM; $MgCl_2$ + $6H_2O$ 1.2 mM) supplemented with 0.5% BSA, and transferred into six-well plates containing 2.5 mL RH/0.5% BSA in each well. Next, 1.5 mL RH/0.5% BSA/LY with 12 nM of either [^{3}H]-inulin or ultrapure Aß peptides were placed on the filters. During the 2-hour transport assay, cells were incubated at 37°C with very slight agitation. The BBB's permeability and non-receptor-mediated transport were respectively evaluated by measuring LY permeability (see below) and [^{3}H]-inulin transport with a liquid scintillation counter (TriCarb 2100TR, PerkinElmer). Radioactivity was measured as disintegrations per minute (DPM). Each form of Aß peptides ($Aß_{1-40}$ and $Aß_{1-42}$) was assayed with appropriate ELISA kits (Life Technologies), according to the manufacturer’s instructions. Briefly, a monoclonal antibody

specific for the NH2-terminus of $A\beta_{1-40}$ and $A\beta_{1-42}$ peptides was coated onto the wells. Next, a rabbit antibody specific for the COOH-terminus of the $A\beta_{1-40}$ or $A\beta_{1-42}$ sequences was co-incubated with samples. The mass balance was calculated in order to estimate peptide aggregation and degradation. Experiments with at least 90% of Aß peptide mass balance were taken into consideration. The percentage passage calculation consisted in dividing the amounts of [^{3}H]-inulin or Aß peptides in the basolateral compartment (modeling the brain) by the initial concentration added to the apical compartment (modeling the blood). To consider the influence of the filter and the collagen coating on molecular transport, the percentage passage was calculated in the presence and absence of BCECs. The final transport percentage was thus calculated by dividing the value obtained in the presence of cells by the value obtained in the absence of cells.

Since LY is the most commonly used control molecule for both [^{3}H]-inulin and Aß peptide conditions, the percentage of test compound across BCECs was evaluated according to the following equation:

% "normalized" compound transport = 100 x (% transport of a test compound across the filter)/ (% LY transport across the filter).

Each assay was performed using three filters and each experiment was performed three times.

For inhibition studies, $Aß_{1-40}$ peptide influx was assayed for 2h, as described below. RH/0.5% BSA/[^{14}C]-sucrose (as BBB integrity marker) was supplemented with 12 nM FITC-labeled $Aß_{1-40}$ or [^{3}H]-inulin in the presence of absence of 10 µM probucol. As influx studies using ultrapure forms of Aß peptides:

% "normalized" FITC-$Aß_{1-40}$ peptide or [^{3}H]-inulin transport = 100 x (% FITC-$Aß_{1-40}$ transport or [^{3}H]-inulin transport across the filter in the presence or absence of probucol)/ (% [^{14}C]-sucrose transport for the corresponding filter).

Each assay was performed using three filters and each experiment was performed at least twice.

4.7. [^{3}H]-Cholesterol efflux studies

Radioactive HS/CS medium was obtained by incorporating [^{3}H]-cholesterol (0.5 µCi/mL) with HS and CS for 6 h at 37°C. Cells were incubated for 36 h with this medium to allow incorporation of the labeled cholesterol. Cells were then rinsed twice with pre-warmed PBS-CMF buffer and once with pre-warmed DMEM/0.1% BSA. Next, the cells were equilibrated in DMEM/0.1% BSA for 24 h. During this step, 10 µM of 24S-OH-chol or 27-OH-chol were added in the compartment in which they are usually generated in vivo (ie. abluminal compartment (brain) for 24S-OH-chol and luminal compartment (blood) for 27-OH-chol). Cells were rinsed once with pre-warmed DMEM/0.1% BSA. ApoA-I (20 µg/mL) or HDLs (50 µg/mL) were then added for 8 h. After this period, apical and basolateral media were collected and cell debris was removed by centrifugation at 4000 rpm for 4 min at 4°C. The cells were washed four times with cold RH buffer and lysed with RH/1% Triton X-100. Aliquots of cell lysates and both apical and basolateral media were analyzed in a liquid scintillation counter (Tri-Carb 2100TR). Cellular cholesterol efflux was calculated according to the following equation:

$$\% \text{ total efflux} = (DPM_{apical} + DPM_{basolateral}) \times 100/(DPM_{apical} + DPM_{basolateral} + DPM_{cell\ lysate}).$$

Each assay was performed using three filters and each experiment was run at least three times.

4.8. ABCB1 activity assay

Brain capillary endothelial cells were first treated for 24h with either DMSO (the control condition) or 10 µM 24S-OH-chol or 27-OH-chol. [^{3}H]-colchicine was used as the ABCB1 substrate (Balayssac et al., 2005). Before starting apical-to-basolateral transport experiments, filters containing BCECs were rinsed for 10 minutes in RH buffer supplemented with 0.5% BSA and then transferred into six-well plates containing 2.5 mL RH/0.5% BSA per well. Experiments started when 1.5 mL RH/0.5% BSA/LY with 50 nM [^{3}H]-colchicine was added to the luminal compartment. During the 2-hour transport assay, cells were incubated at 37°C with very slight agitation. Apical and basolateral media were collected and measured for LY and [^{3}H]-colchicine amounts. Cells were rinsed four times in cold RH/0.5% BSA and lysed with RH/0.5% BSA/1%

Triton X-100. The BBB's permeability was evaluated by measuring LY permeability. The [^{3}H]-colchicine radioactivity was measured in DPM. As mentioned for Aß peptide influx experiments, we considered the influence of the filter and the collagen coating on molecular transport and so calculated the percentage passage in the presence and absence of BCECs. The percentage of [^{3}H]-colchicine influx across BCECs was evaluated according to the following equation:

% "normalized" [^{3}H]-colchicine transport = 100 x (% [^{3}H]-colchicine transport across the filter)/ (% LY transport across the filter).

Each assay was performed using three filters and each experiment was performed at least twice. For competition assays, 60 nM of ultrapure Aß$_{1-40}$ competed with 50 nM [^{3}H]-colchicine as a ABCB1 substrate. Transport was evaluated as previously described:

% "normalized" [^{3}H]-colchicine transport = 100 x (% [^{3}H]-colchicine transport across the filter in the presence or absence of ultrapure Aß$_{1-40}$)/ (% LY transport across the corresponding filter).

In reverse experiments, apical-to-basolateral transport of 12 nM of ultrapure Aß$_{1-40}$ was measured in presence of colchicine (240 nM). Experiments and calculation method were similar to what is described above.

Each assay was performed using three filters, and each experiment was performed at least twice.

4.9. Statistical analysis

All statistical analyses were performed with Prism 6.0 software (GraphPad Software Inc., San Diego, CA, USA), using a one-way analysis of variance (ANOVA) and then appropriate post hoc tests. Data are reported as the mean ± SD or (where specified) the mean ± SEM.

Acknowledgements

This research was funded by grants from the Coeur & Artères foundation (Grant 06T6) and LECMA (Grant 09752). Julien Saint-Pol received a doctoral fellowship from the French Ministère de l'Enseignement Supérieur et de la Recherche. The authors have declared no conflicts of interest.

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References

Abbott, N.J., Patabendige, A.A., Dolman, D.E., Yusof, S.R., Begley, D.J., 2010. Structure and function of the blood-brain barrier. Neurobiology of disease. 37, 13-25.

Abildayeva, K., Jansen, P.J., Hirsch-Reinshagen, V., Bloks, V.W., Bakker, A.H., Ramaekers, F.C., de Vente, J., Groen, A.K., Wellington, C.L., Kuipers, F., Mulder, M., 2006. 24(S)-hydroxycholesterol participates in a liver X receptor-controlled pathway in astrocytes that regulates apolipoprotein E-mediated cholesterol efflux. The Journal of biological chemistry. 281, 12799-12808.

Akanuma, S., Hori, S., Ohtsuki, S., Fujiyoshi, M., Terasaki, T., 2008a. Expression of nuclear receptor mRNA and liver X receptor-mediated regulation of ABC transporter A1 at rat blood-brain barrier. Neurochemistry international. 52, 669-674.

Akanuma, S., Ohtsuki, S., Doi, Y., Tachikawa, M., Ito, S., Hori, S., Asashima, T., Hashimoto, T., Yamada, K., Ueda, K., Iwatsubo, T., Terasaki, T., 2008b. ATP-binding cassette transporter A1 (ABCA1) deficiency does not attenuate the brain-to-blood efflux transport of human amyloid-beta peptide (1-40) at the blood-brain barrier. Neurochemistry international. 52, 956-961.

Balayssac, D., Authier, N., Cayre, A., Coudore, F., 2005. Does inhibition of P-glycoprotein lead to drug-drug interactions? Toxicology letters. 156, 319-329.

Bjorkhem, I., Diczfalusy, U., Lutjohann, D., 1999. Removal of cholesterol from extrahepatic sources by oxidative mechanisms. Current opinion in lipidology. 10, 161-165.

Bjorkhem, I., 2006. Crossing the barrier: oxysterols as cholesterol transporters and metabolic modulators in the brain. Journal of internal medicine. 260, 493-508.

Brillault, J., Berezowski, V., Cecchelli, R., Dehouck, M.P., 2002. Intercommunications between brain capillary endothelial cells and glial cells increase the transcellular permeability of the blood-brain barrier during ischaemia. Journal of neurochemistry. 83, 807-817.

Burns, M.P., Vardanian, L., Pajoohesh-Ganji, A., Wang, L., Cooper, M., Harris, D.C., Duff, K., Rebeck, G.W., 2006. The effects of ABCA1 on cholesterol efflux and Abeta levels in vitro and in vivo. Journal of neurochemistry. 98, 792-800.

Candela, P., Gosselet, F., Miller, F., Buee-Scherrer, V., Torpier, G., Cecchelli, R., Fenart, L., 2008. Physiological pathway for low-density lipoproteins across the blood-brain barrier: transcytosis through brain capillary endothelial cells in vitro. Endothelium : journal of endothelial cell research. 15, 254-264.

Candela, P., Gosselet, F., Saint-Pol, J., Sevin, E., Boucau, M.C., Boulanger, E., Cecchelli, R., Fenart, L., 2010. Apical-to-basolateral transport of amyloid-beta peptides through blood-brain barrier cells is mediated by the receptor for advanced glycation end-products and is restricted by P-glycoprotein. Journal of Alzheimer's disease : JAD. 22, 849-859.

Cecchelli, R., Dehouck, B., Descamps, L., Fenart, L., Buee-Scherrer, V.V., Duhem, C., Lundquist, S., Rentfel, M., Torpier, G., Dehouck, M.P., 1999. In vitro model for evaluating drug transport across the blood-brain barrier. Advanced drug delivery reviews. 36, 165-178.

Cecchelli, R., Berezowski, V., Lundquist, S., Culot, M., Renftel, M., Dehouck, M.P., Fenart, L., 2007. Modelling of the blood-brain barrier in drug discovery and development. Nature reviews. Drug discovery. 6, 650-661.

Chobanian, A.V., Hollander, W., 1962. Body cholesterol metabolism in man. I. The equilibration of serum and tissue cholesterol. The Journal of clinical investigation. 41, 1732-1737.

Culot, M., Lundquist, S., Vanuxeem, D., Nion, S., Landry, C., Delplace, Y., Dehouck, M.P., Berezowski, V., Fenart, L., Cecchelli, R., 2008. An in vitro blood-brain barrier model for high throughput (HTS) toxicological screening. Toxicology in vitro : an international journal published in association with BIBRA. 22, 799-811.

Daneman, R., Zhou, L., Kebede, A.A., Barres, B.A., 2010. Pericytes are required for blood-brain barrier integrity during embryogenesis. Nature. 468, 562-566.

de Vries, N.A., Zhao, J., Kroon, E., Buckle, T., Beijnen, J.H., van Tellingen, O., 2007. P-glycoprotein and breast cancer resistance protein: two dominant transporters working together in limiting the brain penetration of topotecan. Clinical cancer research : an official journal of the American Association for Cancer Research. 13, 6440-6449.

Deane, R., Du Yan, S., Submamaryan, R.K., LaRue, B., Jovanovic, S., Hogg, E., Welch, D., Manness, L., Lin, C., Yu, J., Zhu, H., Ghiso, J., Frangione, B., Stern, A., Schmidt, A.M., Armstrong, D.L., Arnold, B., Liliensiek, B., Nawroth, P., Hofman, F., Kindy, M., Stern, D., Zlokovic, B., 2003. RAGE mediates amyloid-beta peptide transport across the blood-brain barrier and accumulation in brain. Nature medicine. 9, 907-913.

Deane, R., Singh, I., Sagare, A.P., Bell, R.D., Ross, N.T., LaRue, B., Love, R., Perry, S., Paquette, N., Deane, R.J., Thiyagarajan, M., Zarcone, T., Fritz, G., Friedman, A.E., Miller, B.L., Zlokovic, B.V., 2012. A multimodal RAGE-specific inhibitor reduces amyloid beta-mediated brain disorder in a mouse model of Alzheimer disease. The Journal of clinical investigation. 122, 1377-1392.

Decleves, X., Niel, E., Debray, M., Scherrmann, J.M., 2006. Is P-glycoprotein (ABCB1) a phase 0 or a phase 3 colchicine transporter depending on colchicine exposure conditions? Toxicology and applied pharmacology. 217, 153-160.

Dehouck, B., Fenart, L., Dehouck, M.P., Pierce, A., Torpier, G., Cecchelli, R., 1997. A new function for the LDL receptor: transcytosis of LDL across the blood-brain barrier. The Journal of cell biology. 138, 877-889.

Dehouck, M.P., Meresse, S., Delorme, P., Fruchart, J.C., Cecchelli, R., 1990. An easier, reproducible, and mass-production method to study the blood-brain barrier in vitro. Journal of neurochemistry. 54, 1798-1801.

Dehouck, M.P., Jolliet-Riant, P., Bree, F., Fruchart, J.C., Cecchelli, R., Tillement, J.P., 1992. Drug transfer across the blood-brain barrier: correlation between in vitro and in vivo models. Journal of neurochemistry. 58, 1790-1797.

Do, T.M., Ouellet, M., Calon, F., Chimini, G., Chacun, H., Farinotti, R., Bourasset, F., 2011. Direct evidence of abca1-mediated efflux of cholesterol at the mouse blood-brain barrier. Molecular and cellular biochemistry. 357, 397-404.

Donkin, J.J., Stukas, S., Hirsch-Reinshagen, V., Namjoshi, D., Wilkinson, A., May, S., Chan, J., Fan, J., Collins, J., Wellington, C.L., 2010. ATP-binding cassette transporter A1 mediates the beneficial effects of the liver X receptor agonist GW3965 on object recognition memory and amyloid burden in amyloid precursor protein/presenilin 1 mice. The Journal of biological chemistry. 285, 34144-34154.

Elali, A., Hermann, D.M., 2012. Liver X receptor activation enhances blood-brain barrier integrity in the ischemic brain and increases the abundance of ATP-binding cassette transporters ABCB1 and ABCC1 on brain capillary cells. Brain pathology. 22, 175-187.

Favari, E., Zanotti, I., Zimetti, F., Ronda, N., Bernini, F., Rothblat, G.H., 2004. Probucol inhibits ABCA1-mediated cellular lipid efflux. Arteriosclerosis, thrombosis, and vascular biology. 24, 2345-2350.

Fenart, L., Buee-Scherrer, V., Descamps, L., Duhem, C., Poullain, M.G., Cecchelli, R., Dehouck, M.P., 1998. Inhibition of P-glycoprotein: rapid assessment of its implication in blood-brain barrier integrity and drug transport to the brain by an in vitro model of the blood-brain barrier. Pharmaceutical research. 15, 993-1000.

Fitz, N.F., Cronican, A., Pham, T., Fogg, A., Fauq, A.H., Chapman, R., Lefterov, I., Koldamova, R., 2010. Liver X receptor agonist treatment ameliorates amyloid pathology and memory deficits caused by high-fat diet in APP23 mice. The Journal of neuroscience : the official journal of the Society for Neuroscience. 30, 6862-6872.

Fitz, N.F., Cronican, A.A., Saleem, M., Fauq, A.H., Chapman, R., Lefterov, I., Koldamova, R., 2012. Abca1 deficiency affects Alzheimer's disease-like phenotype in human ApoE4 but not in ApoE3-targeted replacement mice. The Journal of neuroscience : the official journal of the Society for Neuroscience. 32, 13125-13136.

Fujiyoshi, M., Ohtsuki, S., Hori, S., Tachikawa, M., Terasaki, T., 2007. 24S-hydroxycholesterol induces cholesterol release from choroid plexus epithelial cells in an apical- and apoE isoform-dependent manner concomitantly with the induction of ABCA1 and ABCG1 expression. Journal of neurochemistry. 100, 968-978.

Gosselet, F., Candela, P., Sevin, E., Berezowski, V., Cecchelli, R., Fenart, L., 2009. Transcriptional profiles of receptors and transporters involved in brain cholesterol homeostasis at the blood-brain barrier: use of an in vitro model. Brain research. 1249, 34-42.

Hallier-Vanuxeem, D., Prieto, P., Culot, M., Diallo, H., Landry, C., Tahti, H., Cecchelli, R., 2009. New strategy for alerting central nervous system toxicity: Integration of blood-brain barrier toxicity and permeability in neurotoxicity assessment. Toxicology in vitro : an international journal published in association with BIBRA. 23, 447-453.

Hartz, A.M., Miller, D.S., Bauer, B., 2010. Restoring blood-brain barrier P-glycoprotein reduces brain amyloid-beta in a mouse model of Alzheimer's disease. Molecular pharmacology. 77, 715-723.

Hirsch-Reinshagen, V., Maia, L.F., Burgess, B.L., Blain, J.F., Naus, K.E., McIsaac, S.A., Parkinson, P.F., Chan, J.Y., Tansley, G.H., Hayden, M.R., Poirier, J., Van Nostrand, W., Wellington, C.L., 2005. The absence of ABCA1 decreases soluble ApoE levels but does not diminish amyloid deposition in two murine models of Alzheimer disease. The Journal of biological chemistry. 280, 43243-43256.

Karasinska, J.M., Rinninger, F., Lutjohann, D., Ruddle, P., Franciosi, S., Kruit, J.K., Singaraja, R.R., Hirsch-Reinshagen, V., Fan, J., Brunham, L.R., Bissada, N., Ramakrishnan, R., Wellington, C.L., Parks, J.S., Hayden, M.R., 2009. Specific loss of brain ABCA1 increases brain cholesterol uptake and influences neuronal structure and function. The Journal of neuroscience : the official journal of the Society for Neuroscience. 29, 3579-3589.

Kim, W.S., Weickert, C.S., Garner, B., 2008. Role of ATP-binding cassette transporters in brain lipid transport and neurological disease. Journal of neurochemistry. 104, 1145-1166.

Koldamova, R., Staufenbiel, M., Lefterov, I., 2005a. Lack of ABCA1 considerably decreases brain ApoE level and increases amyloid deposition in APP23 mice. The Journal of biological chemistry. 280, 43224-43235.

Koldamova, R.P., Lefterov, I.M., Staufenbiel, M., Wolfe, D., Huang, S., Glorioso, J.C., Walter, M., Roth, M.G., Lazo, J.S., 2005b. The liver X receptor ligand T0901317 decreases amyloid beta production in vitro and in a mouse model of Alzheimer's disease. The Journal of biological chemistry. 280, 4079-4088.

Kolsch, H., Ludwig, M., Lutjohann, D., Rao, M.L., 2001. Neurotoxicity of 24-hydroxycholesterol, an important cholesterol elimination product of the brain, may be prevented by vitamin E and estradiol-17beta. Journal of neural transmission. 108, 475-488.

Kuhnke, D., Jedlitschky, G., Grube, M., Krohn, M., Jucker, M., Mosyagin, I., Cascorbi, I., Walker, L.C., Kroemer, H.K., Warzok, R.W., Vogelgesang, S., 2007. MDR1-P-Glycoprotein (ABCB1) Mediates Transport of Alzheimer's amyloid-beta peptides--implications for the mechanisms of Abeta clearance at the blood-brain barrier. Brain pathology. 17, 347-353.

Langmann, T., Mauerer, R., Schmitz, G., 2006. Human ATP-binding cassette transporter TaqMan low-density array: analysis of macrophage differentiation and foam cell formation. Clinical chemistry. 52, 310-313.

Lefterov, I., Bookout, A., Wang, Z., Staufenbiel, M., Mangelsdorf, D., Koldamova, R., 2007. Expression profiling in APP23 mouse brain: inhibition of Abeta amyloidosis and inflammation in response to LXR agonist treatment. Molecular neurodegeneration. 2, 20.

Leoni, V., Masterman, T., Patel, P., Meaney, S., Diczfalusy, U., Bjorkhem, I., 2003. Side chain oxidized oxysterols in cerebrospinal fluid and the integrity of blood-brain and blood-cerebrospinal fluid barriers. Journal of lipid research. 44, 793-799.

Lutjohann, D., Breuer, O., Ahlborg, G., Nennesmo, I., Siden, A., Diczfalusy, U., Bjorkhem, I., 1996. Cholesterol homeostasis in human brain: evidence for an age-dependent flux of 24S-

hydroxycholesterol from the brain into the circulation. Proceedings of the National Academy of Sciences of the United States of America. 93, 9799-9804.

Meaney, S., Bodin, K., Diczfalusy, U., Bjorkhem, I., 2002. On the rate of translocation in vitro and kinetics in vivo of the major oxysterols in human circulation: critical importance of the position of the oxygen function. Journal of lipid research. 43, 2130-2135.

Osono, Y., Woollett, L.A., Herz, J., Dietschy, J.M., 1995. Role of the low density lipoprotein receptor in the flux of cholesterol through the plasma and across the tissues of the mouse. The Journal of clinical investigation. 95, 1124-1132.

Panzenboeck, U., Balazs, Z., Sovic, A., Hrzenjak, A., Levak-Frank, S., Wintersperger, A., Malle, E., Sattler, W., 2002. ABCA1 and scavenger receptor class B, type I, are modulators of reverse sterol transport at an in vitro blood-brain barrier constituted of porcine brain capillary endothelial cells. The Journal of biological chemistry. 277, 42781-42789.

Panzenboeck, U., Kratzer, I., Sovic, A., Wintersperger, A., Bernhart, E., Hammer, A., Malle, E., Sattler, W., 2006. Regulatory effects of synthetic liver X receptor- and peroxisome-proliferator activated receptor agonists on sterol transport pathways in polarized cerebrovascular endothelial cells. The international journal of biochemistry & cell biology. 38, 1314-1329.

Pfrieger, F.W., 2003. Outsourcing in the brain: do neurons depend on cholesterol delivery by astrocytes? BioEssays : news and reviews in molecular, cellular and developmental biology. 25, 72-78.

Qosa, H., Abuznait, A.H., Hill, R.A., Kaddoumi, A., 2012. Enhanced brain amyloid-beta clearance by rifampicin and caffeine as a possible protective mechanism against Alzheimer's disease. Journal of Alzheimer's disease : JAD. 31, 151-165.

Querfurth, H.W., LaFerla, F.M., 2010. Alzheimer's disease. The New England journal of medicine. 362, 329-344.

Repa, J.J., Liang, G., Ou, J., Bashmakov, Y., Lobaccaro, J.M., Shimomura, I., Shan, B., Brown, M.S., Goldstein, J.L., Mangelsdorf, D.J., 2000. Regulation of mouse sterol regulatory element-binding protein-1c gene (SREBP-1c) by oxysterol receptors, LXRalpha and LXRbeta. Genes & development. 14, 2819-2830.

Riddell, D.R., Zhou, H., Comery, T.A., Kouranova, E., Lo, C.F., Warwick, H.K., Ring, R.H., Kirksey, Y., Aschmies, S., Xu, J., Kubek, K., Hirst, W.D., Gonzales, C., Chen, Y., Murphy, E., Leonard, S., Vasylyev, D., Oganesian, A., Martone, R.L., Pangalos, M.N., Reinhart, P.H., Jacobsen, J.S., 2007. The LXR agonist TO901317 selectively lowers hippocampal Abeta42 and improves memory in the Tg2576 mouse model of Alzheimer's disease. Molecular and cellular neurosciences. 34, 621-628.

Riendeau, V., Garenc, C., 2009. Effect of 27-hydroxycholesterol on survival and death of human macrophages and vascular smooth muscle cells. Free radical research. 43, 1019-1028.

Saher, G., Brugger, B., Lappe-Siefke, C., Mobius, W., Tozawa, R., Wehr, M.C., Wieland, F., Ishibashi, S., Nave, K.A., 2005. High cholesterol level is essential for myelin membrane growth. Nature neuroscience. 8, 468-475.

Saint-Pol, J., Vandenhaute, E., Boucau, M.C., Candela, P., Dehouck, L., Cecchelli, R., Dehouck, M.P., Fenart, L., Gosselet, F., 2012. Brain pericytes ABCA1 expression mediates cholesterol efflux but not cellular amyloid-beta peptide accumulation. Journal of Alzheimer's disease : JAD. 30, 489-503.

Spady, D.K., Huettinger, M., Bilheimer, D.W., Dietschy, J.M., 1987. Role of receptor-independent low density lipoprotein transport in the maintenance of tissue cholesterol balance in the normal and WHHL rabbit. Journal of lipid research. 28, 32-41.

Stefulj, J., Panzenboeck, U., Becker, T., Hirschmugl, B., Schweinzer, C., Lang, I., Marsche, G., Sadjak, A., Lang, U., Desoye, G., Wadsack, C., 2009. Human endothelial cells of the placental barrier efficiently deliver cholesterol to the fetal circulation via ABCA1 and ABCG1. Circulation research. 104, 600-608.

Tai, L.M., Loughlin, A.J., Male, D.K., Romero, I.A., 2009a. P-glycoprotein and breast cancer resistance protein restrict apical-to-basolateral permeability of human brain endothelium to amyloid-beta. Journal of cerebral blood flow and metabolism : official journal of the International Society of Cerebral Blood Flow and Metabolism. 29, 1079-1083.

Tai, L.M., Reddy, P.S., Lopez-Ramirez, M.A., Davies, H.A., Male, D.K., Loughlin, A.J., Romero, I.A., 2009b. Polarized P-glycoprotein expression by the immortalised human brain endothelial cell line, hCMEC/D3, restricts apical-to-basolateral permeability to rhodamine 123. Brain research. 1292, 14-24.

Terwel, D., Steffensen, K.R., Verghese, P.B., Kummer, M.P., Gustafsson, J.A., Holtzman, D.M., Heneka, M.T., 2011. Critical role of astroglial apolipoprotein E and liver X receptor-alpha expression for microglial Abeta phagocytosis. The Journal of neuroscience : the official journal of the Society for Neuroscience. 31, 7049-7059.

van Assema, D.M., Lubberink, M., Boellaard, R., Schuit, R.C., Windhorst, A.D., Scheltens, P., Lammertsma, A.A., van Berckel, B.N., 2012. P-glycoprotein function at the blood-brain barrier: effects of age and gender. Molecular imaging and biology : MIB : the official publication of the Academy of Molecular Imaging. 14, 771-776.

Vaya, J., Schipper, H.M., 2007. Oxysterols, cholesterol homeostasis, and Alzheimer disease. Journal of neurochemistry. 102, 1727-1737.

Vogelgesang, S., Cascorbi, I., Schroeder, E., Pahnke, J., Kroemer, H.K., Siegmund, W., Kunert-Keil, C., Walker, L.C., Warzok, R.W., 2002. Deposition of Alzheimer's beta-amyloid is inversely correlated with P-glycoprotein expression in the brains of elderly non-demented humans. Pharmacogenetics. 12, 535-541.

Wahrle, S.E., Jiang, H., Parsadanian, M., Hartman, R.E., Bales, K.R., Paul, S.M., Holtzman, D.M., 2005. Deletion of Abca1 increases Abeta deposition in the PDAPP transgenic mouse model of Alzheimer disease. The Journal of biological chemistry. 280, 43236-43242.

Wahrle, S.E., Jiang, H., Parsadanian, M., Kim, J., Li, A., Knoten, A., Jain, S., Hirsch-Reinshagen, V., Wellington, C.L., Bales, K.R., Paul, S.M., Holtzman, D.M., 2008. Overexpression of ABCA1 reduces amyloid deposition in the PDAPP mouse model of Alzheimer disease. The Journal of clinical investigation. 118, 671-682.

Whitney, K.D., Watson, M.A., Collins, J.L., Benson, W.G., Stone, T.M., Numerick, M.J., Tippin, T.K., Wilson, J.G., Winegar, D.A., Kliewer, S.A., 2002. Regulation of cholesterol homeostasis by the liver X receptors in the central nervous system. Molecular endocrinology. 16, 1378-1385.

Wijesuriya, H.C., Bullock, J.Y., Faull, R.L., Hladky, S.B., Barrand, M.A., 2010. ABC efflux transporters in brain vasculature of Alzheimer's subjects. Brain research. 1358, 228-238.

Wilson, J.D., 1970. The measurement of the exchangeable pools of cholesterol in the baboon. The Journal of clinical investigation. 49, 655-665.

Wong, J., Quinn, C.M., Brown, A.J., 2006. SREBP-2 positively regulates transcription of the cholesterol efflux gene, ABCA1, by generating oxysterol ligands for LXR. The Biochemical journal. 400, 485-491.

Zelcer, N., Khanlou, N., Clare, R., Jiang, Q., Reed-Geaghan, E.G., Landreth, G.E., Vinters, H.V., Tontonoz, P., 2007. Attenuation of neuroinflammation and Alzheimer's disease pathology by liver x receptors. Proceedings of the National Academy of Sciences of the United States of America. 104, 10601-10606.

Zlokovic, B.V., 2008. The blood-brain barrier in health and chronic neurodegenerative disorders. Neuron. 57, 178-201.

Figure legends:

Table 1: List of the custom primers used for PCR analysis

From left to right: cDNA targeted for PCR amplification, species used for primer design, size (in bp) of the amplification products, forward (F) and reverse (R) primer sequences, cDNA accession numbers from the NCBI database.

Fig. 1: Brain capillary endothelial cell integrity after 24S-OH-chol, 27-OH-chol or T0901317 treatment. The cells were pre-treated for 24h with 0 µM, 0.01 µM, 0.1 µM, 1 µM or 10 µM of 24S-OH-chol, 27-OH-chol or T0901317. Cells were incubated for 1h (with a measurement every 20 min) with LY (an integrity marker for BCECs). Each point represents Pe LY, relative to the control (vehicle-treated) condition. n=6.

Fig. 2: 24S-OH-chol and 27-OH-chol induce ABCA1 expression in BCECs. Cells were pre-treated for 24h with DMSO (control) or different concentrations of 24S-OH-chol (abluminal treatment) and 27-OH-chol (luminal treatment). The LXR, ABCA1 and SCARB1 mRNAs (A) were analyzed using RT-PCR with the primers listed in Table 1. The ABCA1 and SCARB1 mRNAs were then quantified (B) using RT-qPCR. Each bar represents mRNA expression normalized against the housekeeping gene ß-actin. The results correspond to the mean ± SEM of two experiments pooled from three filters. Statistical analysis was performed using regular two-way ANOVA with Tukey's multiple comparisons tests. Protein expression levels for ABCA1 and SCARB1 (C) were assessed by immunoblotting of a membrane-enriched BCEC fraction, as described in the Experimental Procedure. T0901317 (10 µM) was used as a positive control for LXR pathway stimulation. SCARB1 was used as a membrane control, since its expression was not regulated by either of the oxysterols.

Fig. 3: LXR pathway activation by natural ligands leads to an increase in BCEC cholesterol release to ApoA-I or HDL particles. The BCECs were first labeled with [^{3}H]-cholesterol (0,5 µCi/mL) for 36h at 37°C and then equilibrated for 24h in DMEM/0.1% BSA at 37°C in either the absence of oxysterol (DMSO, control) or with 10 µM 24S-OH-chol or 10 µM 27-OH-chol. Cholesterol release was measured after 8h at 37°C in absence of any particles (BSA only) or in the presence of either ApoA-I (20 µg/mL) or HDL (50 µg/mL) particles. A represents cholesterol release from BCECs without oxysterol treatment (the control condition). The effect of oxysterol treatment is observed for the BSA-only condition (B), the ApoA-I condition (C) and the HDL condition (D). Each bar represents the mean ± SEM; n=12-18. NS: non-significant; *p<0.05; ***p<0.001 (in a one-way ANOVA, followed by Bonferroni's correction for multiple comparisons).

Fig. 4: Apical-to-basolateral transport (influx) of Aß peptides across BCECs is decreased by both oxysterols. The BCECs were pre-treated at 37°C for 24h with either DMSO (the control condition) or 10 µM 24S-OH-chol or 27-OH-chol. Cells were then incubated for 2h with $Aß_{1-40}$ or $Aß_{1-42}$ peptides or with [^{3}H]-inulin during gentle agitation at 37°C. Aß peptides were assayed with ELISAs and [^{3}H]-inulin was measured (in dpm) in a scintillation counter. Influx of Aß peptides or [^{3}H]-inulin was calculated first by dividing the amount measured in the basolateral (brain) compartment by the amount in the luminal (blood) compartment. These values were then divided by those obtained in the absence of cells. The final influx percentage was obtained by dividing each value by the corresponding Pe LY, in order to take account of any slight, post-treatment changes in monolayer integrity. Each bar represents the mean ± SEM; n=9-12. The percentages of apical-to-basolateral transport for $Aß_{1-40}$ and $Aß_{1-42}$ peptides were respectively 13.06 ± 0.85% and 12.98 ± 0.90%. NS: non-significant; **p<0.01; ***p<0.001 (in a one-way ANOVA, followed by Bonferroni's correction for multiple comparisons).

Fig. 5: ABCA1 is not involved in Aß$_{1-40}$ influx across BCECs. Cells were pre-treated with either DMSO (control), 24S-OH-chol (10 µM) or 27-OH-chol (10 µM) for 24H at 37°C. The cells were then incubated for 2h with FITC-Aß$_{1-40}$ or [^{3}H]-inulin during gentle agitation at 37°C in the presence or absence of 10 µM probucol. Aß$_{1-40}$ peptide or [^{3}H]-inulin influx was calculated by dividing the amount measured in the basolateral (brain) compartment by the amount in the luminal (blood) compartment. These values were then divided by those obtained in the absence of cells. The final influx percentage was obtained by dividing each value by the corresponding Pe [^{14}C]-sucrose, to take into account any slight post-treatment changes in monolayer integrity. Each bar represents the mean ± SEM; n=6. NS: non-significant; *p<0.05 (in a one-way ANOVA, followed by Bonferroni's correction for multiple comparisons).

Fig. 6: Effect of 24S-OH-chol and 27-OH-chol on transporters involved in Aß peptide influx across BCECs. Cells were pre-treated for 24h with DMSO (control), 24S-OH-chol (10 µM) or 27-OH-chol (10 µM). ABCB1, RAGE and ABCC1 and ABCG2 mRNA (A) were analyzed using RT-qPCR with the primers listed in Table 1. Each bar corresponds to the mean ± SEM of mRNA expression normalized against ß-actin. Statistical analysis was performed using regular two-way ANOVA with Tukey's multiple comparisons test. Protein expression of ABCB1 (B) were assessed by immunoblotting the membrane-enriched fraction of BCECs in the absence of treatment or treated for 24h with either 24S-OH-chol (10 µM), 27-OH-chol (10 µM) or T0901317 (10 µM). SCARB1 was used as a loading control. (C) ABCB1 activity after treatment with 10 µM 24S-OH-chol or 27-OH-chol was assessed by measuring the apical-to-basolateral transport of 50 nM [^{3}H]-colchicine for 2h. Each bar corresponds to the mean ± SEM; n=6. NS: non-significant; *p<0.05 (in a one-way ANOVA, followed by Bonferroni's correction for multiple comparisons).

Fig. 7: ABCB1 is involved in the oxysterol-mediated reduction of Aß peptide influx. (A) Accumulation of [^{3}H]-colchicine in BCECs and its influx (B) were measured after competition

experiments for 2h, with 60 nM ultrapure Aß$_{1-40}$ used as a competitive ABCB1 substrate. In (C), Aß peptide (12 nM) apical-to-basolateral transport was also investigated in presence of colchicine (240 nM) as a competitive inhibitor. Each bar corresponds to the mean ± SEM; n=6. *p<0.05; **p<0.01; ***p<0.001 (in a paired t-test).