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Perdeuteration of cholesterol for neutron scattering applications using recombinant *Pichia pastoris*

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ABSTRACT

Deuteration of biomolecules has a major impact on both quality and scope of neutron scattering experiments. Cholesterol is a major component of mammalian cells, where it plays a critical role in membrane permeability, rigidity and dynamics, and contributes to specific membrane structures such as lipid rafts. Cholesterol is the main cargo in low and high-density lipoprotein complexes (i.e. LDL, HDL) and is directly implicated in several pathogenic conditions such as coronary artery disease which leads to 17 million deaths annually. Neutron scattering studies on membranes or lipid-protein complexes exploiting contrast variation have been limited by the lack of availability of fully deuterated biomolecules and especially perdeuterated cholesterol. The availability of perdeuterated cholesterol provides a unique way of probing the structural and dynamical properties of the lipoprotein complexes that underly many of these disease conditions. Here we describe a procedure for in vivo production of perdeuterated recombinant cholesterol in lipid-engineered *Pichia pastoris* using flask and fed-batch fermenter cultures in deuterated minimal medium. Perdeuteration of the purified cholesterol was verified by mass spectrometry and its use in a neutron scattering study was demonstrated by neutron reflectometry measurements using the FIGARO instrument at the ILL.

1. Introduction

Neutron scattering studies offer unique insights to structural biology, especially when used in conjunction with selective and non-selective deuteration approaches (Haertlein et al., 2016). In neutron crystallography, hydrogen atoms are readily visible, yielding crucial information on protonation states of active site residues, charge transfer processes, and hydration (Howard et al., 2011; Cuypers et al., 2013a,b; Casadei et al., 2014; Haupt et al., 2014; Blakeley et al., 2015; Cuypers et al., 2016; Kwon et al., 2016). Small-angle neutron scattering (SANS) studies have the significant advantage that contrast variation methods can be used to distinguish and model different components of a macromolecular complex (Vijayakrishnan et al., 2010; Cuypers et al., 2013a,b; Ibrahim et al., 2017, Appoire et al., 2014, Edlich-Muth et al., 2015), and in a comparable way, neutron reflection studies allow strongly complementary information to be provided in the analysis of membranous interfaces (Grage et al., 2011; Fragneto, 2012). Furthermore, important aspects of macromolecular dynamics and its coupling to hydration water dynamics are provided by neutron incoherent scattering studies (Schirot et al., 2015). These insights result mainly from the fact that the scattering powers for neutrons of both hydrogen and deuterium are of comparable magnitude (although, crucially, their scattering lengths differ in sign) with those of the other atoms typically found in biological macromolecules - in strong contrast to the situation

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for X-rays where hydrogen/deuterium atoms scatter very weakly. This is of crucial importance given that about half of the atoms in biological molecules are hydrogen and that they are often highly significant to biological structure, dynamics, and function. Deuteration, the replacement of hydrogen atoms by the stable isotope deuterium, is a powerful method for the investigation of the structure and dynamics of biomolecules by means of NMR, Raman/infrared spectroscopy and neutron scattering. In the case of neutron analyses, the pronounced differences between the scattering lengths of hydrogen- and deuterium-containing molecules enable parts of molecular complexes to be highlighted by neutron scattering methods such as small-angle neutron scattering (SANS), neutron reflectometry (NR), or neutron crystallography (NMX).

In the case of structural work on lipid systems by SANS and NR as well as NMR (Stockton et al. (1977); Hagn et al. (2013), the deuteration of phospholipids and other membrane components can be heavily exploited (Maric et al., 2014; de Ghellinck et al., 2014; Gerelli et al., 2014; Foglia et al., 2011). However, chemical synthesis of unsaturated perdeuterated lipids and sterols still remains challenging. de Ghellinck et al. (2014) have demonstrated that perdeuterated phospholipids and sterols can be extracted from P. pastoris cells grown in deuterated minimal medium. These authors have also shown that while the phospholipid and ergosterol homeostasis is maintained in deuterated cultures, the fatty acid unsaturation level is modified; the production of perdeuterated unsaturated lipids is significantly enhanced when P. pastoris is grown at lower temperatures.

The multi-lamellar organization of fully deuterated lipid extracts of P. pastoris membranes has been shown using neutron diffraction (Gerelli et al., 2014). This study showed that at high relative humidity, non-deuterated and deuterated lipids are similar in their multi-lamellar organization. However, at low relative humidity, non-deuterated lipids are characterized by a larger single lamellar structure than observed for the deuterated samples. Furthermore, perdeuterated lipids have been used to characterize structural changes in the membrane of P. pastoris induced by the antifungal Amphotericin B (de Ghellinck et al., 2015).

In addition to the extraction of lipids from non-recombinant P. pastoris cultures, perdeuterated lipids have also been isolated from non-recombinant E. coli (Lind et al., 2015) and a recombinant E. coli expression system was successfully used for the biosynthesis of selectively deuterated phosphatidylcholine (PC) (Maric et al., 2014, Maric et al., 2015).

Chemically synthesised cholesterol molecules that are partially deuterated – such as cholesterol-D$_6$ (deuteration in ring) and cholesterol-D$_{25}$ (deuteration in tail) – are commercially available (Kessner et al., 2013). However, fully deuterated cholesterol (cholesterol-D$_{46}$) is difficult to synthesize chemically. Since high concentrations of deuterium are toxic for mammals and mammalian cell lines, perdeuterated d-cholesterol in neutron scattering studies is demonstrated by NR measurements from perdeuterated and unlabelled cholesterol in a synthetic lipid monolayer.

2. Materials and methods

2.1. Growth of recombinant P. pastoris in perdeuterated flask cultures

The cholesterol producing strain CBS7435 Δhis4 Δku70 Δerg5;ppGPAG-Zeoicin$^{\text{TM}}$-[DHCR7] Δerg6-pGAP-G418[DHCR24] (Hirz et al., 2013) was first grown in YPD medium (1% yeast extract, 2% peptone, 2% glucose, 300 mg/l geneticin sulfate and 100 mg/l Zeoicin$^{\text{TM}}$). This pre-culture was used to inoculate a culture in basal salts medium (BSM): 38.1 g/l H$_2$PO$_4$, 0.93 g/l MgSO$_4$, 4.13 g/l KOH, 40 g/l glycerol, 4 × 10$^{-5}$% biotin, 2 × 10$^{-6}$% histidine, 300 mg/l geneticin sulfate, 100 mg/l Zeoicin$^{\text{TM}}$ and 4.35 ml/l PTM1 trace salts. The composition of PTM1 trace salts was the following: cupric sulphate pentahydrate 6 g/l, sodium iodide 0.08 g/l, manganese sulphate monohydrate 3.0 g/l, sodium molybdate dihydrate 0.2 g/l, boric acid 0.02 g/l, cobalt chloride 0.5 g/l, zinc chloride 20.0 g/l, ferrous sulphate heptahydrate 65.0 g/l, biotin 0.2 g/l, sulphuric acid, 5 ml/l. The deuterated medium was prepared in the following way: 1 l of non-deuterated BSM without glycerol was flash evaporated, the powder was resuspended in 250 ml of 99.85% D$_2$O (Euriso-top) and flash evaporated again. This process was repeated twice to get rid of trace H$_2$O. Finally, the powder was resuspended in 11 D$_2$O (purity > 99.9%,) containing 40 g d$_8$-glycerol (Euriso-top).

900 ml of deuterated BSM were inoculated with 100 ml of a starting culture (OD$_{600}$ of about 20). The culture was incubated at 29 °C under shaking at 200 rpm and harvested after 10 days. A final OD$_{600}$ of about 25 g of Pichia cellular wet weight was obtained.

2.2. Growth of recombinant P. pastoris in perdeuterated fed-batch cultures

900 ml of deuterated BSM containing 10 g of d$_8$-glycerol was inoculated with 100 ml of preculture in a 31 fermenter (Labfors, Infors). During the batch and fed-batch phases the pH was adjusted to 6.0 by the addition of NaOD and the temperature was adjusted to 28 °C. The gas flow rate of sterile filtered air was 2.0 l/min. Stirring was adjusted to ensure a dissolved oxygen tension (DOT) of 30%. The initial OD$_{600}$ was 0.9. After 7 days the glycerol from the batch phase was consumed and the fed-batch phase was initiated by constant feeding of 30 g of d$_8$-glycerol over 12 days. The final OD$_{600}$ was 40 and 32 g of Pichia cellular wet weight was obtained.

2.3. Determination of sterol production

15 mg of deuterated or non-deuterated Pichia cell paste was transferred to Pyrex tubes and resuspended in 1 ml of 0.2% pyrogallol in MeOH and 400 µl of 60% KOH. Five µl of ergosterol (2 mg/ml) were added as internal standard (IS) and samples were saponified at 90 °C for 2 h. Sterols were extracted three times with n-heptane and dried under a stream of nitrogen. Dried extracts were dissolved in 10 µl of pyridine and derivatized with 10 µl of N′O-bis(trimethylsilyl)-tri-fluoracetamide. Samples were diluted with 50 µl of ethyl acetate and analyzed by gas chromatography–mass spectrometry (GC–MS) (Hirz et al., 2013).

2.4. Isolation and purification of perdeuterated cholesterol

Cholesterol was extracted from P. pastoris cell paste using an organic solvent extraction procedure. The cell paste was transferred into a 500 ml round-bottomed flask to which was added 65 g potassium hydroxide, 43 ml water, 200 ml methanol and 350 mg pyrogallol. This mixture was heated for 3 h under gentle reflux while keeping the stirring at a minimum to avoid foaming. After cooling to room temperature, insoluble materials were filtered off and the methanolic solution was extracted three times - each with 100 ml cyclohexane. The combined extracts were washed with 100 ml water, dried over sodium sulphate and concentrated under reduced pressure. The crude material
was treated with 10 ml ethyl acetate and passed through a short plug of silica gel to remove polar impurities and insoluble materials. The perdeuterated cholesterol was isolated in pure form using a ThermoFisher UltiMate 3000 binary semipreparative HPLC system equipped with a NUCLEODUR® 100-10 C18ec column (125 mm × 21 mm, 5 μm, Macherey-Nagel, Düren, Germany) and a VP 20/16 NUCLEODUR® C18 guard column. Using an isocratic mixture consisting of acetonitrile/methanol (9:1) at a flow rate of 20 ml/min at 30 °C using a detection wavelength of 210 nm, pure perdeuterated cholesterol was baseline-separated between 18.7 and 25.0 min. After removing the solvent under reduced pressure, pure perdeuterated cholesterol was obtained. HPLC analysis was conducted on an Agilent 1100, equipped with a DAD detector and a NUCLEODUR® Gravity column (150 mm × 3 mm, 3 μm, Macherey-Nagel, Düren, Germany) using an isocratic mixture of acetonitrile/methanol 9:1 at a flow rate of 0.70 ml/min at 30 °C.

2.5. Neutron reflectometry measurements

NR measurements were carried out using the FIGARO instrument at the Institut Laue-Langevin (ILL) (Campbell et al., 2011). Data were recorded using neutrons with wavelengths of 2–30 Å at incident angles of 0.62° and 3.8°. Data from three samples were recorded to illustrate the effect of replacing the h-cholesterol by d-cholesterol. A mixture of 1:4 cholesterol to dipalmitoylphosphatidylcholine (DPPC) by mole was prepared in each case as a chloroform solution. After spreading and compression to a surface pressure of 25 mN m⁻¹, the reflectivity was measured, which was normalized with respect to a measurement of pure D₂O. Three neutron contrasts were studied (i) h-cholesterol with d₄₂-DPPC on null reflecting water (NRW), (ii) h-cholesterol with d₄₂-DPPC on D₂O and (iii) d-cholesterol with h-DPPC on NRW, where NRW is a mixture of 8.1% v/v D₂O in H₂O that has zero scattering length density. Data fitting was carried out using a two layer model of tails and hydrated lipid head, with the cholesterol included in the tail layer. A two-layer model was applied where the one in contact with air comprising the acyl chains of the lipid together with cholesterol, and the one in contact with the water comprised solvated head groups. The number of chains was constrained to be equal to the number of head groups of the phospholipid in the layers and the surface excess of the lipid and of the cholesterol were constrained to be equal in the three measured contrasts. The scattering length density of the d-cholesterol was taken as 7.65 × 10⁻⁶ Å⁻², h-cholesterol as 0.21 × 10⁻⁶ Å⁻², the tails of d₄₂-DPPC to 8.15 × 10⁻⁶ Å⁻², the tails of h-DPPC to −0.43 × 10⁻⁶ Å⁻² and the heads of DPPC to 1.85 × 10⁻⁶ Å⁻². Note that the value of 8.15 × 10⁻⁶ Å⁻² was calculated for the lipid tails (C₃₀D₆₂) for the d₄₂-

DPPC using a volume for the tails corresponding to the liquid condensed phase (752 Å³, Small, 1984; Marsh, 2010). Recent papers have followed such an approach (Miccella et al., 2018; Sheridan et al., 2017; Braun et al., 2017). The d₄₂-DPPC was obtained from Avanti Polar lipids.

3. Results

3.1. Cell growth

The cholesterol producing P. pastoris strain was grown in unlabelled as well as in deuterated basal salt medium with d₈-glycerol as carbon source. A similar approach has been used by de Ghellinck et al. (2014) to produce perdeuterated non-recombinant yeast lipids. The growth behaviour of both the yeast lipid producing and the lipo-engineered cholesterol producing deuterated Pichia cultures showed a longer lag phase in D₂O containing medium by comparison with cultures grown in unlabelled media. This was even more pronounced for the cholesterol producing culture (4 vs. 2 days). The growth rate in the exponential phase was the same for the perdeuterated and the unlabelled cholesterol producing cultures and a final OD₆₀₀ of about 30 was obtained after 10 days. The non-recombinant yeast lipid producing cultures reached higher OD₆₀₀ values (about 80 vs. 30) with shorter doubling times – indicating the growth inhibiting effect of cholesterol production in P. pastoris grown in deuterated minimal media.

3.2. Sterol analysis – deuterated versus non-deuterated samples

Samples of the unlabelled (control) and perdeuterated cholesterol producing P. pastoris cell paste from flask cultures were analysed by gas chromatography-mass spectrometry (GC-MS) for their sterol composition as described above. Deuterated sterols show a shorter retention time (between 0.6 and 0.9 min) by comparison with their non-labelled analogues, in accordance with the published data on perdeuterated ergosterol produced in P. pastoris. Fig. 1 shows the gas chromatogram for the sterols produced by the strain (i.e. cholesterol, 7-dehydroxysterol (7-DHC) and zymosterol) under both non-deuterated (Fig. 1(a)), and deuterated (Fig. 1(b)) conditions. Tables 1a and 1b show the sterol compositions of both unlabelled and perdeuterated cholesterol-producing P. pastoris cell pastes. The largest observed mass was 503 Da as expected for trimethylsilylated perdeuterated cholesterol. In the deuterated samples, additional peaks occur, which relate to intermediates in the sterol biosynthetic pathway. These compounds may arise as a result of a lower activity of deuterated DHCR7 (7-dehydrocholesterol reductase), DHCR24 (24-dehydrocholesterol reductase) and ERG24 (C-14 sterol reductase) enzymes. The results indicate that cholesterol

Fig. 1. Gas chromatography-mass spectrometry (GC-MS) analysis showing sterol components in (a) unlabelled and (b) perdeuterated flask cultures. Each measurement was repeated 3 times (green, red and blue curves). The various peaks indicated are identified in Table 1. The main component is clearly cholesterol, but other sterols are identified such as 7-DHC and zymosterol. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
biosynthesis may not occur as efficiently in deuterated media as it does in unlabelled growth media; this is also reflected in the lower amounts of total sterols extracted from the deuterated cell paste (see Table 1b). The molecular structures of the main sterol species synthesized in P. pastoris under non-deuterated and deuterated conditions are shown in Fig. 2.

With a cholesterol content greater than 50% of total sterols and a total sterol production of about 6 mg per gram of Pichia wet weight (CWW), the sterol analysis clearly demonstrates the feasibility of producing significant amounts of perdeuterated cholesterol using recombinant P. pastoris (> 3 mg/g cellular wet weight).

3.3. The effect of flask/fermenter cultures on deuterated sterol production

Since deuterated media components such as D2O and d8-glycerol are costly, the possibility of using deuterated high-cell density cultures as a cost efficient alternative to flask cultures was investigated. A fed-batch culture was grown using deuterated minimal medium and a d8-glycerol feeding regime was followed. Full details of GC–MS analyses for the sterol content obtained using comparable flask and fermenter cultures are given in the Supplementary materials (Tables S1 and S2 respectively). The sterol composition and yields from perdeuterated flask cultures and perdeuterated fed-batch fermenter cultures are shown in Fig. 3.

In the fermenter cultures, there was an immediate gain associated with the volumetric yield of cell paste, typically by a factor at least 10 (Haertlein et al., 2016). Furthermore, despite the fact that the sterol yield (per gram of cell paste) was lower in fermenter cultures, the fraction of d-cholesterol in the sterol pool was significantly higher (Fig. 3(b)), and facilitated subsequent purification.

3.4. Purification and characterisation by mass spectrometry of perdeuterated cholesterol

Starting with 31 g of perdeuterated cell paste grown in a fed-batch culture, the organic solvent extraction yielded 263 mg crude extract after solvent removal under reduced pressure. Purification using reverse-phase HPLC yielded 42.6 mg of perdeuterated cholesterol. The retention time of the perdeuterated cholesterol was 9.19 min. Purity of the isolated material was found to be 98.5% by both HPLC (detection wavelength 210 nm, data not shown) and GC–MS (see Fig. 4).

### Table 1a
Sterol composition of unlabelled cholesterol-producing P. pastoris cell paste (mean values ± SD of triplicates are shown). Ergosterol was used as an internal standard (IS).

| Peak | Compound Description | Retention time (RT) (min) | Rel. RT | Peak area (μg) | % of total sterols |
|------|----------------------|---------------------------|---------|---------------|-------------------|
| 1    | Cholesterol          | 26.46                      | 1.000   | 2027067085    | 76.6 ± 0.4        | 100 ± 5          |
| 2    | 7-dehydrocholesterol (7-DHC) | 26.858                  | 1.015   | 400667110     | 15.1 ± 0.3        | 29 ± 2           |
| 3    | Zymosterol           | 27.161                     | 1.026   | 168125109     | 6.3 ± 0.1         | 8 ± 1            |
| 4    | Ergosterol (IS)      | 27.480                     | 1.038   | 202322149     | 10               |
| 5    | Cholest-7,24(25)-dieneol | 27.619                  | 1.044   | 15999901      | 0.5 ± 0.0         | 1 ± 0            |
| 6-8  | not identified       |                           | 39377438 |               | 1.5 ± 0.1        | 2 ± 0            |
| Total sterols |                   |                           | 8.4 ± 0.4 mg/g CWW |               |                   |

### Table 1b
Sterol composition of deuterated cholesterol-producing P. pastoris cell paste (mean values ± SD of triplicates are shown). Asterisks indicate the most likely sterol; identification is uncertain. Ergosterol was used as an internal standard (IS).

| Peak | Compound Description | Retention time (RT) (min) | Rel. RT | Major mass peaks (silylated) | Peak area (μg) | % of total sterols |
|------|----------------------|---------------------------|---------|------------------------------|---------------|-------------------|
| 1    | Cholesterol          | 25.626                     | 1.000   | 503, 488, 487, 411 (412), 393, 369, 133 | 89.7 ± 2.3 | 50 ± 1            |
| 2    | Cholest-5,8-dienol*  | 25.693                     | 1.003   | 499, 389, 362 | 32905514 | 1.9 ± 0.0        | 2 ± 0            |
| 3    | 7-Dehydrocholesterol | 26.262                     | 1.025   | 499, 407, 389, 362 | 475755029 | 7.3 ± 0.1        | 28 ± 5           |
| 4    | Zymosterol           | 26.472                     | 1.033   | 499, 480, 389, 233, 78 | 85384591 | 4.9 ± 0.1        | 5 ± 1            |
| 5    | Cholest-5,7,14,24(25)-tetradienol* | 26.874                  | 1.049   | 495, 403, 385, 358 | 221871342 | 12.7 ± 0.2       | 13 ± 3           |
| 6    | Cholest-7,24(25)-dienol | 26.995                     | 1.053   | 499, 480, 369 | 28264322 | 1.6 ± 0.0        | 2 ± 0            |
| 7    | Ergosterol (IS)      | 27.402                     | 1.069   | 468, 378, 363, 337 | 174234398 | 10               |
| 8    | not identified       | 27.961                     | 1.091   | 496 (497, 498), 480, 352, 73 | 12625260 | 0.7 ± 0.1        | 1 ± 0            |
| Total sterols |                   |                           | 6.0 ± 0.7 mg/g CWW |               |                   |                   |
Rheinländer and Mouritsen (2013). As the cholesterol is distributed over a considerable thickness (about the length of a cholesterol molecule), it is not possible to directly estimate an orientation or tilt of the molecules since the neutron reflection technique is sensitive only to the overall scattering length density distribution. Future diffraction studies of multiple bilayers that contain deuterated cholesterol could be helpful to give more information about the arrangement in three-dimensions.

4. Discussion

In neutron scattering experiments such as neutron reflection (NR) or small-angle neutron scattering (SANS), as well as in techniques such as NMR, deuterated membrane components provide important contrast when present in a mixture with other labelled or unlabelled lipids or when used to highlight membrane proteins. However, in common with perdeuterated proteins, perdeuterated cholesterol cannot be matched out in pure D₂O since its scattering length density is higher than that of D₂O. For protein labelling, protocols for match-out deuteration have been developed using *E. coli* or *P. pastoris* high cell-density cultures (Dunne et al., 2017) and protocols for match-out deuteration of cholesterol are currently undertaken in ILL’s Life Sciences Group. As noted previously, the availability of d-cholesterol can be broadly exploited in neutron scattering studies – particularly those relating to lipid systems of various types. This capability is likely to provide novel information on the structural arrangement of mammalian membranes. Examples include small-angle neutron scattering (SANS) of solutions or neutron reflection measurements of interfacial systems that are of direct relevance to membranes and membrane proteins, high density lipoprotein/low density lipoprotein (HDL/LDL) exchange phenomena related to atherosclerosis (Browning et al., 2017), properties of alveolar...
Fig. 4. Characterisation of purified perdeuterated cholesterol by gas chromatography-mass spectrometry (GC-MS) (a) showing the main peaks, including ergosterol as an internal standard (b) associated data extracted from GC-MS results (c) m/z plot of peak 1 as shown in 4(a).
surfaces, and lung surfactant systems (Thompson et al., 2010, 2013; Hemming et al., 2015) where it is desirable to identify the physical and chemical changes of specific components. Other applications are possible in neutron crystallographic studies of proteins that interact with cholesterol, and neutron incoherent scattering studies that focus on the dynamics of specific components of a membranous system. Besides its use for neutron scattering and possibly for NMR applications, perdeuterated cholesterol, in combination with stimulated Raman scattering (SRS), could be extremely valuable in imaging approaches for the study of intracellular cholesterol trafficking mechanisms (Lee et al., 2015). The combination of microscopic information with Raman spectroscopy provides a powerful molecular imaging method, and allows visualization at the diffraction limit of the laser light used, and biochemical characterization through associated spectral information. In order to distinguish the molecules of interest from other naturally occurring biomolecules spectroscopically, deuterium labels are needed. The introduction of carbon-deuterium (C–D) bonds into biomolecules or drug compounds by in vivo deurteration approaches (Haertlein et al., 2016) or by organic synthesis (Bergner et al., 2011) is a relatively non-invasive labelling approach that does not cause major changes to the chemical and physiological properties of the molecules. In Raman imaging, C-deuterated molecules exhibit characteristic vibrational signatures in the C–D stretching region around 2100–2300 cm−1, avoiding spectral interference with contributions from a complex biological environment. Raman microscopy, in combination with deuteration of fatty acids, has been used to contribute to the metabolism of such lipids in macrophages and to trace their subsequent storage patterns. The appearance of cytosolic lipid droplets is a hallmark of macrophage transformation into foam cells, a key step in early atherosclerosis (Matthäus et al., 2012). Perdeuterated cholesterol may also be used for highly efficient screening of drugs that target cholesterol metabolism.

Low level deuterium incorporation from heavy water into fatty acids and cholesterol is an attractive method for determining their fractional synthesis in humans (Leitch and Jones, 1993). Diraison et al. (1996) found that the maximum in vivo incorporation number of deuterium atoms into plasma cholesterol was 27 out of the 46 hydrogen atoms present in the molecule. Since in mammals the toxicity of deuterium becomes evident at about 20% replacement of body water by deuterium oxide (Katz et al., 1962), full deuterization of cholesterol requires a recombinant expression system that can cope with high deuterium concentrations.

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**Appendix A. Supplementary data**

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.chemphyslip.2018.01.006.

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