Differential response of the liver to bile acid treatment in a mouse model of Niemann-Pick disease type C [version 1; referees: 1 approved, 1 not approved]

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Abstract
Niemann-Pick disease type C (NPC) disease is a neurodegenerative lysosomal storage disease caused by mutations in the NPC1 or NPC2 genes. Liver disease is also a common feature of NPC that can present as cholestatic jaundice in the neonatal period. Liver enzymes can remain elevated above the normal range in some patients as they age.

We recently reported suppression of the P450 detoxification system in a mouse model of NPC disease and in post-mortem liver from NPC patients. As bile acids regulate the P450 system, we tested bile acid treatment using ursodeoxycholic acid (UDCA; 3α, 7β-dihydroxy-5β-cholanic acid), a hydrophilic bile acid, which is used to treat several cholestatic disorders. In this study, we compared UDCA treatment with the bile acid cholic acid (CA), and found unexpected hepatotoxicity in response to CA in Npc1 mice, but not to UDCA, suggesting that only UDCA should be used as an adjunctive therapy in NPC patients.

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Competing interests: FP is a co-founder and consultant to IntraBio.

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Introduction
Niemann-Pick disease type C (NPC) is a rare progressive neurodegenerative lysosomal disorder, which affects 1:100,000 live births\(^1\). In addition to the central nervous system, the liver also plays a role in this disease, either presenting in infancy as cholestatic jaundice or if these patients survive as elevated levels of liver enzymes suggestive of chronic liver dysfunction\(^2\).

We recently discovered that the hepatic cytochrome P450 system is suppressed in the Npc1 null mouse model (Npc1\(^{-/-}\)), in the feline model of NPC disease and in three NPC human liver samples (post-mortem)\(^3\). In NPC, the efflux of unesterified cholesterol from late endosomes/lysosomes to the endoplasmic reticulum (ER) is inhibited, leading to a shift in the spectrum of bile acids synthesized\(^4\), which suppresses gene expression of the P450 system\(^1\). Treatment of Npc1\(^{+/+}\) mice with ursodeoxycholic acid (UDCA; 3\(\alpha\), 7\(\beta\)-dihydroxy-5\(\beta\)-cholanic acid) rescued gene expression and P450 system enzyme activity\(^1\). In this study, we compared the effects of UDCA (soluble bile acid) and cholic acid (CA; hydrophobic bile acid) in the Npc1\(^{-/-}\) mouse and discovered hepatotoxic adverse effects on the liver in response to CA, but not to UDCA, suggesting UDCA is the bile acid of choice for clinical treatment of NPC patients.

Methods
Npc1 mouse model
Npc1\(^{-/-}\) mutant (BALB/cNctr-Npc1m1Ji, Npc1\(^{-/-}\)) and control (Npc1\(^{+/+}\)) were generated from heterozygote breeding. Genotyping was performed as described and mixed sex groups analysed. All mice were maintained under a standard 12h light/12h dark cycle with water and food available ad libitum. All procedures were performed according to the Animals (Scientific Procedures) Act 1986 under a project license (PPL No. 30/2923) from the UK Home Office. Care was taken to minimise suffering through euthanising the animals once liver enlargement was unambiguously detected by visual inspection (i.e. 3 weeks after initiation of treatment).

Bile acid supplementation
Npc1\(^{-/-}\) and Npc1\(^{+/+}\) mice (n = 9-17 per group) were fed either normal chow (RM1 maintenance diet; SDS, London, UK) or normal chow supplemented with UDCA (0.5\%, w/w, Sigma-Aldrich) or CA (0.5\%, w/w, Sigma-Aldrich) mixed with powdered diet. Treatment started at weaning (3 weeks of age) and mice were sacrificed at 6 weeks of age by intraperitoneal injection with an overdose of phenobarbital.

Histology
Animals were euthanized at 6 weeks of age and were trans-cardiac perfused with 4\% paraformaldehyde (PFA); samples of liver were fixed in 4\% PFA, dehydrated and processed to wax using standard procedures. The wax blocks were cut at 4-\(\mu\)m-thick sections, mounted on SuperFrost Plus slides (Thermo Scientific, Waltham, MA, USA) and subjected to hematoxylin and eosin (H&E) staining by standard methods. Images were taken on a Nikon eclipse E200 microscope with a Leica digital camera system.

Statistical analysis
Two-way ANOVA with Tukey’s multiple comparison was used to analyse all sets of data comparing Npc1\(^{-/-}\) and Npc1\(^{+/+}\) mice. Statistical analysis was performed with GraphPad Prism version 6.

Results
We investigated the effects of UDCA and CA treatment in the Npc1\(^{-/-}\) mouse model, relative to wild type (Npc1\(^{+/+}\)) mice. Mice were fed on a diet containing either 0.5\% UDCA or CA from weaning (3 weeks of age). After 3 weeks of treatment there was gross abdominal distention observed in all CA treated mice, irrespective of genotype, but the degree of distension appeared greater in the Npc1\(^{-/-}\) mice. No distension of the abdomen was observed in UDCA treated Npc1\(^{-/-}\) and Npc1\(^{+/+}\) mice. On necropsy, it was apparent that the abdominal distension in the CA treated group was due to liver enlargement (Figures 1A and B), and there was a statistically significant increase of liver weight in the Npc1\(^{-/-}\) and Npc1\(^{+/+}\) relative to UDCA and untreated mice (p<0.0001). No significant changes in liver volume were observed in the UDCA treated mice irrespective of genotype (Figures 1A and B). Npc1\(^{-/-}\) mice have a lower body weight than wild type control mice\(^2\), and so the ratio of liver/body weight was calculated (Figure 1C). The liver enlargement in response to CA as a function of body weight was greater in the Npc1\(^{-/-}\) than in the Npc1\(^{+/+}\) mice. The liver-to-body weight ratios were the same in untreated Npc1\(^{+/+}\) and Npc1\(^{-/-}\) mice and in the UDCA treated mice, irrespective of genotype. Histopathological analysis of liver (Figure 1D) showed the typical vacuolated appearance of the liver characteristic of Npc1\(^{-/-}\) mice relative to wild type mice. UDCA treatment had no impact on the histopathology of wild type and Npc1\(^{+/+}\) mice, whereas CA treatment led to hepatocyte enlargement and a foamy appearance indicative of lipid accumulation that often displaced the nucleus to the pole of the cell.

Discussion
NPC disease cells display a complex cellular pathophysiology, including impaired movement of LDL-derived cholesterol from late endosomes/lysosomes to the ER\(^5\) and the generation of non-enzymatically generated oxysterols\(^6\). As a consequence, the bile acid profile is altered in NPC disease\(^7\), and this change in bile acid composition leads to a secondary suppression of the P450 system family, as they are bile acid regulated\(^8\). The expression of the P450 system genes could be rescued in Npc1\(^{-/-}\) mice by administering the bile acid UDCA, leading to clinical benefit\(^1\). In another study, UDCA was trialed in four clinical NPC cases and liver function improved in patients with elevated liver enzymes at baseline\(^9\).

In this study, we investigated whether CA, another bile acid used in routine clinical practice for bile acid disorders\(^10\) would also be beneficial. Therefore, we treated Npc1\(^{-/-}\) mice with UDCA or CA to investigate this further. However, three weeks into the treatment the CA mice presented with gross abdominal distension so they were culled to determine the basis for this adverse finding. It was clear on gross necropsy that the livers were significantly enlarged in CA
treated wild type and Npc1+ mice, and when we adjusted for body weight it was apparent that the liver enlargement was greater in the Npc1-/+ mice relative to Npc1-/- mice. Looking at the adjusted liver weight with the body weight, CA treated wild type mice had increased liver volume of 165.5% when compared with untreated wild type, whereas the Npc1-/+ mice showed 179.1% increase in liver volume when compared with the untreated Npc1-/+ mice.

Histopathology revealed lipid laden distended hepatocytes in the CA treated Npc1-/+ mice. These data suggest CA is more hepatotoxic in mice than UDCA, consistent with the differential chemical properties of these two bile acids. The NPC1 protein, deficient in most cases of NPC disease, is a conserved member of a protein family, the RND permeases. In bacterial systems they serve to efflux multiple classes of substrates across the periplasmic space, allowing bacteria to thrive in hostile environments. CA’s hydrophobic chemistry suggest it may be a potential substrate for NPC1, so it may itself be stored in the late endocytic system in NPC1 deficient cells and adversely affect the acidic compartment of the cell leading to further lipid storage. This hypothesis merits further investigation.

When four NPC1 patients were treated with UDCA, benefit was observed based on improved liver function. Very interestingly, one patient was switched from UDCA to CA and their clinical status declined but was recovered on switching back to UDCA, and this has striking parallels with this study in mice. Taken together, these data strongly support the use of UDCA as an adjunctive therapy.

Figure 1. Effects of cholic acid (CA) and ursodeoxycholic acid (UDCA) on 6-week old Npc1 mouse liver. Npc1+/+ and Npc1-/- mice were treated with 0.5% UDCA or CA as admix with powdered diet from three weeks of age. The mice were euthanized at 6 weeks of age when the Npc1-/- exhibited abdominal distension due to liver enlargement. (A) Liver weights of Npc1 mice untreated, treated with 0.5% UDCA and 0.5% CA; average body weight ± SD of the mice are shown beneath each bar for each group. (B) Gross morphology of the liver. (C) Ratio of liver weight to mouse body weight. Data are presented as mean ± SEM, n = 9-17 animals per group/genotype, **** p < 0.0001 calculated using two-way Anova with Tukey’s multiple comparison test. (D) H&E histopathology of liver sections, bars represent 10μm for high magnification inset panels and 5μm the main panel.
to treat residual liver disease in NPC patients, but CA is contraindicated due to acute hepatotoxicity that is most pronounced in an NPC1 deficient background.

**Data availability**

Raw data have been uploaded to the online data repository OSF:

http://dx.doi.org/10.17605/OSF.IO/5A2F9

**Grant information**

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**References**

Open Peer Review

Current Referee Status: ✔️ ✗

Version 1

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Although the rationale for this study is clearly explained, the relevance of the data obtained to the management of liver disease in NPC1 deficiency is questionable for reasons relating mainly but not fully to the methodological approaches that were used. The following points warrant close consideration.

1. Although the dietary level of BA supplementation employed is in line with what is often used in animal models, the changes in bile acid pool and composition that ensue when the amount of dietary BA is set at 0.5% w/w are beyond extreme and result in shifts in cholesterol metabolism at multiple levels that would never occur in humans taking approved doses of any specific BA. At a dietary level of 0.5%, the dose used in these studies was the equivalent of around 800 mg/day/kg bw which far exceeds what most human subjects taking oral BAs consume during a 24 hour period. When BA pool size and composition change in extreme ways there are invariably marked shifts in intestinal cholesterol absorption and this in turn has a major impact on the amount of chylomicron cholesterol reaching the liver from the small intestine (and therefore in the amounts of unesterified chol—UC—becoming subsequently trapped in the late /E/L compartment when NPC1 or NPC2 are mutated). There is an excellent study by Wang et al. (2003) showing how a range of BAs including UDCA and CA (added to the diet at a level of 0.5%) affect intestinal cholesterol absorption in a normal mouse model (see Fig 3 in particular). While a BA pool enriched with UDCA drives down intestinal cholesterol absorption, the opposite effect occurs with CA. Another example illustrating how BA pool size and composition are major determinants of cholesterol absorption is seen in a study by Schwarz et al. (1998)—see solid histograms for WT mice given hyodeoxycholic acid vs cholic acid in Fig 5. Anyone who knows about the properties of CA and who also understands the biochemical consequences of NPC1 deficiency would view the effects of CA described in the current report as “totally predictable” especially given the massive dose that was fed to the mice. It would have been better to use two different doses of UDCA.

2. The bottom line in all this is that the differing impacts on liver “health” of UDCA vs CA supplementation in NPC1/-/- mice shown here are likely fully explainable on the basis of major differences in the amount of intestinally derived cholesterol trapped in the livers of the KOs given these two particular BAs. Although no data are presented for hepatic total chol concs (mg/g), one might predict from other studies in the NPC1 mouse model that a several fold greater level of unesterified chol (UC) would be seen in the livers of the CA supplemented mice vs those given UDCA. There is no question that it is the cytotoxic effects of the entrapped UC in all organs, especially the liver, that has the most damaging impact in NPC1 (or NPC2) dysfunction.
While it is recognized that this is a preliminary report, it is essential that more informed conclusions be reached about what UDCA supplementation might conceivably be doing in the human NPC1-deficient liver. To achieve this, definitely the liver UC and EC concentrations in these mice, along with their plasma/serum ALT and AST levels should be measured. Such measurements are needed if these mouse model experiments are to provide any credible guide as to how UDCA supplementation in human NPC1 patients might be acting. The benefit most likely has nothing to do with putative improvement in functionality of the P450 detoxification system.

3. As it is currently written, this report will likely attract criticism because of its lack of acknowledgement of significant published work documenting the beneficial impact of other types of treatment modalities for improving liver function in NPC1 deficiency, mostly based on in vivo experiments using primarily the NPC1−/− mouse model. In 2007 Beltroy et al. showed that the cholesterol absorption inhibitor, ezetimibe, given in the diet from the time of weaning, at doses far below those of other treatments (ie 20 or less mg/day/kg bw), reduced hepatomegaly and lowered liver cholesterol content (nearly all UC) by almost 50% (Fig 4). The benefit of ezetimibe in this disease is largely in the liver. After that, a series of definitive publications from a number of labs attesting the potency of subcutaneously administered 2HPBCD in diminishing hepatic UC content and markedly improving liver function tests (and increasing lifespan) in NPC1 mouse models helped establish this agent as one of great potential for managing multisystem disease in NPC1 deficiency.

Although this preliminary report will be of interest to many working in the field of NPCD management, it should not generate the impression that UDCA has a clear potential to become a treatment modality for liver disease in NPCD patients. Citation of the earlier papers noted above documenting the decisive benefits of ezetimibe and 2HPBCD in NPC1 mice will allow readers to gain a better perspective of what these initial data in the UDCA treated NPC1 mouse model are telling us.

References

Is the work clearly and accurately presented and does it cite the current literature? 
No

Is the study design appropriate and is the work technically sound? 
No
1. Are sufficient details of methods and analysis provided to allow replication by others?
   Yes

2. If applicable, is the statistical analysis and its interpretation appropriate?
   Partly

3. Are all the source data underlying the results available to ensure full reproducibility?
   Yes

4. Are the conclusions drawn adequately supported by the results?
   No

**Competing Interests:** No competing interests were disclosed.

**Referee Expertise:** Control of cholesterol metabolism in the liver and other major organs in lysosomal cholesterol storage diseases resulting from mutations in the LIPA, NPC1 or NPC2 genes

I have read this submission. I believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

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The article by Nicoli et al. entitled “Differential response of the liver to bile acid treatment in a mouse model of Niemann-Pick disease type C” reports the effect of bile acid treatment on the liver pathology in a mouse model of NPC disease. Although, NPC is primarily considered a neurodegenerative disease, defects in systemic organs including liver have been seen in many patients. The authors previously reported suppression of cytochrome P450 detoxification system in the liver of NPC mice and limited set of human samples. Cytochrome P450 enzymes are also involved in the synthesis of bile acids from cholesterol. The authors hypothesize that exogenously supplied bile acid could potentially alleviate liver disease in NPC. In the study, they used a mouse model to test the hypothesis. The study comes from a lab that holds expertise in NPC and actively advancing the NPC research since last many years. The study was elegantly designed, results are clearly presented and the manuscript is well written and discussed. The conclusions drawn are based on the results reported. The manuscript is suitable to be published in the current form, however if the authors addressed the following comments, it would further enhance the quality of this publication.

1. In NPC, many systemic organs including liver show elevated inflammation. One would expect decreased cholesterol burden after UDCA treatment would reduce infiltration of inflammatory cells such as macrophages and neutrophils. It would be nice to have results of a couple of inflammatory marker analysis included in the liver of UDCA treated mice. In addition, it would also be interesting to see how liver enzymes (such as ALT & AST) in mice respond to UDCA treatment.
2. In a separate manuscript (submitted for peer review, ref #10), the authors report the clinical data of four NPC patients treated with bile acid. The results presented in ref#10 show significant improvement in the liver function in UDCA-treated patients. The submission is a useful extension of this study and shows how findings in an animal model translate to clinics. I would have preferred if both manuscripts were combined. This would allow readers to have a better understanding of the effect of bile acid treatment in NPC in the mouse model as well as in clinics without going through two separate publications. Nevertheless, this manuscript on its own reports interesting findings.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.