Vulnerability of *DHCR7*$^{+/-}$ mutation carriers to aripiprazole and trazodone exposure

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Running Title: antipsychotics effects on cholesterol biosynthesis

Abbreviations: DHCR7: 7-dehydrocholesterol reductase; 7DHC: 7-dehydrocholesterol; ARI: aripiprazole; SLOS: Smith-Lemli-Opitz syndrome; 8DHC: 8-dehydrocholesterol; Des: desmosterol; Lan: lanosterol; Chol: cholesterol; DHCR24: 24-dehydrocholesterol reductase; EBP: emopamil binding protein; BHT: butylated hydroxytoluene; TPP: triphenylphosphine; PTAD: 4-Phenyl-1,2,4-triazoline-3,5-dione; APCI: atmospheric pressure chemical ionization; SRM: selected reaction monitoring; TRZ: trazodone; UPLC/MS: ultra-high pressure liquid chromatography-mass spectrometry; HPLC/UV: high pressure liquid chromatography-ultraviolet spectroscopy; MeOH: methanol; TIC: total ion current; HF: human fibroblasts.

Abstract

Smith-Lemli-Opitz syndrome is a recessive disorder caused by mutations in 7-dehyrocholesterol reductase (DHCR7) with a heterozygous carrier frequency of 1-3%. A defective DHCR7 causes accumulation of 7-DHC, which is a highly oxidizable and toxic compound. Recent studies suggest that several antipsychotics, including the highly-prescribed pharmaceuticals aripiprazole (ARI) and trazodone (TRZ), increase 7-DHC levels *in vitro* and in humans. Our investigation was designed to compare the effects of ARI and TRZ on cholesterol synthesis in fibroblasts from *DHCR7*$^{+/-}$ human carriers and controls. Six matched pairs of fibroblasts were treated and their sterol profile analyzed by LC-MS. Significantly, upon treatment with ARI and TRZ the total accumulation of 7-DHC was higher in *DHCR7*-heterozygous cells than in control fibroblasts. The same set of experiments was repeated in the presence of ^{13}C-lanosterol to determine residual cholesterol synthesis revealing that ARI and TRZ strongly inhibit *de novo* cholesterol biosynthesis. The results suggest that *DHCR7*-carriers have increased vulnerability to both ARI and TRZ exposure compared to controls. Thus, the 1 to 3% of the population who are DHCR7-carriers may be more likely to sustain deleterious health consequences on exposure to compounds like ARI and TRZ that increase levels of 7-DHC, especially during brain development.

Keywords: 7-dehydrocholesterol, aripiprazole, trazodone, fibroblasts, carriers, antipsychotics

INTRODUCTION

Smith-Lemli-Opitz syndrome, SLOS, is an autosomal recessive disorder caused by mutations of *DHCR7*, the gene that encodes 7-dehydrocholesterol reductase, the enzyme that converts 7-dehydrocholesterol (7-DHC) to cholesterol (Chol), see **Figure 1** for selected sterols in the Chol biosynthesis pathway.(1-8) There are nearly two hundred mutations in *DHCR7* reported to date, most of them within a coding region of 1425 open reading frame bases.(9-13) Furthermore, a recent analysis of exome sequencing databases led to the conclusion that the carrier frequency of pathogenic *DHCR7* mutations is 1 to 3% in the human population.(14) Given the number of known *DHCR7* mutations, most SLOS cases are compound heterozygous with different inherited maternal and paternal alleles. The incidence of clinical SLOS cases has been estimated to be between 1 in 10,000 to 70,000.(8) Mildly affected patients may have minimal symptoms and severely affected individuals may suffer pre-term demise, making ascertainment of clinical incidence problematic.(15)

While there are many studies on SLOS patients to date, the health status of heterozygous *DHCR7*$^{+/-}$ mutation carriers has been less extensively investigated. *DHCR7*$^{+/-}$ carriers are reported to have marginally higher plasma levels of 7-DHC than DHCR7$^{+/+}$ controls(16) and animal studies also argue that a single mutant copy of *Dhcr7* might affect homeostasis. 7-DHC levels are increased in *Dhcr7*$^{+/-}$ heterozygous mice, with the highest levels of 7-DHC found in the nervous system.(17) Furthermore, the *Dhcr7*$^{+/-}$ mutant mice show increased aggressiveness and elevated head-twitch response to a challenge with a 5-HT2A agonist.(18)

Circulating blood levels of 7-DHC in control populations are very low, less than 0.5 ng/uL, but recent studies have shown that psychiatric patients taking either aripiprazole (ARI) or trazodone (TRZ) have greatly increased plasma levels of 7-DHC.(19) In addition, a clinical

report also noted that 15 of 22 individuals who have been treated with either or both ARI and TRZ were misdiagnosed as SLOS patients based upon their 7-DHC plasma levels.(20) Furthermore, an unbiased cell culture study of pharmacologically active compounds also identified over 5% of 700 7-DHC-elevating compounds.(21) Finally, a recent comprehensive review of the effect of DHCR7 inhibitors on human health revealed that *in utero* exposure to DHCR7 inhibitors during the first trimester of pregnancy produces outcomes similar to those of known teratogens.(22)

Exposure to DHCR7 inhibitors such as ARI and TRZ may have a significant impact on fetal health and development, especially since their use is widespread: ARI is a highly-prescribed drug in the US, often used during pregnancy. The fact that the carrier frequency of *DHCR7*$^{+/-}$ mutations is high and significant exposures to drugs that affect this enzyme have been reported raises the question of whether there are groups of genetically distinct individuals who show increased vulnerability to exposure to DHCR7 inhibitors. Therefore, we monitored the response of *DHCR7*$^{+/+}$ (WT) and *DHCR7*$^{+/-}$ (HET) fibroblasts to two compounds that strongly inhibit the enzymatic transformation of 7-DHC to cholesterol, ARI and TRZ. Our results suggest that exposure to ARI and TRZ may be deleterious to individuals who are heterozygous carriers of a *DHCR7* mutation. We note again that ARI and TRZ are only two of some thirty-five known pharmaceuticals that affect levels of 7-DHC in cell culture, so the studies reported here may point to a problem of broad scope.

MATERIALS AND METHODS

Materials. Unless otherwise noted, all chemicals were purchased from Sigma-Aldrich Co (St. Louis, MO). HPLC grade solvents were purchased from Thermo Fisher Scientific Inc (Waltham, MA). All cell culture reagents were from Mediatech (Manassas, VA), Life

Technologies (Grand Island, NY), and Greiner Bio-One GmBH (Monroe, NC). All sterol standards, natural and isotopically labeled, used in this study are available from Kerafast, Inc. (Boston MA). Delipidated FBS was prepared as previously described and LC-MS was used to confirm that it does not have a detectable cholesterol level.(23)

Control and DHCR7-heterozygous fibroblasts genotyping*:* Molecular genetic analysis of the *DHCR7* gene was performed as previously described.(10) Briefly, after amplification of exons 3–9 (coding region) and exon/intron boundaries, bidirectional amplicon sequencing was performed using the BigDye Terminator v3.1 Cycle Sequencing kit (Applied Biosystems, Foster City, CA) according to the manufacturer's instructions. Samples were run on the ABI PRISM 310 Genetic Analyzer and data were analyzed using the Sequencing Analysis Software (Applied Biosystems, Foster City, CA). Reference sequence: NM_001360.2. Sequence analysis of *DHCR7* gene detects approximately 96% of pathogenic variants. Variant classification was performed according to Richards, et al.(24) In control samples CTR 1-4, exclusively benign variants were detected (minor allele frequency, MAF>5%, rs1044482, rs1790334, rs4316537, rs949177, rs736894, rs760241, rs909217). In control sample VUS-1 a synonymous/silent variant (MAF<0.01, rs13972775, c1341C>T, p.Asp447Asp) was detected in heterozygous form. In control sample VUS-2 a non-synonymous variant (MAF<0.01, rs72954276, c1012G>A (p.Val338Met) was detected in heterozygous form. With the evidence that we have, both variants were classified as a variant of uncertain significance (VUS).

All *DHCR7*$^{+/-}$ fibroblasts were obtained from parents of biochemically and genetically confirmed SLOS patients. The affected patients were: A) compound heterozygous c.[1097G>T];(964–1G>C): typical/classical phenotype (severity score 25 calculated according to Kelley and Hennekam (3)); B) compound heterozygous c.[1295A>G];[1328G>A]:mild (severity

score 15); C) compound heterozygous c.[730G>A];[976G>T]: typical/classical phenotype (severity score 40). In general, genotype/phenotype correlations are very weak in SLOS as most of the patients are compound heterozygous and there are only a low number of patients with the same genotype. Except for common mutations (~60%) many are unique or infrequent. Patients with the same genotype can have different phenotypes even intra familiar variability has been observed. A detailed genotypic description is presented in **Figure 2.** All described mutations are classified as pathogenic or likely pathogenic DHCR7 variants.

Cell cultures, sterol extraction and LC-MS/MS measurements, and statistical analyses were described in details in previous publications and they are in Supplementary Information.

RESULTS

The biosynthesis of cholesterol is a complex process that proceeds from the isoprenoid squalene through its epoxide to the tetracyclic sterol precursor lanosterol.(25) The post-lanosterol biosynthetic pathway to cholesterol consists of two parallel sequences, the Bloch and Kandutsch-Russell pathways shown in **Figure 1**. 7-Dehydrocholesterol reductase (DHCR7) is an NADPH-dependent enzyme(25) that reduces the Δ7-8 double bond of 7-DHC or the corresponding Bloch pathway sterol, 7-dehydrodesmosterol (7-DHD). A cell with DHCR7 having reduced functional activity leads to elevated cellular levels of 7-DHC or 7-DHD and if a functioning DHCR24 is present in the cell, levels of 7-DHC can be used as the principal biomarker to identify a compromised DHCR7. Monitoring levels of 7-DHC of cells in culture therefore provides a straightforward method to determine if DHCR7 activity is affected, either by a genetic mutation or by an enzyme inhibitor.(17, 26-30)

DHCR7 genetic variants

A number of different cell types have been used to assess the effects of small molecules on cholesterol biosynthesis. While we have successfully used *DHCR7*-deficient and wild-type Neuro2a cells(17, 21, 31) in the past for screening purposes, human patient-derived dermal fibroblasts represent an ideal model for follow-up experiments.(32) As a result, for the purpose of assessing the effect of small molecule DHCR7 inhibitors on a cell having only one allele bearing a *DHCR7* mutation, we chose human fibroblasts from six $DHCR7^{+/-}$ heterozygous (HET) parents of a SLOS offspring and six age and sex matched donors from a control (CTR) population. These HET fibroblast cell lines were heterozygous for pathogenic or likely pathogenic *DHCR7* variants previously reported in SLOS patients. Details on these $DHCR7^{+/-}$ mutations are presented in **Figure 2**. Subsequent to our analysis of the effect of ARI and TRZ on all twelve CTR and HET fibroblasts, we carried out genomic analysis of *DHCR7* of the control HFs as well, and in two of the six CTR cell lines we identified *DHCR7* variations of uncertain significance (VUS). One of these variants, VUS#1, is a synonymous/silent codon variant that could potentially affect splicing (*Mutation Taster, www.mutationtaster.org; Human Splicing Finder, http://www.umd.be/HSF3 HSF.html*) while the other, VUS#2 (Val338Met) is at a residue that is not evolutionary conserved. Importantly, neither of these variants has previously been associated with SLOS. Because of the outcomes of these *post-hoc* sequence analyses, the mutant-control comparisons of sterol biosynthesis were performed and are reported in six $DHCR7^{+/-}$ and four $DHCR7^{+/+}$ HF lines harboring no sequence variants. Data for the two VUS cells with *DHCR7* variants of uncertain significance are reported separately in Supplementary Information.

Analysis of Fibroblast Sterols

Cellular levels of endogenous sterols in cultured fibroblasts were determined by methods

previously reported for 7-DHC, desmosterol (Des), lanosterol (Lan) and Chol.(21) Measurement of cholesterol synthesis in the presence of ARI or TRZ is confounded by the large amounts of preexisting cholesterol that persists, even while cholesterol synthesis occurs in drug-treated fibroblasts. Nevertheless, ARI and TRZ have been shown to have a significant effect on sterol homeostasis as measured by absolute levels of 7-DHC and Chol, by the ratio of these two sterols 7-DHC/Chol, or by the fractional Chol/(7-DHC+Chol) determined in a cell.(21)

To isolate the effect of a drug on biosynthesis, methods making use of isotopically labeled sterol biosynthetic precursors have been developed to measure *de novo* or "residual cholesterol synthesis" (**RCS**) during a treatment regimen.(27, 33) For the ARI and TRZ studies reported here, **RCS** was assessed by the use of an isotopically labeled lanosterol (Lan), 3^{13}C-Lan, bearing ^{13}C at carbons C25, C26 and C27 of the sterol, which was added to fibroblasts during incubations with ARI or TRZ, see **Figure 3**. **RCS**, defined in **Figure 3**, reports the levels of 3^{13}C -7-DHC and 3^{13}C-Chol formed during fibroblast exposures to drug. In practice, we report both the ratio of 3^{13}C-7-DHC / 3^{13}C-Chol after exposure of fibroblasts to ARI and TRZ and the calculated **RCS** based on those isotopic sterol values. The structures of 3^{13}C-Lan, 3^{13}C-7-DHC and 3^{13}C-Chol are presented in **Figure 3**.

Sterol levels can be measured in as few as 5000 fibroblasts using the PTAD procedures described in Supporting Information and in previous publications.(21) At baseline, we found significant differences for sterol levels between HET and CTR fibroblasts for cholesterol, 7-DHC and desmosterol while levels of 8-DHC and lanosterol did not meet the criteria for difference in these cells, see **Table 1**. Modestly elevated 7-DHC and reduced cholesterol levels have previously been reported in fibroblasts from obligate SLOS heterozygotes compared to control cells but desmosterol levels were not reported in those studies.(16, 27)

There is a growing body of evidence suggesting that DHCR7 is part of a larger complex that includes another sterol reductase, DHCR24.(34) It is of some interest that small molecules that increase levels of 7-DHC in cell culture do not cause a comparable increase in desmosterol. If anything, changes in levels of 7-DHC and desmosterol tend to occur in opposite directions. The difference between desmosterol levels is significant between *DHCR7*$^{+/-}$ fibroblasts and controls, see Table 1, but the effect of ARI and TRZ on desmosterol levels is not observed in fibroblasts, see Supplemental Information.

Human DHCR7*$^{+/-}$ *fibroblasts are preferentially affected by exposures to* DHCR7 *inhibitors

Subsequently, *DHCR7*$^{+/-}$ and CTR dermal human fibroblasts were treated with three different concentrations of either ARI or TRZ and cellular sterols were measured after six days in culture. **Figure 4** summarizes the results for six *DHCR7*$^{+/-}$ HET and the four sequence-verified CTR fibroblasts. For all three concentrations tested, the treatments with ARI and TRZ resulted in significantly elevated cellular levels of 7-DHC in both HET and CTR cells (**Figures 4A** and **4C**). ARI appears to be more potent than TRZ in increasing 7-DHC in both control and HET human fibroblasts. In addition, while 7-DHC levels were increased in response to both treatments, cholesterol levels were significantly decreased in the same HET and CTR fibroblast cultures (**Figure 4B** and **4D**). Importantly, the decrease in the percentage of Chol present in the sterol profile is more pronounced in *DHCR7*$^{+/-}$ HET than in CTR fibroblasts (**Figure 4E** and **4F**), suggesting an increased vulnerability of *DHCR7*$^{+/-}$ HET to both tested compounds. Thus, ARI caused a decrease in the fraction of Chol present in the cells from nearly 1.0 (DMSO control) to 0.73 at 50 nM ARI, while this fraction dropped to only 0.85 for the CTR fibroblasts. The levels of desmosterol and lanosterol were not significantly affected by treatment and are reported in Supporting Information. The data for all individual twelve cell lines (including the cells

harboring *DHCR7* variants of unknown significance) are also reported in Supporting Information.

ARI and TRZ alter de novo cholesterol biosynthesis

To test if ARI and TRZ act by affecting the stability of cholesterol precursors, or *de novo* lipid biosynthesis, we exposed CTR and HET fibroblasts to 500 nM of 3^{13}C-Lan at the same time that the cells were exposed to 10, 25 and 50 nM ARI or TRZ. This permitted assessment of the levels of newly synthetized cholesterol and its precursors by measuring the incorporation of isotopic label. After six days in culture, lipids were extracted and cellular levels of 3^{13}C-sterols were determined by the same methods used to analyze endogenous cellular sterols, with the exception that the masses monitored in the LC-MS protocol were 3 *m/z* units higher than the natural *m/z* values for Des, 7-DHC and Chol. Isotopically labeled sterols made up approximately 10% of the total sterols present in the cells after six days of incubation. The HET and CTR cell lines showed a different biosynthesis profile as a function of ARI or TRZ concentration: for example, at 50 nM ARI the ratio 3^{13}C-7-DHC/3^{13}C-Chol found in HET cells was 3:1 while the same ratio was only1.2:1 in CTR fibroblasts (see **Figure 5A**). Indeed, the 3^{13}C-7-DHC to 3^{13}C-Chol ratio determined was found to be significantly higher for HET fibroblasts than the same ratio found in CTR cells at every concentration of ARI and TRZ studied.

ARI and TRZ induced de novo synthesized 3^{13}C-7-DHC and 3^{13}C-Chol depends on genotype

The drug exposure-dependent residual cholesterol synthesis (**RCS**) is presented in **Figure 5C** and **D**. In the absence of drug, CTR cells synthesized cholesterol more efficiently than HET cells, as evidenced by the higher **RCS** (~0.97-0.98 for CTR cells and ~0.93-0.95 for HET cells). Furthermore, the effect of ARI and TRZ on HET cells was larger than the effect of these drugs on CTR fibroblasts. Thus, on treatment with 10 nM ARI, the **RCS** for HET cells dropped to

0.65 while the **RCS** for CTR cells under the same treatment was 0.89. At 50 nM ARI, **RCS** drops to 0.24 for HET fibroblasts, a value lower than reported for the **RCS** in some SLOS fibroblasts.(33) Chol biosynthesis was further impaired by 100 nM ARI, but inspection of the cells showed evidence of toxicity at these concentrations and our studies were thus limited to concentrations of 50 nM and below. The effects of ARI on **RCS** were almost twice the magnitude of TRZ for exposure to the same drug concentration, as seen by comparison of **Figures 5C** and **4D**.

The data for the two fibroblasts with single-copy *DHCR7* variants of uncertain significance (VUS) are of some interest since these mutations have not previously been associated with SLOS, see **Supplemental Figure S1** in Supporting Information. VUS#1, a cell line with a variant that potentially could disrupt *DHCR7* splicing (c.[1341C>T];[=]), responds to treatment with ARI in a manner that parallels that of HET rather than CTR cells. However, based on the response to TRZ, VUS#1 is more similar to CTR cells than HETs. In contrast, the VUS#2 cell line responds to treatment with both ARI and TRZ like other CTR cells, suggesting that this genetic variant is unlikely to be pathogenic in the human population. This highlights our limited understanding of how the wide range of single-copy *DHCR7* mutations affect function, and underscores their potential importance on the health of heterozygous individuals.

DISCUSSION

The findings of our study can be summarized in several main points: 1) ARI and TRZ treatments significantly elevate 7-DHC levels and alter the 7-DHC/Chol ratio in human fibroblasts regardless of genotype. 2) Response of HFs to both ARI and TRZ is dose-dependent. 3) $DHCR7^{+/+}$ CTR and $DHCR7^{+/-}$ HET HFs respond differentially to both ARI and TRZ treatments in the human therapeutic range, with HET samples exhibiting a stronger response

with elevated 7-DHC levels and an altered 7-DHC/Chol ratio. Importantly, this is not a "higher starting point, higher end point" finding. 4) Isotope experiments revealed that both ARI and TRZ act through altering *de novo* biosynthesis, rather than affecting the stability/turnover of cholesterol and its precursors. The effect of ARI and TRZ on "residual cholesterol synthesis" is more pronounced for HET samples than on CTR cells. 5) The primary action of ARI and TRZ at the concentrations studied is at the step of 7-DHC→Chol in the biosynthesis, as the rest of the cholesterol precursor profile is unaffected by these treatments.

Our studies were performed on human fibroblasts, yet these studies have clear **implications for brain function**: the cholesterol biosynthesis pathway is conserved across different tissue types. Although the human brain only accounts for about 2% of total body weight, it contains as much as 25% of cholesterol and cholesterol derivatives.(35, 36) Importantly, cholesterol is synthesized by neurons: DHCR7, the last enzyme in the cholesterol biosynthesis pathway, is strongly expressed at high levels in neurons throughout the brain.(37, 38) The function of cholesterol in the CNS goes beyond being a structural component of cellular membranes and lipid rafts: it is required for synapse and dendrite formation, axonal guidance, and serves as a precursor for various biosynthetic pathways. Thus, the impact of ARI and TRZ on human dermal fibroblasts and brain tissue is likely to be very similar at a level of biochemistry, and primarily consist of 7-DHC elevation.

It is well established that **7-DHC elevation in cells is a deleterious event**. 7-DHC is a highly reactive lipid molecule,(39) and it undergoes spontaneous free radical peroxidation, producing over a dozen oxidation products (i.e., oxysterols) *in vitro* and *in vivo*.(40, 41) These 7-DHC-derived oxysterols exert cytotoxicity, reduce cell proliferation, induce premature cell differentiation and affect Hedgehog signal transduction.(42) They also lead to a host of gene

expression changes that are consistent across the human/mouse and *in vivo/in vitro* models.(40, 43-45)

There is evidence in human and mouse that **single-allele *DHCR7*** mutations lead to elevation of 7-DHC levels.(17, 27) Yet, our understanding of single copy mutations of *DHCR7* on health remains mostly unknown to date. With nearly two hundred different mutations in the human population, and with a carrier rate of approximately 1-3% in the US (and 4% in Utah and 3% in European ancestry),(10, 22) their importance on health is potentially quite significant. A previous publication reports a correlation between birth weight and fetal DHCR7 gene/SNP combinations and cholesterol metabolism genes and preterm delivery.(46) This view is also supported by animal experiments: assessment of behavioral differences between $Dhcr7^{+/-}$ heterozygous and wild-type mice revealed that mutant mice were significantly more likely to win on the social dominance test, and showed impairments in the response to 5-HT2A agonists.(18)

Developmental defects are found in ~3-5% of liveborn children.(47) It is estimated that pharmaceuticals account for approximately 1% of teratogenic effects.(48) Our results **do not necessarily indicate that ARI and TRZ are unsafe** for use in the general population. These drugs have been extensively tested, and have proven themselves as very effective medications that help patients live more productive lives. Aripiprazole, marketed under the name of Abilify® was the most prescribed medication in the US in 2013 (http://www.drugs.com/stats/abilify), with ~2.5 million units sold quarterly, exceeding yearly sales of 6.9 billion dollars. However, it is noteworthy that the FDA classified both ARI and TRZ as "Class C" compounds, stating: *"Risk not ruled out: Animal reproduction studies have shown an adverse effect on the fetus and there are no adequate and well-controlled studies in humans, but potential benefits may warrant use of the drug in pregnant women despite potential risks"*. A recent report suggested that intrauterine

exposure of rats to ARI may not be safe for developing fetuses and offspring health, and that ARI exposure might significantly contribute to gastrointestinal congenital malformations.(49) Human studies also highlighted the interaction between ARI/TRZ and cholesterol biosynthesis: ARI and TRZ treatment lead to elevated 7-DHC levels in the patient population, leading to a false-positive diagnosis of SLOS in patients treated with these two compounds.(20)

It should be noted that 7-DHC elevation **may not be limited to ARI and TRZ exposure**. Previous screening of the NIH Clinical Collection (NCC), consisting of 727 small molecules that have a history of use in human clinical trials identified 30 compounds that significantly increased 7-DHC levels in Neuro2a cells.(21) Many of these compounds (in addition to ARI and TRZ) have been classified as class C compounds by the FDA, and are widely used in medicine, even during pregnancy. These data suggest that exposure to heterocyclic cationic amphiphiles, dependent on timing, duration and concentration, could be harmful to the 1-3% of the human population who carry a single-copy of a *DHCR7* missense mutation.

In summary, our approach is directly relevant to developing personalized medicine approaches, as understanding pharmacogenomics interactions are essential to ensure positive treatment outcomes. For example, genotyping patients for their ability to metabolize warfarin could avoid 85,000 serious bleeding events, 17,000 strokes, and $1 billion in annual costs of care in the US alone.(50) We argue that in the era of precision medicine, potential differences in response to compounds that disrupt the cholesterol biosynthesis pathway must be respected, especially as their effect may be defined by both genetic makeup and life events at the same time. Thus, in the context of our studies, we suggest that treatment with 7-DHC elevating substances (such as ARI and TRZ) raise issues for the population that carries single-allele disruptions of the *DHCR7* gene. In addition, we propose that the vulnerability to 7-DHC-

elevating compounds is perhaps most pronounced during pregnancy and brain development, especially when both the mother and the fetus carry a single, potentially disruptive *DHCR7* allele. This complex *drug exposure*maternal genotype*fetus genotype*developmental time point* interaction may elevate 7-DHC levels into a toxic range comparable to that seen in SLOS patients, resulting in deleterious developmental outcomes.

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Footnotes to text: The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Table 1

Table 1. Sterol levels in cultured control and *DHCR7* heterozygous human fibroblasts

nmol/1x10^6 cells	**Cholesterol**	**7DHC**	**8DHC**	**Desmosterol**	**Lanosterol**
DHCR7$^{+/+}$	59.6±2.8	0.34±0.08	0.81±0.07	1.14±0.08	0.16±0.01
DHCR7$^{+/-}$	48.3±0.9	0.86±0.08	1.03±0.07	0.75±0.07	0.14±0.01
p	5.16E-05	4.03E-06	=0.054	0.00041	=0.478

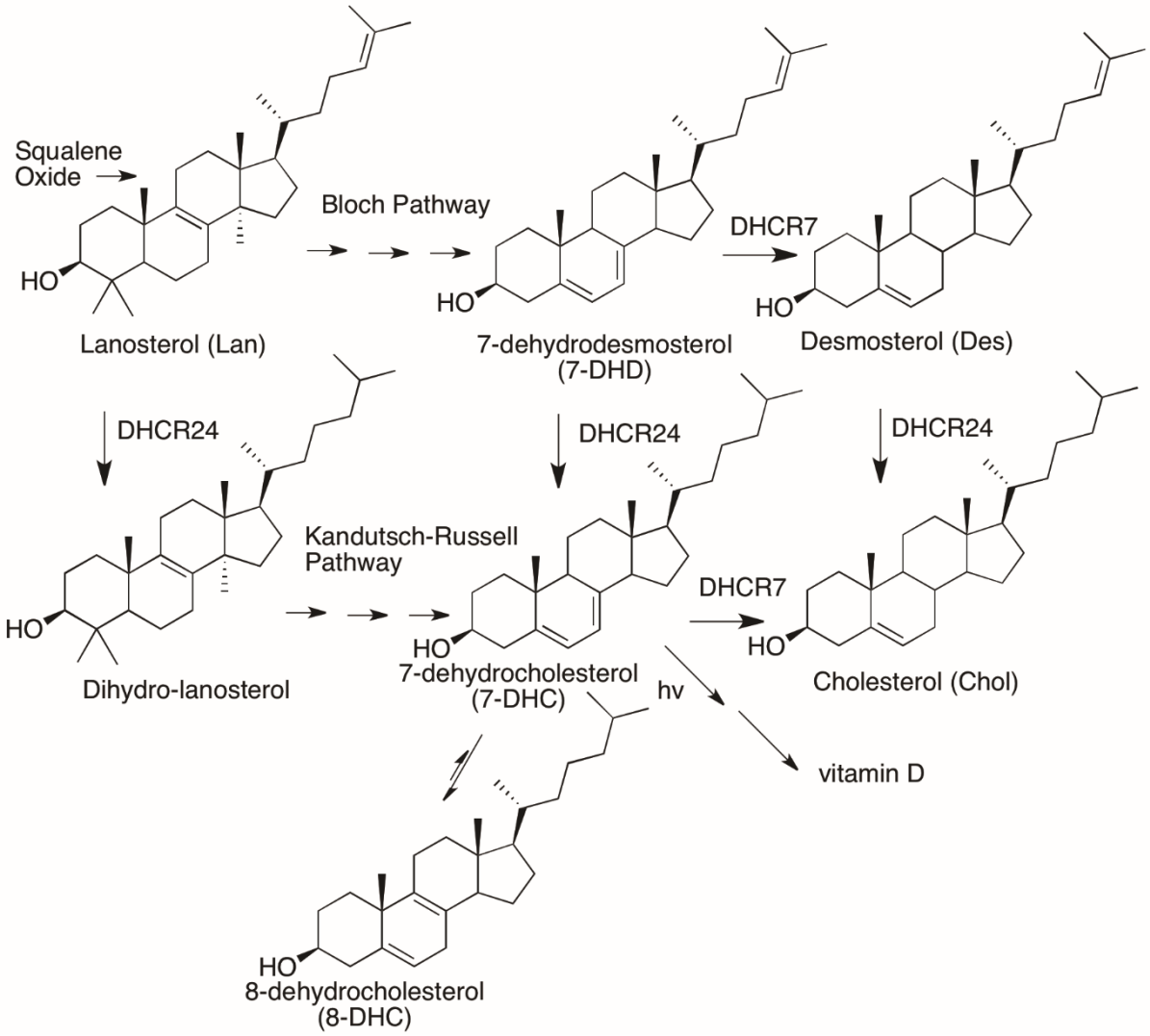

Figure 1. Chemical structures of selected sterols in the cholesterol biosynthesis pathway.

ID (gender, age)	Genotype	Effect on protein level/splicing	Variant Classicfication	Reference (Primary Report)
Het-A (M,46)	c.[1097G>T;[=]	p.[Gly366Val];[=]	likely pathogenic	Szabo et al, 2010, PMID: 19365639
Het-B (F,44)	c.[964-1G>C;[=]	splice disruption	pathogenic	Fitzky et. al., 1998, PMID: 9653161
Het-C (M,34)	c.[1295A>G];[=]	p.[Tyr432Cys];[=]	likely pathogenic	Witsch-Baumgartner et al, 2001,PMID: 11175299
Het-D (F,34)	c.[1328G>A];[=]	p.[Arg443His];[=]	likely pathogenic	Witsch-Baumgartner et al, 2001,PMID: 11175299
Het-E (M,43)	c.[730G>A];[=]	p.[Gly244Arg];[=]	likely pathogenic	Waterham et al, 2012, PMID: 23042628
Het-F (F,37)	c.[976G>T];[=]	p.[Val326Leu];[=]	pathogenic	Fitzky et. al., 1998, PMID: 9653161
Con-B (F,44)	---			
Con-C (M,37)	---			
Con-D (F,27)	---			
Con-F (F,40)	---			
VUS-1 (M,48)	c.[1012G>A];[=]	p.[Val338Met];[=]	uncertain	This report; dbSNP: 72954276
VUS-2 (M,38)	c.[1341C>T];[=]	splice disruption?	uncertain	This report; dbSNP: 139721775

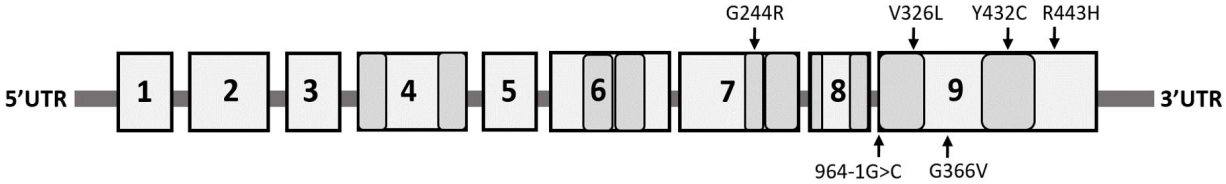

Figure 2. Genotyping results of human fibroblasts. Parents of children with SLOS clinical phenotypes Het-A to F were gender and age-matched with control fibroblasts. Mutations in Het A-F are classified as pathogenic or likely pathogenic *DHCR7* variants. Genotyping of control HF revealed two variants of unknown significance that were not previously described in SLOS clinical cases.

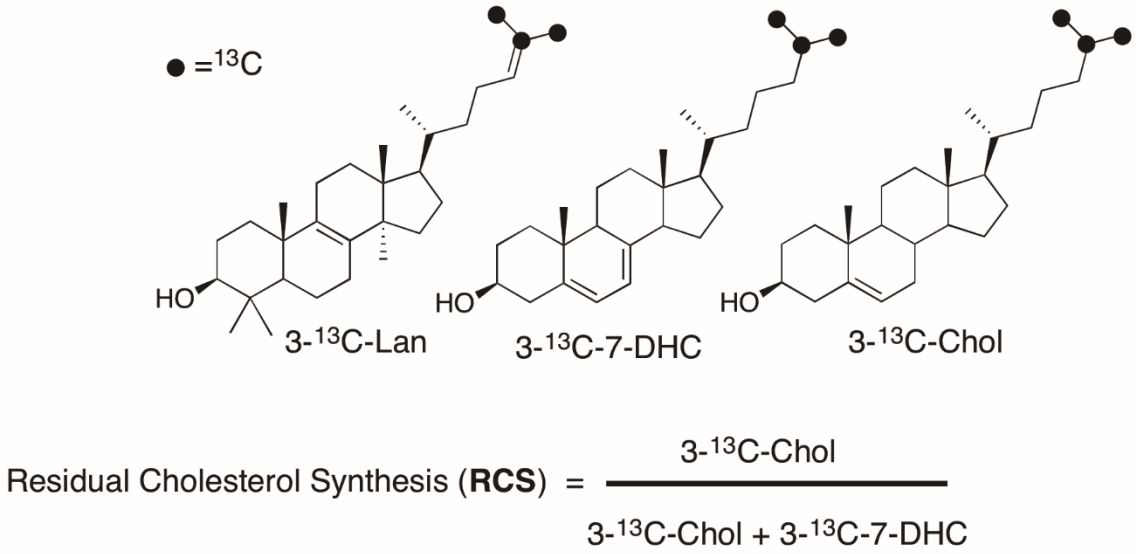

Figure 3. Chemical structures of 3-^{13}C-labeled sterols and the formula used to calculate residual cholesterol synthesis (**RCS**).

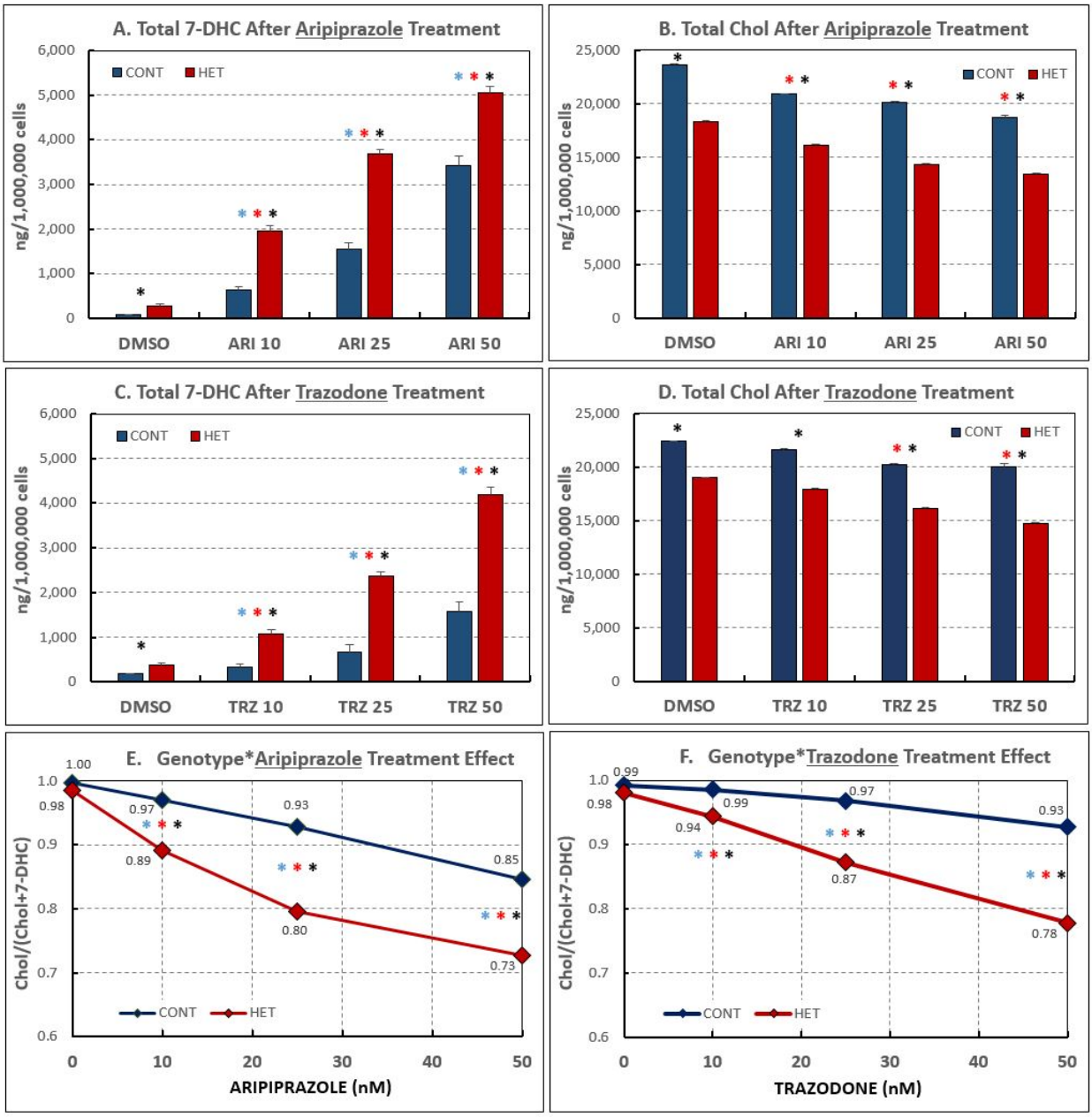

Figure 4. Human *DHCR7*-HET fibroblasts are preferentially affected by exposures to DHCR7 inhibitors. Summary of 7-DHC and cholesterol levels in HF in response to various concentrations of aripiprazole (ARI) and trazodone (TRZ). A and C graphs show average 7-DHC levels in ng/million cells for six *DHCR7*-HET and four CTR HF. B and D graphs show average cholesterol levels in ng/million cells for six *DHCR7*-HET and four CTR HF. E and F are graphic representation of increasing amount of 7-DHC and decreasing amount of cholesterol in response to increasing amount of ARI or TRZ as measured by the ratio [Chol]/[Chol +7-DHC] Stars above bars show p values <0.01. Blue is the difference among control samples, red is the difference among heterozygous samples and black is the difference between control and

heterozygous samples. Supplemental Tables S1A and S1B contain companion data for Figure 4 showing mean, STDEV and SEM as well as p values.

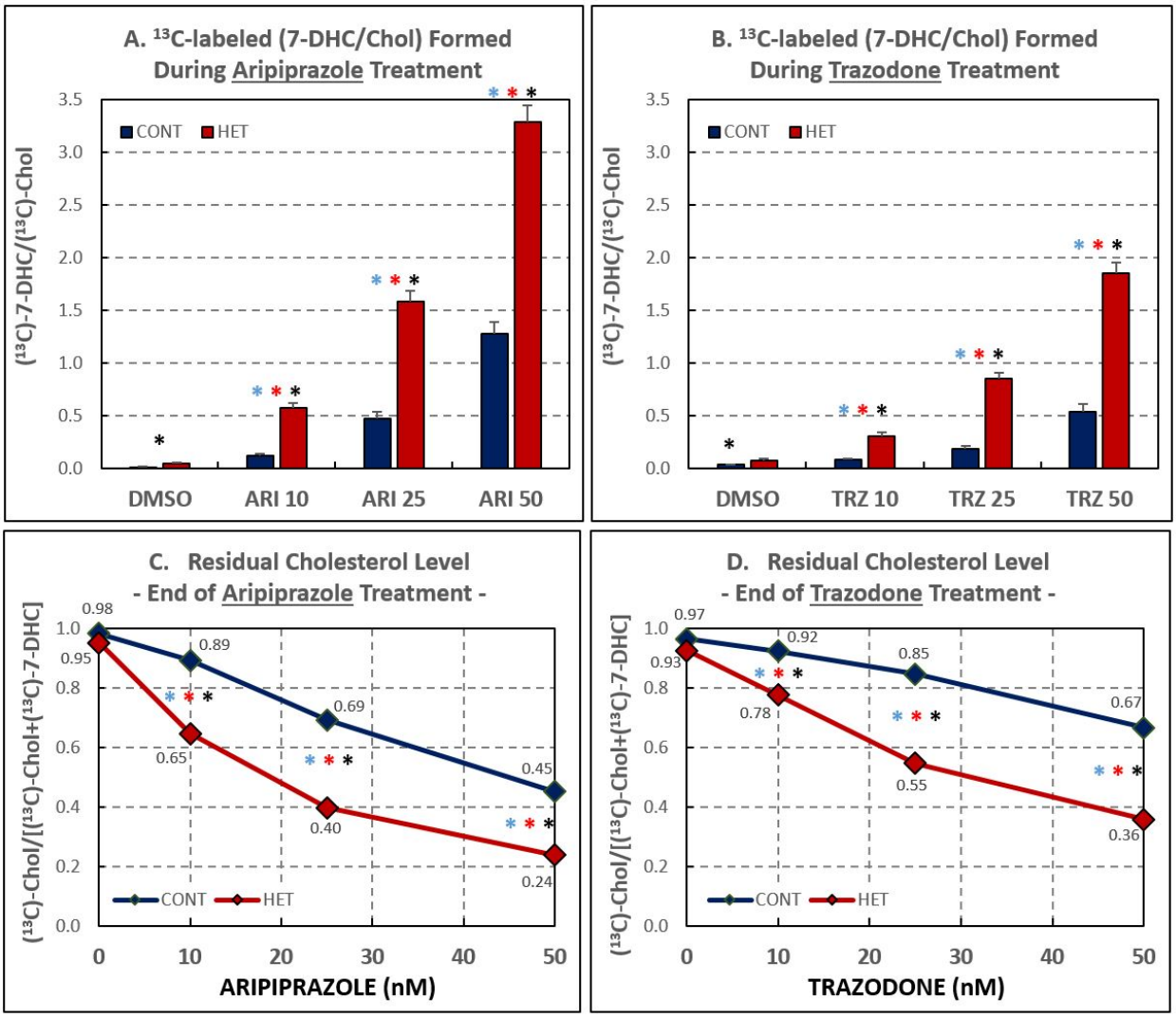

Figure 5. Aripiprazole (ARI) or trazodone (TRZ) alter residual cholesterol biosynthesis. Six *DHCR7*-HET and four CTR HF were cultured in the presence of 500 nM 3^{13}C-Lan and different concentrations of ARI or TRZ. A and B graphs show the ratio of 3^{13}C-derived 7-DHC/3^{13}C-derived cholesterol, the 7-DHC is normalized to cholesterol. Stars above bars show p values <0.01. Blue is the difference among control samples, red is the difference among heterozygous samples and black is the difference between control and heterozygous samples. C and D show calculated residual cholesterol synthesis (**RCS**) in response to ARI or TRZ. Supplemental Tables S2A and S2B contain companion data for Figure 5 showing mean, STDEV and SEM as well as p values.