Abnormal Newborn Screens and Acylcarnitines in HIV-exposed and ARV-exposed Infants

Brian Kirmse, MD, Charlotte V. Hobbs, MD,† Inga Peter, PhD,‡ Bryan LaPlante, BS,§ Michele Caggana, ScD,§ Karen Kloke, MS,¶ Kimiyo Raymond, MD,¶ Marshall Summar, MD,* and William Borkowsky, MD‖*

Background: Antiretroviral drugs (ARV), specifically nucleoside analogs, are toxic to mitochondrial oxidative phosphorylation. Other metabolic pathways, such as fatty acid oxidation, organic acid metabolism and amino acid metabolism, are dependent on normal oxidative phosphorylation but remain unexamined as potential points of ARV toxicity.

Methods: We analyzed newborn screening data from New York and compared proportions of abnormal newborn metabolic screens in HIV antibody screen–positive and HIV screen–negative neonates. Subsequently, we compared acylcarnitine levels in ARV-exposed (n = 16) and ARV-unexposed (n = 14) HIV-exposed infants to assess for dysfunctional fatty and organic acid metabolism.

Results: The rate of abnormal newborn metabolic screens in HIV screen–positive infants was higher than that in the general population (2.2% versus 1.2%; $P = 0.00025$), most of which were for disorders of mitochondria-related metabolism. Abnormal acylcarnitine levels occurred more frequently in ARV-exposed compared with ARV-unexposed infants (43% versus 0%; $P = 0.02$).

Conclusions: A higher proportion of positive metabolic screens in HIV screen–positive neonates suggests that HIV or ARV exposure is associated with dysfunctional intermediary metabolism in newborns. Abnormal acylcarnitine levels were more frequent in ARV-exposed infants, suggesting that ARV may perturb normal fatty acid oxidation in some infants. Studies designed to validate and determine the clinical significance of these findings are warranted.

Key Words: HIV/AIDS, mitochondrial toxicity, newborn screening, metabolism

(*Pediatr Infect Dis J* 2013;32: 146–150)

Although antiretroviral drugs (ARV) are generally considered safe, they have been associated with mitochondrial toxicity in experimental and clinical studies,[1–4] and they have been linked to a wide range of clinical problems in children, including lactic acidosis, acute liver injury and myopathy.[5] The focus of mitochondrial toxicity investigations has been on the effects of nucleoside and nucleotide reverse-transcriptase inhibitor (NRTI) effects on oxidative phosphorylation (OXPHOS) through inhibition of the mitochondrial polymerase gamma.[6] In children, there is evidence that exposure to NRTIs in utero and in the newborn period causes lactic acidosis and abnormal mitochondria number and function,[7] and that dysfunction may persist after the exposure ends, potentially affecting growth and development.[8] Despite the fact that many pathways of intermediary metabolism (including fatty acid oxidation, organic acid metabolism and amino acid metabolism) are dependent on normal OXPHOS and that dysfunction of these steps can lead to clinical problems, such as those seen in ARV-exposed patients,[9,10] there is little known in humans about whether these pathways are points of ARV toxicity.

In the past decade, the number of metabolic disorders (or inborn errors of metabolism) included in newborn screening panels in the United States has increased dramatically because of the implementation of tandem mass spectrometry (MS/MS).[11] MS/MS is a sensitive and specific platform for the quantitation of the substrates and products of intermediary metabolism, including acylcarnitines and amino acids, abnormal levels of which indicate dysfunctional fatty acid oxidation and organic acid metabolism or amino acid metabolism, respectively.[12] Levels of acylcarnitines and amino acids can also be abnormal in patients with inherited mitochondrial diseases representing secondary dysfunction in metabolic pathways biochemically related to OXPHOS.[13]

We hypothesized that HIV-exposed and ARV-exposed children would have disruption of metabolic pathways that are normally dependant on functional OXPHOS, leading to a greater incidence of positive newborn metabolic screens compared with the general newborn population. We then specifically assessed fatty acid oxidation and organic acid metabolism in a group of HIV-exposed and ARV-exposed infants and a group of HIV-exposed and ARV-unexposed infants by measuring acylcarnitine levels in plasma.

METHODS

New York State Newborn Screening

The state of New York screens all neonates for HIV (by enzyme-linked immunosorbent assay) and metabolic disorders (by MS/MS). We analyzed New York state newborn screens for metabolic disorders in HIV screen–positive and HIV screen–negative infants. In collaboration with New York State Newborn Screening Program, we retrospectively reviewed newborn screening data from between 2005 and 2008, inclusive. We defined an abnormal newborn metabolic screen as any result above the laboratory's cutoff value that necessitated collection of a repeat sample or that prompted referral to a state-designated specialty treatment center. For the period of this study, we assumed that virtually all infants exposed to HIV in New York state also would have been exposed to antiretroviral drugs (including peripartum and postnatal AZT)

Accepted for publication May 01, 2012.

From the *Genetics & Metabolism, Children's National Medical Center, Washington, DC; †National Institutes of Health (NIAID), Laboratory of Malaria Immunology and Vaccinology, Rockville, MD; ‡Department of Genetics and Genomic Sciences, Mount Sinai School of Medicine, New York, NY; §New York State Department of Health/Wadsworth Center, Albany, NY; ¶Biochemical Genetics Laboratory, Mayo Medical Laboratories, Rochester, MN; and ‖Division of Infectious Disease and Immunology, Department of Pediatrics, New York University/Bellevue Medical Center, New York, NY.

BK and CVH contributed equally to this work.

Supported by National Institutes of Health T32 Grant, New York State (Empire Clinical Research Investigator Program) and Thrasher Research Fund. The authors have no other funding or conflicts of interest to disclose.

Address for correspondence: Brian Kirmse, MD, Genetics & Metabolism, Children's National Medical Center, 111 Michigan Avenue, NW, Suite 4800, Washington, DC 20016. E-mail: bkirmse@cnmc.org.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's website (www.pidj.com).

ISSN: 0891-3668/13/3202-0146
DOI: 10.1097/INF.0b013e31827030a6

in the perinatal period because New York state mandates first-trimester HIV screening in all pregnant women and recommends third-trimester screening. Individual exposures vary depending on maternal ARV regimen and adherence.

Acylcarnitine Profiles in ARV-exposed and ARV-unexposed Infants

To explore the relationship between abnormal intermediary metabolism and ARV exposure, we compared acylcarnitine levels from a random selection of HIV-exposed and ARV-exposed infants with those in HIV-exposed and ARV-unexposed infants. Samples were from New York University's Department of Pediatrics, Division of Immunology and Infectious Diseases and were stored at −80°C since collection. Plasma samples collected at or near birth as well as at or near 2 months of age were obtained from 14 randomly selected HIV-exposed subjects who had no documented exposure to ARV and 16 subjects who were exposed to AZT prenatally and postnatally. Blood specimen volume requirements of the parent studies ensured the exclusion of subjects born at gestational age less than 37 weeks. The plasma samples were de-identified and Mayo Medical Laboratories (Rochester, MN) measured acylcarnitine levels using MS/MS as previously described.[14] The "average of the averages" for each acylcarnitine species was analyzed for direct comparison between groups, although an individual acylcarnitine profile was called abnormal only if at least 1 metabolite was >99th percentile compared with age-matched references (Mayo Medical Laboratories). Institutional Review Board exemption was obtained at participating institutions before initiation of the study.

Newborn screening data and subsequent acylcarnitine profiles in the New York University samples were summarized as proportions and means (± standard deviation), respectively. Numbers of subjects positive for newborn metabolic screening were compared between HIV screen–positive and HIV screen–negative groups (Table 1) using 2-sided Fisher exact test. Mean acylcarnitine levels (Fig. 1) were compared by ARV exposure status using the *t* test. Statistical tests were performed using SAS/STAT software 9 (SAS Institute, Cary, NC).

RESULTS

New York State Newborn Screening

Of 1,006,325 newborns who underwent mandated screening, 11,949 had at least 1 abnormal newborn screen for an inborn error of metabolism as measured by MS/MS, and 2371 had a positive enzyme-linked immunosorbent assay for HIV antibody. The average gestational ages for the HIV screen–positive population (data collected between 2007 and 2009) and for the general population of newborns were 37 weeks and 39 weeks, respectively. The average birth weights for the HIV screen–positive population and for the general population of newborns were 2894 g and 3311 g, respectively.

There was a significantly ($P = 0.000025$) higher proportion of HIV screen–positive/ARV–exposed newborns who also screened positive for any inborn error of metabolism (2.2% of 2371) compared with the proportion with such abnormal metabolic screens in the general population of New York state newborns (1.2% of 1,003,953) born between 2005 and 2008 (Table 1). Mean carnitine levels were 26.92 ± 10.71 µmol/L in the HIV screen–positive group and 28.56 ± 10.27 µmol/L in the general newborn population ($P < 0.0001$). Only 1 of the HIV/metabolic screen–positive newborns was confirmed through subsequent testing to meet diagnostic criteria for a metabolic disorder (inherited form of 3-methylcrotonyl carboxylase deficiency).

Acylcarnitine Profiles in ARV-exposed and ARV-unexposed Infants

The mean plasma-free carnitine levels in the ARV-exposed infants and in the ARV-unexposed infants were not significantly different (10.99 µmol/mL versus 12.91 µmol/mL; $P = 0.89$). Of the 42 acylcarnitine species that were analyzed as part of an acylcarnitine profile, mean levels of 7 species were significantly different between the groups. At least 1 acylcarnitine level was abnormal (>99th percentile for age) in 7 of 16 (43%) ARV-exposed infants, whereas no abnormal acylcarnitine level was detected in the 14 ARV-unexposed infants ($P = 0.02$). Figure 1 shows acylcarnitine levels for clinically relevant species and indicates individuals who had at least 1 acylcarnitine level >99th percentile of age-matched reference values for at

TABLE 1. Proportions of Positive Newborn Screens for Metabolic Disorders in HIV Screen–positive and HIV Screen–negative Neonates in New York State Between 2005 and 2008

Positive NBS	HIV NBS-positive (N = 2371)	HIV NBS-negative (N = 1,003,954)	*P*
Any metabolic disorder	53 (2.2%)	11,949 (1.2%)	**2.5×10^{-5}**
Mitochondrial metabolic disorder*	42 (1.8%)	8118 (0.8%)	**5.0×10^{-6}**
Urea cycle disorder	3 (0.1%)	1310 (0.1%)	0.99
Organic academia	14 (0.6%)	1220 (0.1%)	**2.2×10^{-6}**
Fatty acid oxidation disorder†	20 (1.0%)	4130 (0.4%)	**0.001**
MCADD/MADD	5 (0.2%)	923 (0.09%)	0.07
CPT1/2	8 (0.3%)	471 (0.05%)	**2.3×10^{-5}**
Carnitine deficiency	9 (0.4%)	1869 (0.2%)	**0.05**
Amino acid disorder	11 (0.5%)	3831 (0.4%)	0.5
PKU	8 (0.3%)	1027 (0.1%)	**0.004**
MSUD	1 (0.04%)	916 (0.09%)	0.65
Tyrosinemia	1 (0.04%)	497 (0.04%)	0.76
Homocystinuria	1 (0.04%)	900 (0.03%)	0.67

P values in boldface indicate statistical significance.

*Includes urea cycle disorders, organic acidemias and fatty acid oxidation disorders.

†Two newborns were positive for both MCADD/MADD and CPT1/2.

CPT indicates carntine palmitoyltransferase; MCADD, medium-chain acyl-CoA dehydrogenase deficiency; MADD, multiple acyl-CoA dehydrogenase deficiency (glutaric aciduria, type 2); MSUD, maple syrup urine disease; NBS, newborn screen; PKU, phenylketonuria.

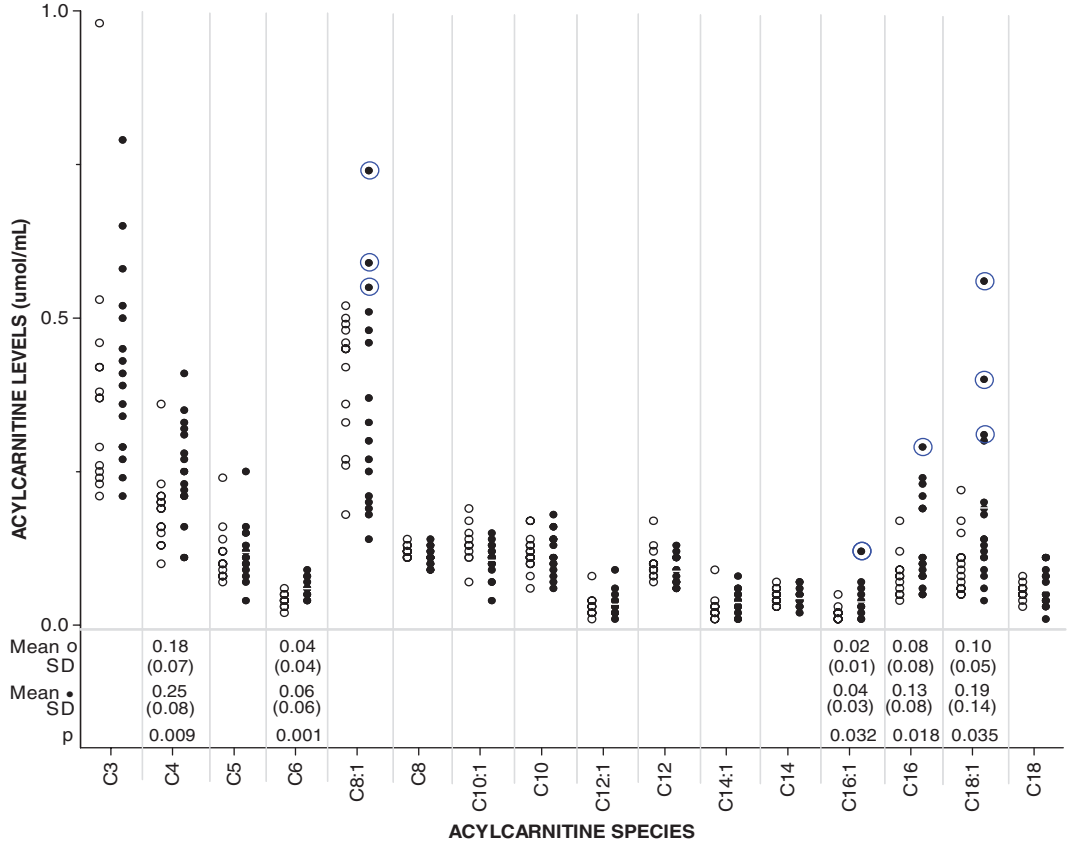

FIGURE 1. Acylcarnitine levels in ARV-unexposed (o) and ARV-exposed (•) infants. Each acylcarnitine species (C3–C18) corresponds to a substrate for a step of either fatty acid oxidation or organic acid catabolism. Group means, standard deviations and *P* values for significant differences are listed under corresponding species. Circled measurements represent values of birth sample or 2-month sample that were >99th percentile of age-matched reference values.

least 1 of their 2 samples. Mean levels of butyrylcarnitine/isobutyrylcarnitine (C4), hexanoylcarnitine (C6), palmitoleylcarnitine (C16:1), palmitoylcarnitine (C16) and oleoylcarnitine (C18:1) were significantly higher in the ARV-exposed group. In the ARV-exposed group, there were 10 measurements spread over 7 subjects that were >99th percentile for age-matched reference values for 5 different acylcarnitine species (octenolycarnitine [C8:1], palmitoleylcarnitine [C16:1], palmitoylcarnitine [C16], oleoylcarnitine [C18:1] and linoleylcarnitine [C18:2]). Of these, abnormal levels of C8:1 (3 subjects) and C18:1 (3 subjects) represented the most consistent abnormalities detected. All acylcarnitine species that were abnormal corresponded to fatty acid oxidation (even carbon number) and not organic acid metabolism (short-chain, odd carbon number).

DISCUSSION

Our analysis of newborn screening data reveals a higher proportion of positive metabolic screens in HIV-exposed newborns compared with the HIV screen–negative population. Furthermore, we found that full-term, ARV-exposed infants were more likely than ARV-unexposed infants to have fatty acid oxidation dysfunction as measured by acylcarnitne analysis. Together, these results suggest that ARV may negatively affect intermediary energy metabolism, particularly fatty acid oxidation.

Taken as a group, the frequency of positive screens (Table 1) for the disorders that correspond to reactions that take place completely in the mitochondria (fatty acid oxidation), partially in the mitochondria (urea cycle), or that produce substrate for the citric acid cycle (organic acid metabolism) was significantly higher in the HIV screen–positive group. In contrast, the frequency of positive screens for amino acid disorders, the corresponding reactions for which occur in the cytosol, was not significantly higher in the HIV screen–positive group. This apparent dichotomy suggests a mechanism of generalized mitochondrial dysfunction possibly attributable to NRTI-induced disruption of OXPHOS (Fig., Supplemental Digital Content 1, http://links.lww.com/INF/B339).

A more detailed comparison reveals that positive newborn screening for long-chain fatty acid abnormalities (ie, CPT1/2) and carnitine deficiency predominated in the HIV screen–positive newborn population. Moreover, mean carnitine levels for the HIV screen–positive population were significantly lower than those observed in the general population, a phenomenon previously described.[15] Mitochondrial fatty acid oxidation, which depends on normal carnitine metabolism, is the primary cellular means of catabolizing free fatty acids for energy and is an important source of cellular fuel during times of metabolic stress, fasting and moderate to vigorous exercise.[10] In the extreme, inherited disorders of fatty acid oxidation present in childhood during times of catabolic stress and manifest as hypoglycemia, hypoketonemia, acute liver injury and myopathy. There are also less severe variants of fatty acid oxidation disorders that may present similarly in late childhood

or adulthood when there is sufficient catabolic stress.[16] Intact fatty acid oxidation is essential for normal health and development throughout childhood, and there is evidence that abnormal levels of acylcarnitines, particularly the long-chain species, may themselves be toxic.[17] The second most common abnormality seen in the HIV screen–positive population was analytes used to screen for organic acidemias. The majority of the positive screens were for 3-methylcrotonyl carboxylase deficiency, a biochemical finding of unclear clinical significance.[18] Phenylketonuria was the only disorder of amino acid metabolism that was significantly more common in the HIV screen–positive group than the general population. Whereas elevated phenylalanine levels have been observed previously in HIV-infected patients,[19] phenylalanine metabolism is dependent on hepatocyte function and immune system activation, and normalize after effective antiretroviral treatment.[20]

Besides direct effects on neonatal metabolism, the increased frequency of abnormal metabolic screens in the HIV screen–positive newborn population may be attributable to the effects of HIV or ARV treatment on maternal intermediary metabolism. It is known that some analytes that are detected on newborn screen cross the placenta. There are several reports of asymptomatic metabolic disorders being diagnosed in mothers of infants with positive newborn screens but no overt disease.[21–23] Other maternal factors that may have contributed to our observations include renal function, liver health,[24,25] and possibly immunologic/virological status. Because there is little known about the effects of HIV or ARV on adult intermediary metabolism alone or maternal–fetal intermediary metabolism during pregnancy, future studies should ideally include concomitant analysis of biomarkers and clinical data from mother and infant.

Because the average gestational age and birth weight were lower for HIV screen–positive infants, it is possible that "metabolic immaturity" may, at least in part, be responsible for an increase in false-positive screens for some metabolic disorders. Although it is known that there is an inverse correlation between birth weight and false-positive newborn screens, 1 study found that this correlation did not hold for C4 and long-chain acylcarnitine species (C14 and C16 were considered in this study)[26] and was most pronounced for very low birth weight infants (<1000 g). Although there remains the possibility that immature metabolic pathways play a role in an increased false-positive rate for disorders of amino and organic acid metabolism, this may not fully explain the difference in positive screens for fatty acid oxidation disorders.

To determine whether the increased frequency of abnormal metabolic screens in HIV screen–positive newborns was associated with HIV or ARV exposure, we next compared mean values of acylcarnitine species in ARV-exposed and ARV-unexposed infants who were born at ≥37 weeks of gestation and who were all HIV-exposed. In this study, we observed higher mean levels of some short-chain and long-chain acylcarnitine species in the ARV-exposed subjects (Fig. 1). Some of the ARV-exposed newborns had acylcarnitine levels outside the normal range, and those who did tended to have abnormalities in similar species, including C8:1 and C18:1. Whereas C8:1 is not currently associated with any clinical disorder, C18:1 elevation is used as a marker for carnitine palmitoyltransferase 2 or carnitine-acylcarnitine translocase deficiency. This finding agrees with the increased frequency of CPT1/2-positive newborn screens in HIV screen–positive infants described previously. Moreover, there is experimental evidence of a direct effect of NRTIs on fatty acid oxidation,[27,28] including a negative affect on carnitine palmitoyltransferase 2.

It is biochemically plausible that fatty acid oxidation dysfunction is secondary to NRTI-associated OXPHOS dysfunction. Acylcarnitine profiles are recommended as a screening test for those suspected of having inherited OXPHOS disorders[29] and can be abnormal in those with established mitochondrial disease.[13] There is a known biochemical link between fatty acid oxidation and OXPHOS through the former's production of acetyl-CoA for the Krebs cycle and the donation of reducing equivalents to complexes I and III of the respiratory transport chain. Whereas HIV itself has been shown to adversely affect mitochondria, it is through influence over the mitochondrial apoptotic pathway and not through its effects on OXPHOS[30] or related metabolic systems.

Possible explanations for why some of the ARV-exposed infants had acylcarnitine levels above the 99th percentile and others did not include variations in maternal ARV regimen and timing of exposure to ARV. It is also possible that individual genetic variation in 1 gene or multiple genes regulating fatty acid oxidation or OXPHOS renders some, but not all, susceptible to dysfunction in these pathways.

The abnormalities of intermediary metabolism described herein, especially those of fatty acid oxidation, suggest that metabolic toxicity in HIV-exposed and ARV-exposed children extends beyond mitochondrial DNA abnormalities and OXPHOS dysfunction. Validation of these observations is necessary in other populations and future studies will need to define the clinical ramifications of such biochemical abnormalities, especially in the context of worldwide efforts to scale-up access to ARV in pregnant women and 1.49 million pregnancies each year that are potentially at risk.[31] It is important that we determine the full scope and depth of ARV effects on energy metabolism and that studies be conducted in children who depend on all aspects of normally functioning metabolism for optimum growth and development.

REFERENCES

1. Dagan T, Sable C, Bray J, et al. Mitochondrial dysfunction and antiretroviral nucleoside analog toxicities: what is the evidence? *Mitochondrion.* 2002;1:397–412.
2. Lewis W, Day BJ, Copeland WC. Mitochondrial toxicity of NRTI antiviral drugs: an integrated cellular perspective. *Nat Rev Drug Discov*. 2003;2: 812–822.
3. Divi RL, Leonard SL, Kuo MM, et al. Transplacentally exposed human and monkey newborn infants show similar evidence of nucleoside reverse transcriptase inhibitor-induced mitochondrial toxicity. *Environ Mol Mutagen*. 2007;48:201–209.
4. Arnaudo E, Dalakas M, Shanske S, et al. Depletion of muscle mitochondrial DNA in AIDS patients with zidovudine-induced myopathy. *Lancet*. 1991;337:508–510.
5. Foster C, Lyall H. HIV and mitochondrial toxicity in children. *J Antimicrob Chemother*. 2008;61:8–12.
6. Lewis W, Kohler JJ, Hosseini SH, et al. Antiretroviral nucleosides, deoxynucleotide carrier and mitochondrial DNA: evidence supporting the DNA pol gamma hypothesis. *AIDS*. 2006;20:675–684.
7. Alimenti A, Burdge DR, Ogilvie GS, et al. Lactic acidemia in human immunodeficiency virus-uninfected infants exposed to perinatal antiretroviral therapy. *Pediatr Infect Dis J*. 2003;22:782–789.
8. Blanche S, Tardieu M, Rustin P, et al. Persistent mitochondrial dysfunction and perinatal exposure to antiretroviral nucleoside analogues. *Lancet*. 1999;354:1084–1089.
9. Krivitzky L, Babikian T, Lee HS, et al. Intellectual, adaptive, and behavioral functioning in children with urea cycle disorders. *Pediatr Res*. 2009;66: 96–101.
10. Wilcken B. Fatty acid oxidation disorders: outcome and long-term prognosis. *J Inherit Metab Dis*. 2010;33:501–506.
11. Therrell BL, Johnson A, Williams D. Status of newborn screening programs in the United States. *Pediatrics*. 2006;117(5, pt 2):S212–S252.
12. Wilcken B, Wiley V, Hammond J, et al. Screening newborns for inborn errors of metabolism by tandem mass spectrometry. *N Engl J Med*. 2003; 348:2304–2312.

13. Sim KG, Carpenter K, Hammond J, et al. Acylcarnitine profiles in fibroblasts from patients with respiratory chain defects can resemble those from patients with mitochondrial fatty acid beta-oxidation disorders. *Metab Clin Exp*. 2002;51:366–371.
14. Rinaldo P, Cowan TM, Matern D. Acylcarnitine profile analysis. *Genet Med*. 2008;10:151–156.
15. Ilias I, Manoli I, Blackman MR, et al. L-Carnitine and acetyl-L-carnitine in the treatment of complications associated with HIV infection and antiretroviral therapy. *Mitochondrion*. 2004;4:163–168.
16. Raymond K, Bale AE, Barnes CA, et al. Medium-chain acyl-CoA dehydrogenase deficiency: sudden and unexpected death of a 45 year old woman. *Genet Med*. 1999;1:293–294.
17. Sewell AC, Böhles HJ. Acylcarnitines in intermediary metabolism. *Eur J Pediatr*. 1995;154:871–877.
18. Arnold GL, Salazar D, Neidich JA, et al. Outcome of infants diagnosed with 3-methyl-crotonyl-CoA-carboxylase deficiency by newborn screening. *Mol Genet Metab*. 2012;106:439–441.
19. Ollenschläger G, Jansen S, Schindler J, et al. Plasma amino acid pattern of patients with HIV infection. *Clin Chem*. 1988;34:1787–1789.
20. Zangerle R, Kurz K, Neurauter G, et al. Increased blood phenylalanine to tyrosine ratio in HIV-1 infection and correction following effective antiretroviral therapy. *Brain Behav Immun*. 2010;24:403–408.
21. Gibson KM, Bennett MJ, Naylor EW, et al. 3-Methylcrotonyl-coenzyme A carboxylase deficiency in Amish/Mennonite adults identified by detection of increased acylcarnitines in blood spots of their children. *J Pediatr*. 1998;132(3, pt 1):519–523.
22. McGoey RR, Marble M. Positive newborn screen in a normal infant of a mother with asymptomatic very long-chain Acyl-CoA dehydrogenase deficiency. *J Pediatr*. 2011;158:1031–1032.
23. Vijay S, Patterson A, Olpin S, et al. Carnitine transporter defect: diagnosis in asymptomatic adult women following analysis of acylcarnitines in their newborn infants. *J Inherit Metab Dis*. 2006;29:627–630.
24. Murphy WJ, Steiber A, Connery GC, et al. Altered carnitine metabolism in dialysis patients with reduced physical function may be due to dysfunctional fatty acid oxidation. *Nephrol Dial Transplant*. 2012;27:304–310.
25. Shneider BL, Rinaldo P, Emre S, et al. Abnormal concentrations of esterified carnitine in bile: a feature of pediatric acute liver failure with poor prognosis. *Hepatology*. 2005;41:717–721.
26. Slaughter JL, Meinzen-Derr J, Rose SR, et al. The effects of gestational age and birth weight on false-positive newborn-screening rates. *Pediatrics*. 2010;126:910–916.
27. Igoudjil A, Abbey-Toby A, Begriche K, et al. High doses of stavudine induce fat wasting and mild liver damage without impairing mitochondrial respiration in mice. *Antivir Ther (Lond)*. 2007;12:389–400.
28. Igoudjil A, Massart J, Begriche K, et al. High concentrations of stavudine impair fatty acid oxidation without depleting mitochondrial DNA in cultured rat hepatocytes. *Toxicol In Vitro*. 2008;22:887–898.
29. Haas RH, Parikh S, Falk MJ, et al.; Mitochondrial Medicine Society's Committee on Diagnosis. The in-depth evaluation of suspected mitochondrial disease. *Mol Genet Metab*. 2008;94:16–37.
30. Jacotot E, Ravagnan L, Loeffler M, et al. The HIV-1 viral protein R induces apoptosis via a direct effect on the mitochondrial permeability transition pore. *J Exp Med*. 2000;191:33–46.
31. World Health Organization, UNAIDS, UNICEF. Estimated number of women living with HIV needing and receiving antiretroviral medicine for PMTCT in low- and middle-income countries, 2010 [WHO website]. Available at: http://www.who.int/hiv/data/Table7_5_full.png. Accessed August 1, 2011.