ABSTRACT
Background: Embryonic development may be compromised by dietary and genetic disruptions in folate metabolism because of the critical role of folate in homocysteine metabolism, methylation, and nucleotide synthesis. Methylenetetrahydrofolate reductase (MTHFR), choline, and riboflavin play distinct roles in homocysteine detoxification and generation of one-carbon donors for methylation. The effect of low dietary choline and riboflavin on pregnancy complications and heart development has not been adequately addressed.

Objective: Our goal was to determine whether dietary deficiencies of choline and riboflavin in pregnant mice, with and without mild MTHFR deficiency, affect embryonic development.

Design: Female Mthfr+/- and Mthfr+/+ mice were fed a control diet (CD), a choline-deficient diet (ChDD), or a riboflavin-deficient diet (RbDD) and were then mated with male Mthfr+/- mice. Embryos were collected 14.5 d postcoitum and examined for reproductive outcomes and cardiac defects.

Results: Plasma homocysteine was higher in ChDD- than in CD-fed females. Liver MTHFR enzyme activity was greater in ChDD-fed Mthfr+/- than in CD-fed Mthfr+/+ females. The RbDD resulted in a higher percentage of delayed embryos and smaller embryos than did the CD. There were more heart defects, which were all ventricular septal defects, in embryos from the ChDD- and RbDD-fed females than from the CD-fed females. Dietary riboflavin and MTHFR deficiency resulted in decreased left ventricular wall thickness in embryonic hearts compared with embryos from CD-fed Mthfr+/- females.

Conclusions: Low dietary choline and riboflavin affect embryonic growth and cardiac development in mice. Adequate choline and riboflavin may also play a role in the prevention of these pregnancy complications in women.

INTRODUCTION

Folates are involved in several critical one-carbon transfers that are important for development (1), including nucleotide synthesis and homocysteine remethylation to methionine for methylation reactions. Remethylation also serves to limit the concentrations of homocysteine, a potentially toxic amino acid. A key enzyme of folate metabolism—5,10-methylenetetrahydrofolate reductase (MTHFR)—converts 5,10-methylenetetrahydrofolate (5,10-methyleneTHF) to 5-methyltetrahydrofolate (5-methylTHF), which provides the one-carbon unit for folate-dependent remethylation of homocysteine (Figure 1). A common polymorphism of MTHFR, 677C → T (A222V), results in mild MTHFR deficiency and hyperhomocysteinemia in homozygous TT individuals (2). Hyperhomocysteinemia is also caused or exacerbated by low dietary folate intakes. Both hyperhomocysteinemia and mild MTHFR deficiency are associated with an increased risk of neural tube defects (NTDs) and cardiovascular disease (3–5). Some studies also suggest that low dietary folate and mild MTHFR deficiency may influence pregnancy complications and congenital heart defects, although additional studies are required (6–8).

We previously created a mouse model of MTHFR deficiency and showed that Mthfr+/- mice with a single null allele possess a biochemical phenotype that is similar to humans homozygous for the 677TT genotype (9). Using these mice, we investigated the effects of maternal mild MTHFR deficiency and low dietary folate on reproductive outcomes and heart development. We found that they contributed to increased reproductive loss and intrauterine growth delay or risk of congenital heart defects (10). However, the interaction between MTHFR and other micronutrients in the folate metabolic pathway, in the context of embryo and cardiac development, has not been studied.

Choline catabolism produces betaine, the methyl donor for folate-independent remethylation of homocysteine to methionine (Figure 1) (11). This reaction, catalyzed by betaine homocysteine methyltransferase (BHMT), becomes especially critical when MTHFR activity is compromised (11, 12). Choline is also converted to acetycholine, and several studies have examined the effects of choline deficiency on neural tube development and brain function (13–17). One clinical study showed that higher choline intakes during pregnancy were correlated with a decreased risk of NTD in offspring, whereas studies in mice suggested that low choline intakes increased the incidence of NTDs (14, 16). However, no studies have examined the effects of choline deficiency on the developing heart.

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Riboflavin is the precursor of flavin mononucleotide (FMN) and flavin adenine dinucleotide (FAD), which function as cofactors for methionine synthase reductase (MTRR) and MTHFR, respectively (Figure 1). Clinical reports suggest that homozygous TT individuals with low riboflavin and low folate intakes have higher plasma homocysteine concentrations, which may be reduced by riboflavin supplementation (18, 19). Few clinical studies have examined riboflavin deficiency during pregnancy, although some rodent studies have shown that riboflavin depletion increases the incidence of congenital abnormalities, including ventricular septal defects (VSDs) (20, 21).

This study was conducted to determine the effect of low dietary choline and low dietary riboflavin during pregnancy, in the absence and the presence of mild MTHFR deficiency, on reproductive outcomes and congenital heart defects in mice.

MATERIALS AND METHODS

Mice and diets

Animal handling and experimentation were conducted according to the guidelines of the Canadian Council on Animal Care with approval by the Montreal Children’s Hospital Animal Care Committee. MTHFR-deficient BALB/c mice were generated as reported, and genotyping was performed as previously described (9). On weaning at 4–5 wk of age, Mthfr

\[ +/+ \] and Mthfr

\[ +/2 \] females were fed amino acid–defined diets (Harlan Teklad, Indianapolis, IN) containing amounts of nutrients recommended by the American Institute of Nutrition (22). Mice were fed 1 of 3 diets: a control diet (CD) containing the recommended amount of folic acid, choline, and riboflavin (2, 2.5, and 6 mg/kg diet, respectively) or diets that were identical to the CD except for the following:

- Choline-deficient (ChDD) diet
- Riboflavin-deficient (RbDD) diet

| TABLE 1 | Concentrations of maternal plasma choline/choline metabolites and riboflavin in pregnant Mthfr

\[ +/+ \] and Mthfr

\[ +/2 \] BALB/c mice fed control (CD), choline-deficient (ChDD), or riboflavin-deficient (RbDD) diets.

<table>
<thead>
<tr>
<th></th>
<th>CD diet</th>
<th>ChDD diet</th>
<th>RbDD diet</th>
</tr>
</thead>
</table>
|                         | Mthfr

\[ +/+ \] | Mthfr

\[ +/2 \] | Mthfr

\[ +/+ \] | Mthfr

\[ +/2 \] |
| Choline (nmol/mL)       | 17.69 ± 1.2 | 20.63 ± 0.6 | 13.24 ± 1.3 | 13.16 ± 2.1 |
| Betaine (nmol/mL)       | 37.38 ± 3.7 | 40.31 ± 4.5 | 27.84 ± 3.8 | 25.09 ± 3.9 |
| Dimethylglycine (nmol/mL) | 5.88 ± 0.7 | 6.71 ± 0.2 | 4.12 ± 0.6 | 4.16 ± 0.7 |
| Phosphatidylcholine (nmol/mL) | 1627.71 ± 93.2 | 1647.17 ± 54.4 | 1085.93 ± 78.6 | 800.86 ± 152.4 |
| Lysophosphatidylcholine (nmol/mL) | 291.1 ± 45 | 302.1 ± 7.1 | 208.98 ± 27.2 | 194.98 ± 34.5 |
| Glycerophosphocholine (nmol/mL) | 47.74 ± 12.3 | 51.97 ± 9.6 | 27.1 ± 4.8 | 33.7 ± 6.4 |
| Phosphocholine (nmol/mL) | 1.56 ± 0.16 | 1.79 ± 0.25 | 1.28 ± 0.17 | 1.44 ± 0.27 |
| Sphingomyelin (nmol/mL) | 258 ± 9.5 | 244.25 ± 20.6 | 175.5 ± 33.8 | 217.5 ± 47.1 |
| Riboflavin (nmol/L)     | 19.65 ± 0.45 | 18.58 ± 1.06 | — | 1.9 ± 0.31 |

\[ P \] values were derived from 2-factor ANOVA comparisons between the CD and ChDD groups and between the CD and RbDD groups.

1 All values are means ± SEMs; \( n = 4 \) per group. There were no significant effects of genotype or significant interactions between diet and genotype for choline/choline metabolites or riboflavin (ANOVA and \( t \) test).

2 \( P \) values were derived from 2-factor ANOVA comparisons between the CD and ChDD groups and between the CD and RbDD groups.
Mthfr
RbDD.
(MTHFR) enzyme activity in pregnant mice fed a CD, a ChDD, or an
Mean (±SEM) relative liver 5,10-methylenetetrahydrofolate reductase
Significantly different from CD-fed females of the same genotype,
appeared weightless, and were removed for assessment of implantation and resorption sites. Nonviable or resorbed embryos at 14.5 dpc were considered as resorptions. The resorption rate was calculated as the number of resorption sites divided by the total number of implantation sites. Placentae were removed and weighed, and viable embryos were dissected and examined for gross abnormalities, developmental delay, and embryonic crown-rump length and weight as previously described (10). Developmental delay was assessed by comparison of the gross morphology of individual viable embryos with that of the most-developed embryo of each litter at 14.5 dpc. Embryos with incomplete separation of upper and lower digits, undefined elbows, a cone-shaped head, and absence of hair follicles were considered delayed. The percentage of delayed embryos was calculated as the number of delayed embryos per litter divided by the total number of viable embryos within that same litter. All embryos and placentae were fixed overnight in 4% paraformaldehyde and transferred to 70% ethanol for storage. Yolk sacs were removed and washed in phosphate-buffered saline before Mthfr genotyping as reported previously (10).

Measurements of plasma metabolites
Blood was collected into EDTA-coated tubes and centrifuged at 6000 × g for 6 min at 4°C. Plasma was separated from blood cells and frozen on dry ice before storage at −70°C. Liquid chromatography–mass spectrometry was used to measure plasma choline, betaine, and dimethylglycine (25); plasma phosphatidylcholine, lyso phosphatidylcholine, glycerophosphocholine, phosphocholine, and sphingomyelin (26); and plasma riboflavin (27). Plasma total homocysteine (tHcy) was quantified with an A/C Portable Enzymatic Homocysteine Assay (A/C Diagnostics, San Diego, CA) and an A/C Diagnostics Reader (A/C Diagnostics) according to the manufacturer’s instructions.

Liver protein extraction and MTHFR enzyme assays
Crude liver extracts were prepared, and MTHFR enzyme assays were performed as described previously (28, 29).

Histologic analysis of embryonic hearts
Approximately 10 litters from each of the 6 groups were randomly selected, and all embryos were processed overnight through a series of ethanol, xylene, and paraffin dehydration steps, each lasting 45 min. Embryos were then embedded in paraffin, and 6-μm serial transverse sections were collected. All sections were examined under bright-field illumination with the use of an inverted microscope. Sections were stained with hematoxylin (Sigma Aldrich, Oakville, Canada) and eosin (Sigma Aldrich) and photographed using an Axioplan Zeiss microscope.

One embryo per sectioned litter was randomly selected for measurement of myocardial wall thickness. Sections were stained with hematoxylin and eosin and measurements were taken by using AxioVision LE Image software. Because no atrial defects were observed, the focus was placed on measuring the thickness of the ventricular compact walls. This was calculated as the mean...
TABLE 2
Effects of control (CD), choline-deficient (ChDD), and riboflavin-deficient (RbDD) diets on reproductive outcomes and ventricular septal defects (VSDs) 1

<table>
<thead>
<tr>
<th></th>
<th>CD</th>
<th>ChDD</th>
<th>RbDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Litters (n)</td>
<td>15</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Viable embryos (n per litter)</td>
<td>6.00 ± 0.56 ± 6</td>
<td>4.93 ± 0.44 ± 6</td>
<td>5.93 ± 0.42 ± 6</td>
</tr>
<tr>
<td>Resorption rate (n per litter [%])</td>
<td>27.15 (6.03) ± 6</td>
<td>24.17 (6.25) ± 6</td>
<td>26.56 (4.13) ± 6</td>
</tr>
<tr>
<td>Delayed embryos (%)</td>
<td>5.33 ± 3.50 ± 6</td>
<td>8.65 ± 4.78 ± 6</td>
<td>15.42 ± 6.32 ± 6</td>
</tr>
<tr>
<td>Mean embryonic weight (g)</td>
<td>0.205 ± 0.005 ± 6</td>
<td>0.201 ± 0.005 ± 6</td>
<td>0.196 ± 0.005 ± 6</td>
</tr>
<tr>
<td>Mean embryonic crown-rump length (mm)</td>
<td>10.684 ± 0.100 ± 6</td>
<td>10.662 ± 0.080 ± 6</td>
<td>10.530 ± 0.079 ± 6</td>
</tr>
<tr>
<td>Mean placenta weight (g)</td>
<td>0.104 ± 0.002 ± 6</td>
<td>0.104 ± 0.002 ± 6</td>
<td>0.107 ± 0.002 ± 6</td>
</tr>
<tr>
<td>Embryos with VSD (n/total sectioned [%])</td>
<td>3/60 (5.0) ± 6</td>
<td>3/54 (5.6) ± 6</td>
<td>9/54 (16.7) ± 6</td>
</tr>
</tbody>
</table>

VSDs (n per litter [%]) | 0.30 ± 0.15 (5.1) | 0.27 ± 0.14 (5.1) | 0.90 ± 0.31 (15.9) | 0.54 ± 0.25 (11.0) | 1.20 ± 0.36 (20.6) | 1.00 ± 0.30 (17.6)

1 There was no significant effect of maternal genotype when ChDD groups were compared with CD groups or when RbDD groups were compared with CD groups (2-factor ANOVA). No significant interaction was observed between diet and genotype for delayed embryos, embryonic weights, crown-rump lengths, or VSD incidence (ANOVA).

2 Mean ± SEM (all such values).

3 Fewer litters were examined for delayed embryos in the ChDD groups: 13 litters and 9 litters from ChDD Mthfr ++/+ and Mthfr ++/− females, respectively.

4 Significantly different from CD females, P < 0.05 (2-factor ANOVA).

5 Significantly different from CD females, P < 0.05 (Fisher’s exact test).

of 3 values, measured independently by 2 individuals who were blinded to the groups; the correlation between individuals was 0.80 (P < 0.01). Sections were chosen to be along the same level of the longitudinal axis. BrdU staining was performed as previously described (23).

Statistical analysis

The female or litter was considered as the unit for statistical analysis. Results were expressed as means ± SEMs and examined by 2-factor analysis of variance (ANOVA) or independent-sample t tests. The chi-square test was used to analyze embryonic genotype distributions. The effects of embryonic genotype on embryonic genotype on CHD were analyzed by using the 2-tailed Fisher’s exact test. All statistical analyses were performed with SPSS for WINDOWS software (version 11.0; SPSS Inc, Chicago, IL). P values <0.05 were considered significant, except for the analysis of interactions between diet and genotype, for which P < 0.1 was considered significant.

RESULTS

Plasma concentrations of choline/choline metabolites, riboflavin, and total homocysteine

Concentrations of plasma choline/choline metabolites and riboflavin are shown in Table 1. Mice fed the ChDD had significantly lower concentrations of plasma choline, betaine, dimethylglycine (P < 0.01, ANOVA), phosphatidylylycerol.
(P < 0.001, ANOVA), and lysocephatidylcholine and glycerylethosphocholine (P < 0.05, ANOVA) than did mice fed the CD. No dietary differences were observed for phosphocholine and sphingomyelin, and there were no differences due to Mthfr genotype. Concentrations of plasma riboflavin were significantly lower in mice fed the RbDD than in mice fed the CD (P < 0.001, ANOVA), with no differences due to Mthfr genotype. These results indicate that the diets lowered the concentrations of the relevant nutrients as anticipated.

Plasma tHcy concentrations (Figure 2A) of pregnant CD Mthfr<sup>+/+</sup> and CD Mthfr<sup>+/-</sup> females were consistent with those reported previously (10). Mthfr<sup>+/-</sup> pregnant females had higher plasma tHcy concentrations than Mthfr<sup>+/+</sup> pregnant females overall (P < 0.001, ANOVA) and in each of the 3 dietary groups separately (P < 0.01, independent-samples t test). Females fed the ChDD had higher plasma tHcy concentrations than did the CD-fed mice (P < 0.001, ANOVA) and than their respective genotype groups fed the CD (P < 0.005, t tests). There was also a significant interaction between Mthfr genotype and choline deficiency (P < 0.05, ANOVA). ChDD Mthfr<sup>+/+</sup> females had the highest tHcy concentration of all groups (94.1 ± 12.83 μmol/L). There were no significant differences in tHcy concentrations between the RbDD-fed females and the CD-fed females.

Liver MTHFR enzyme activity

MTHFR enzyme activity was significantly decreased due to MTHFR deficiency (P < 0.001, 2-factor ANOVA; Figure 2B). Choline-deficient diets significantly increased enzyme activity (P < 0.05, 2-factor ANOVA), whereas there was no effect of riboflavin-deficient diets on activity (Figure 2B).

Reproductive outcomes

As shown in Table 2, there were no significant differences due to diet or genotype when resorption rates were compared between the CD and ChDD groups or between the CD and RbDD groups. No significant differences in the percentage of delayed embryos, embryonic weight, or length were observed between the CD and ChDD groups. On the other hand, RbDD females had a greater incidence of delayed embryos and lower embryonic weights and crown-rump lengths than did CD females (P < 0.05, 2-factor ANOVA).

Heart development

All the observed heart defects in embryos were VSDs (Table 2, Tables 3–5, and Figure 3). There was a greater number of embryos with VSDs in ChDD-fed females than in CD-fed females (P < 0.05, Fisher’s exact test). The number of embryos with VSDs was significantly greater in the RbDD-fed groups than in the CD-fed groups (P < 0.005, Fisher’s exact test), and the incidence of VSDs per litter was also significantly higher in embryos of RbDD-fed females due to diet than in those of CD-fed females (P < 0.005, 2-factor ANOVA). Maternal Mthfr

### Table 4

<table>
<thead>
<tr>
<th>Mthfr genotype</th>
<th>Female</th>
<th>Male</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+/+</td>
<td>-/-</td>
</tr>
<tr>
<td>Viable embryos</td>
<td>44</td>
<td>45</td>
</tr>
<tr>
<td>Delayed embryos [n (%)]</td>
<td>4 (9.1)&lt;sup&gt;2&lt;/sup&gt;</td>
<td>5 (11.1)&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Embryonic weight (g)</td>
<td>0.201 ± 0.003&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.193 ± 0.007</td>
</tr>
<tr>
<td>Embryonic crown-rump length (mm)</td>
<td>10.572 ± 0.072</td>
<td>10.338 ± 0.153</td>
</tr>
<tr>
<td>Placenta weight (g)</td>
<td>0.106 ± 0.002</td>
<td>0.107 ± 0.004</td>
</tr>
<tr>
<td>Embryos with VSDs [n/total sectioned (%)]</td>
<td>4/29 (13.8)</td>
<td>5/25 (20.0)</td>
</tr>
</tbody>
</table>

1 No significant differences were observed by embryonic genotype (ANOVA and chi-square test).
2 Fewer litters were examined for delayed embryos.
3 Mean ± SEM per litter (all such values).

### Table 5

<table>
<thead>
<tr>
<th>Mthfr genotype</th>
<th>Female</th>
<th>Male</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+/+</td>
<td>-/-</td>
</tr>
<tr>
<td>Viable embryos</td>
<td>44</td>
<td>45</td>
</tr>
<tr>
<td>Delayed embryos [n (%)]</td>
<td>4 (9.1)</td>
<td>5 (11.1)</td>
</tr>
<tr>
<td>Embryonic weight (g)</td>
<td>0.191 ± 0.005&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.192 ± 0.006</td>
</tr>
<tr>
<td>Embryonic crown-rump length (mm)</td>
<td>10.344 ± 0.105</td>
<td>10.513 ± 0.088</td>
</tr>
<tr>
<td>Placenta weight (g)</td>
<td>0.098 ± 0.002</td>
<td>0.097 ± 0.003</td>
</tr>
<tr>
<td>Embryos with VSDs [n/total sectioned (%)]</td>
<td>6/31 (19.3)</td>
<td>6/25 (24.0)</td>
</tr>
</tbody>
</table>

1 No significant differences were observed by embryonic genotype (ANOVA and chi-square test).
2 Mean ± SEM per litter (all such values).
Effects of embryonic genotype

The distribution of embryonic Mthfr genotypes is shown in Tables 3–5 for female mice fed the CD, ChDD, and RbDD, respectively. No differences in numbers of viable embryos were determined. Small numbers of embryos examined within each genotype group. No other significant effects of embryonic genotype were observed on embryonic length, placental weight, or VSD incidence in the CD group. There were no effects of embryonic genotype for any variable in the ChDD-fed or RbDD-fed groups. These findings suggest that embryonic Mthfr genotype may not modify the risk of development of congenital heart defects; a similar conclusion was reached in our previous study (10). Nevertheless, in this study we observed that maternal riboflavin deficiency and inadequate riboflavin intake may also affect heart development through an influence on ventricular wall thickness.

MTHFR deficiency alone did not appear to affect the incidence of resorption or heart defects, as compared with our previous findings (10). Nevertheless, in this study we observed that maternal MTHFR deficiency resulted in a significant decrease in left ventricular wall thickness in embryos from CD-fed Mthfr+/+ females, with a greater number of delayed Mthfr+/+ embryos than Mthfr+/− embryos (P < 0.05, chi-square test); there were no delayed Mthfr−/− embryos. However, these observations may have been due to the small numbers of embryos examined within each genotype group. No other significant effects of embryonic genotype were observed on embryonic length, placental weight, or VSD incidence in the CD group. There were no effects of embryonic genotype for any variable in the ChDD-fed or RbDD-fed groups. These findings suggest that embryonic Mthfr genotype may not modify the risk of development of congenital heart defects; a similar conclusion was reached in our previous study (10). Nevertheless, in this study we observed that maternal riboflavin deficiency and inadequate riboflavin intake may also affect heart development through an influence on ventricular wall thickness.

MTHFR deficiency alone did not appear to affect the incidence of resorption or heart defects, as compared with our previous findings (10). Nevertheless, in this study we observed that maternal MTHFR deficiency resulted in a significant decrease in left ventricular wall thickness in embryos from CD-fed females at 12.5 dpc, the additional 2 d of development in this study may have revealed an effect of MTHFR deficiency on ventricular wall thickness. The cause of the variability in the nature of the cardiac phenotype conferred by MTHFR deficiency remains to be determined.

The conversion of choline to betaine is important for the regulation of homocysteine concentrations, because betaine is an...
CD-fed Mthfr-fed female mice by genotype (thickness was nearly significantly different between the RbDD- and CD-fed (RbDD) and the mice fed a CD (ChDD) and between the mice fed a choline-deficient diet (ChDD)—genotype between the mice fed a riboflavin-deficient diet (RbDD) and those fed a control diet (CD) (P = 0.07). &Significantly different from CD-fed Mthfr+/+ females, P < 0.005 (t test). Lower left ventricular wall thickness was nearly significantly different between the RbDD- and CD-fed female mice by genotype (P = 0.051, 2-factor ANOVA). *Significantly different from CD-fed Mthfr+/+ females, P < 0.05 (t test). There were no significant differences or significant dietary-genotype interactions (ANOVA).

A clinical study found that changes in maternal choline metabolism may modify the risk of NTD in children (34). Other studies in cell and animal models have shown that choline deficiency caused changes in stem cell proliferation, global DNA methylation, and gene expression, which led to altered structure and development of neural tissues (16, 17, 35, 36). No studies thus far have been conducted on the effects of maternal choline deficiency on congenital heart defects. However, because both neural and cardiac tissues are composed in part of neural crest cells, it is not surprising that a reduction in choline intake would also affect heart development.

Clinical studies have shown that riboflavin intake can influence tHcy concentrations under certain conditions, including the concentrations in individuals with mild MTHFR deficiency due to the 677TT genotype (18, 19). We showed that folate or FAD can stabilize both wild-type MTHFR or mutagenized MTHFR containing the polymorphism (37); consequently, the low-riboflavin diet could have influenced maternal tHcy or MTHFR activity. However, we did not observe an effect of RbDD on these factors. Because the RbDD contained both folate and choline, the effect of low riboflavin may have been limited.

MTHFR activity may not have been affected in this study because FAD can be more firmly bound by certain enzymes than others, even during riboflavin depletion (38). The incidence of delayed embryos was significantly increased in RbDD groups but these observations may or may not have been due to disturbances
related to homocysteine metabolism. Maternal plasma homocysteine was not affected by low riboflavin intake; however, as mentioned previously, maternal plasma homocysteine may not reflect embryonic contributions. Changes in reproductive outcomes in riboflavin deficiency could have resulted from cellular malfunctions through a loss of FMN and FAD cofactors for other enzymes, such as the flavoproteins of the mitochondrial electron transport chain. It has been well-documented that mutations in mitochondrial DNA will lead to various disorders, including defects in cardiac and skeletal muscle (39–41). In this study, we found that embryos from RbDD-fed females also had a significantly increased incidence of VSDs, with many occurring in delayed embryos \( n = 16/22 \) combined VSDs. If the RbDD-induced deficiency had indeed caused defective electron transport chain function, it would have resulted in the accumulation of reactive oxygen species and free radicals (42) and potential effects on apoptosis or cell growth. Thinner myocardial walls often lead to heart failure, and many studies point to mitochondrial defects as causes of a variety of cardiac conditions (43, 44).

Although no clinical reports have indicated riboflavin deficiency as a cause of congenital heart defects, several studies in rodents have suggested that riboflavin is important for heart development. Female rats fed an antagonist of riboflavin produced fewer offspring and many had VSDs, whereas fetal mice from riboflavin-deficient females had cardiovascular abnormalities and cleft palates (20, 21). An additional study conducted in galactoflavin-induced, riboflavin-deficient rats showed a marked decrease in liver FAD concentrations that was correlated with an increase in congenital malformations (45).

In conclusion, our findings emphasize the variable etiology of developmental disorders, which lends support to the importance of adequate dietary riboflavin and choline intake during pregnancy to decrease the risk of developmental defects and congenital heart defects.

We thank Xinying He and Xiao-Ling Wang for their technical assistance. The authors' responsibilities were as follows—JC, LGM, LP, and RR: contributed to the study design, data analysis, and manuscript preparation; and JC, LD, QW, JY, and MAC: contributed to the data collection and manuscript preparation. The authors had no conflicts of interest.

REFERENCES


