Lactating Sows and Suckling Piglets Preferentially Incorporate RRR- over All-rac-α-Tocopherol into Milk, Plasma and Tissues

Charlotte Lauridsen,*2 Harold Engel,† Soren K. Jensen,* A. Morrie Craig† and Maret G. Traber**

*Department of Animal Nutrition and Physiology, Research Centre Foulum, DK-8830 Tjele, Denmark; †School of Veterinary Medicine, Linus Pauling Institute, Oregon State University Corvallis, OR 97331; and the **Department of Internal Medicine, University of California, Davis, School of Medicine, Sacramento, CA 95817

ABSTRACT Synthetic vitamin E, all-rac-α-tocopherol, contains eight different stereoisomers, only one of which, RRR-α-tocopherol, occurs naturally. The objective of this investigation was to evaluate the relative abilities of these two vitamin E forms to enrich piglet tissues when fed as α-tocopheryl acetates to sows during pregnancy and lactation. α-Tocopherol delivery to fetuses and to suckling piglets was monitored by feeding 150 mg each of d6-RRR-α- and d6-all-rac-α-tocopheryl acetate to three pregnant sows daily from 7 d before to 7 d after giving birth. Labeled and unlabeled vitamin E concentration ratios were measured in sow plasma and milk, and in piglet (n = 9) plasma and tissues at birth, 7 and 21 d. At birth, despite elevated sow plasma deuterated α-tocopherol concentrations, no labeled α-tocopherol was detected in piglet plasma or tissues. Sow plasma and milk d6-α- to d6-α-tocopherol concentrations were 2:1, leading to a 2:1 ratio in suckling piglet plasma and tissues. In piglets at d 7 compared with birth, most tissues contained a 10-fold increase in total α-tocopherol; the highest deuterated vitamin E concentrations were in the liver, followed by the lung, heart, kidney, muscle, intestine and brain. In conclusion, pigs discriminate between RRR- and all-rac-α-tocopherol with a preference for RRR-α-tocopherol; thus, the official bioequivalence ratio of 1.36:1 RRR- to all-rac-α-tocopherol is underestimated. After initiation of suckling, piglet plasma and tissues demonstrated a dramatic increase in vitamin E concentrations, emphasizing the limited placental vitamin E transfer and the importance of milk for enhancing the vitamin E status of the newborn. J. Nutr. 132: 1258–1264, 2002.

KEY WORDS: • stable isotopes • bioactivity • α-tocotrienol • γ-tocopherol • γ-tocotrienol • pigs

Vitamin E is an important nutrient for the growth and health status of pigs, which are born with very low body fat reserves and low tissue vitamin E deposits, factors that contribute to the sudden death of baby pigs. Vitamin E cannot be synthesized by pigs and must be provided with the feed. Supplemental vitamin E is almost exclusively added as all-rac-α-tocopheryl acetate to commercial feed. Not only does the vitamin E content ensure the health of the animal, high dietary vitamin E intakes improve meat quality by protecting muscle cells from peroxidative damage (1).

Relatively little information is available in pigs, or even humans, concerning vitamin E delivery to the fetus during pregnancy or to suckling infants from milk. Therefore, studies of vitamin E transport and tissue uptake during pregnancy and lactation in pigs may provide important information applicable to human nutrition. Human babies are born nearly vitamin E-deficient (2,3) and then acquire vitamin E from milk (4–6). It remains controversial whether the low α-tocopherol concentrations measured in cord blood are reflective of low tissue α-tocopherol concentrations or of low plasma lipid and lipoprotein concentrations. In the latter case, plasma α-tocopherol carriers may be unavailable, but tissue α-tocopherol concentrations may be adequate.

Vitamin E has historically included α-, β-, γ-, and δ-tocopherols and α-, β-, γ-, and δ-tocotrienols because they all have similar antioxidant activities. However, α-tocopherol is maintained at the highest level in plasma and tissues of humans and other animals. Therefore, it has been accorded the highest biological activity (7) and vitamin E supplements are marketed as α-tocopherol or its esters. Synthetic α-tocopherol (all-rac-α-tocopherol, [2, 5, 7, 8-tetramethyl-2RS-(4′RS, 8′RS, 12 trimethyltridecyl)-6-chromanol]) is not identical to the naturally occurring form, RRR-α-tocopherol [2, 5, 7, 8-tetramethyl-2RS-(4′RS, 8′RS, 12 trimethyltridecyl)-6-chromanol], which represents only one of the eight stereoisomers present in all-rac-α-tocopherol (RRR-, RRS-, RSS-, SRR-, SSR-, SRS-, SSS). In humans, the 2S-stereoisomers disappear rapidly from the plasma (8); therefore, when RRR- and all-rac-α-tocopheryl acetates are administered in equal amounts to humans, plasma and tissue ratios of natural to synthetic α-tocopherol equal two because only the 2R-stereoisomers are

---

1 Supported by the California Dairy Council and the Danish Agricultural and Veterinary Research Council.
2 To whom correspondence should be addressed.
E-mail: charlotte.lauridsen@agrsci.dk.
retained (9). Thus, deuterated RRR-α-tocopherol concentrations are double those of all-rac-α-tocopherol in plasma (8–12) or tissues (9). The commonly used vitamin E biopotency factor for supplements and food fortificants is 1 u equals 1.00 mg all-rac-α-tocopheryl acetate or 1.36 mg RRR-α-tocopheryl acetate (13). However, this biopotency factor is calculated based on the amount of vitamin E necessary to prevent fetal resorption in pregnant, vitamin E-deficient rats (14,15). The biopotency factor does not take into account the role of the α-tocopherol transfer protein (α-TTP)3, which discriminates between forms of α-tocopherol, maintains plasma α-tocopherol concentrations and has been localized both to the liver and to the pregnant mouse uterus (16,17). These data suggest that the fetoplacental assay for assessing vitamin E biopotency is flawed because the protein in the uterus will facilitate delivery of all forms of vitamin E if the preferred RRR-α-tocopherol is at low concentrations, as would be expected in vitamin E-deficient rats.

The role of the α-TTP in determining plasma and tissue α-tocopherol concentrations was a critical factor for establishing Dietary Reference Intakes for optimal human vitamin E nutriture, as reported by the Food and Nutrition Board in 2000 (18). Their report states that the forms of vitamin E that meet human requirements are only the 2R-stereoisomers of α-tocopherol. Thus, in humans all-rac-α-tocopherol has only one-half of the activity of RRR-α-tocopherol. However, studies comparing natural with synthetic-α-tocopherols in humans during pregnancy suggest that synthetic vitamin E is not even one-half as effective as the natural form (19). Mechanisms to explain a ratio > 2 were suggested to involve additional discriminatory factors in the placental-fetal unit, but such postulated mechanisms have not been elucidated. In sows, supplementation with all-rac-α-tocopheryl acetate before and during lactation increased α-tocopherol concentrations in colostrum and in piglet tissues (20,21). Furthermore, Mahan et al. (22) found higher milk α-tocopherol concentrations in sows fed RRR-α-tocopherol acetate compared with all-rac-α-tocopherol acetate. These data, however, do not give a quantitative measure of the efficacy of the two vitamin E forms because the newly absorbed α-tocopherol replaces the circulating α-tocopherol (23), thereby preventing quantitative estimates of the total dose incorporated into the plasma or milk.

For determination of the relative activities of natural and synthetic vitamin E, the use of stable isotope-labeled α-tocopherols has major advantages over nonlabeled compounds. The natural and synthetic vitamin E forms can be ingested simultaneously for intra-individual comparisons. Using a competitive uptake approach, the plasma isotopic ratio can be used as an indicator of biopotency (9). However, in the case of synthetic α-tocopherol, all eight stereoisomers are equally labeled, and it not possible to measure each individual isomer. Thus, the observed ratio of 2:1, natural to synthetic α-tocopherols observed in previous studies in humans (9), is likely a result of the preference of α-TTP for 2R-α-tocopherols, but this has not been proven directly.

The objective of this investigation was to evaluate the efficacy of natural compared with synthetic vitamin E in lactating sows and their progeny. To carry out the investigation RRR-α-tocopherol acetate labeled with 3 deuterium atoms and all-rac-α-tocopheryl acetates labeled with 6 deuterium atoms replacing the hydrogen atoms in the methyl groups on the chromanol ring were fed for a week to pregnant sows before delivery and then for 1 wk of lactation. Sow plasma and milk, as well as newborn plasma and tissue concentrations of labeled and unlabeled vitamin E were quantitated and the relative concentrations of d3 and d6-α-tocopherols evaluated.

MATERIALS AND METHODS

Animals. The protocol used in this study was approved by the Institutional Animal Care and Use Committee of Oregon State University. The animals were raised and cared for at the Linn-Benton Community College/Oregon State University Swine Research Center. Two of the sows were littermates (age 3 y), while the third sow was a half-sister (age 4 y); all had been pregnant the previous year. In addition, the sows were artificially inseminated with semen from the same boar. The Yorkshire breed sows weighed ~250 kg at the time of the experiment.

Feed, provided twice daily in individual feeding crates, was a commercially available pelleted diet for sows (Purina Mills, St. Louis, MO). The chemical composition of the diet was determined according to the procedure of the Association of Official Analytical Chemists (24), and digestibility of organic matter was determined according to Boisen and Fernandez (25). The dry matter content of the diet was 90.0% and contained 19.1% crude protein, 7.3% crude fat, 6.1% ash, and 3.9% crude fiber. The enzyme digestibility of organic matter was 86.8%. The amount of vitamin E (all-rac-α-tocopheryl acetate) added to the diet was 17.5 m/kg feed. The calculated amount of dietary vitamin E, which was determined as described below, is provided in the Results section.

Protocol. Capsules containing deuterated vitamin E (gift from the Natural Source Vitamin E Association, Washington, DC) were synthesized by Eastman Kodak (Rochester, NY). The isotopic purities of the deuterated compounds (d4-RRR- and d6-all-rac-α-tocopheryl acetates) at their nominal level of deuteration were 84% (d4: 4.0%; d6: 2.0%; d6: 9.7%) and 86% (d6: 0.1%; d6: 0.8%; d6: 1.3%; d6: 11.2%), respectively; the d4/d6 ratio was determined by gas chromatography-mass spectrometry to be 0.98 (12). At d 108 of gestation, and daily for the following 2 wk, two capsules were provided each sow with the morning feed. Each capsule contained 75 mg each of d4-RRR-α- and d6-all-rac-α-tocopheryl acetates (total 300 mg tocopheryl acetates). The sows were observed to ensure that they ate the capsules.

Blood samples were obtained from the marginal ear vein of the sows at d 108 and 112 of gestation (e.g., −7 and −3 d before farrowing), and at d 1, 4, 7, 14 and 21 of lactation, where d 1 is the day of birth. Blood samples were collected in evacuated tubes containing EDTA-containing tubes. Milk samples (e.g., 10 mL per sample) from each sow were obtained at d 1 (the day of farrowing), 7, 14 and 21 of lactation by hand-milking from the teats (samples of the teats were pooled). Plasma and milk samples were immediately placed on ice and stored at −80°C until analysis.

Piglets were weighed individually on the day of birth, and at d 4, 7, 14 and 21 of age. From each piglet, blood samples were drawn from the vena cava at d 4, 7, 14 and 21 of age by the use of vacuum needles and evacuated tubes containing EDTA. In addition, a blood sample of three piglets per litter was obtained from the heart, killed before sucking on the day of birth. Blood samples were treated as described above.

Blood samples from each piglet were killed immediately after birth before sucking by intravenous injection of pentobarbital. In addition, three piglets per litter were killed at d 7 of age (the last day capsules were provided the sows), and at d 21 of age (14 d after capsules had been provided the sows). Heart, liver, lung, kidney and brain were obtained and weighed. The entire organs and samples of small intestine,

---

3 Abbreviation used: α-TTP, α-tocopherol transfer protein.
Deuterated vitamin E

Sows’ plasma and milk. The sows’ plasma deuterated α-tocopherol concentrations from d 108 (d −7) of gestation until d 14 of lactation are shown in Figure 1; by d 21 they were below the levels of detection. Comparing d 108 with d 112 (d −3), both $d_3$ (P = 0.0001) and $d_6$-α-tocopherols (P = 0.0001) increased in response to supplementation (Fig. 1A). On d 112 during delivery, concentrations of both labeled α-tocopherols decreased (P < 0.05, d −3 vs. d 1). Supplementation continued through d 6, and by d 7 plasma concentrations began to decrease.

The percentage of deuterated α-tocopherol [% deuterated α-tocopherol = 100 x ($d_3 + d_6$-α-tocopherols)/($d_3 + d_6$-α-tocopherols)] reached a maximum (54%) on d 4 of lactation (Fig. 1B; P < 0.001, d 1 vs. d 4). Subsequent to cessation of deuterated tocopherol supplementation on d 7 of lactation, a significant decrease in percentage deuterated forms was observed (P < 0.001, d 7 vs. d 14). The plasma $d_3$ to $d_6$-α-tocopherol ratio from d 112 of gestation and until d 14 of lactation remained ~2.

Milk $d_3$-α-tocopherol concentrations were also double those of $d_6$ at all times during lactation (P = 0.0003; Table 1). The percentage of deuterated α-tocopherol reached a maximum on lactation d 4 (coincident with the plasma peak) and decreased thereafter to 10.4% on d 21 of lactation.

Piglets’ plasma. No deuterated α-tocopherol was detected in the umbilical cord blood or in the piglet plasma before suckling, but some unlabeled α-tocopherol was detected (see below). Piglet plasma deuterated tocopherol concentrations during the suckling period are depicted in Figure 2. The highest plasma deuterated tocopherol concentrations were observed on d 4. Although the absolute concentration of deuterated α-tocopherol decreased from 4 to 7 d (P < 0.001; Fig. 2A), the relative percentage of deuterated α-tocopherol remained constant during these 3 d because the fraction unlabeled decreased (see below). By d 7 the percentage of deuterated α-tocopherol had reached a maximum of 43.6% ± 1.8% (Fig. 2B). The plasma $d_3$ to $d_6$-α-tocopherol ratio was ~2 throughout the experiment and was not influenced by the age of piglets.

Piglet tissues. Piglet tissue vitamin E concentrations are shown in Figure 3. At birth (d 1), no deuterated tocopherol

### RESULTS

**TABLE 1**

<table>
<thead>
<tr>
<th>Lactation days</th>
<th>$d_3$-α-tocopherol</th>
<th>$d_6$-α-tocopherol</th>
<th>Deuterated $d_3/d_6$ ratio</th>
<th>%</th>
<th>µmol/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (before delivery)</td>
<td>2.82a&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>1.51&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>30.8&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.9ab</td>
<td></td>
</tr>
<tr>
<td>1 (after delivery)</td>
<td>3.69a</td>
<td>1.93&lt;sup&gt;a&lt;/sup&gt;</td>
<td>30.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.9ab</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4.31a&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>2.54&lt;sup&gt;b&lt;/sup&gt;</td>
<td>40.1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1.8b</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.73&lt;sup&gt;b&lt;/sup&gt;/b&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.89&lt;sup&gt;c&lt;/sup&gt;</td>
<td>35.0&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>2.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>1.70&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.85&lt;sup&gt;b&lt;/sup&gt;</td>
<td>22.3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2.1&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>0.18&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.08&lt;sup&gt;c&lt;/sup&gt;</td>
<td>10.4&lt;sup&gt;d&lt;/sup&gt;</td>
<td>2.1&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>SEM</td>
<td>0.61</td>
<td>0.32</td>
<td>2.5</td>
<td>0.09</td>
<td></td>
</tr>
</tbody>
</table>

<sup>1</sup>Values are least-square means, n = 3. Means in a column not sharing a superscript differ, P < 0.05.
could be detected in the tissues; moreover no adipose tissue was present in the piglets. In all tissues, deuterated α-tocopherols were detected on d 7, and the percentages of deuterated α-tocopherols were at a maximum.

Brain and adipose tissue were unique in that the deuterated α-tocopherol concentrations were unchanged from d 7 to d 21, while all other tissues exhibited a decrease in deuterated α-tocopherol concentrations.

Tissue α-tocopherols were also calculated on an organ weight basis. Remarkably, the deuterated α-tocopherols per brain were higher at d 21 than at d 7 (Table 2), while in all other tissues examined the amounts were lower at d 21. The liver gained the most weight over the 21 d, while the brain gained the least. During the first week of life, the liver acquired the largest amount of labeled α-tocopherol on a per organ basis, followed by the lungs, the heart, the kidney and finally the brain.

**Dietary vitamin E**

**Sows’ feed, plasma and milk.** The sow feed was found to contain various naturally occurring vitamin E forms, including γ-tocotrienol, 11.7 ± 1.9 μmol/kg feed; α-tocotrienol, 8.0 ± 1.4 μmol/kg; γ-tocopherol, 40.8 ± 7.2 μmol/kg; as well as unlabeled α-tocopherol, 51.1 ± 9.2 μmol/kg. However, the sow plasma only contained α- and γ-tocopherols and some minor amounts of α-tocotrienol (Fig. 4).

Vitamin E concentrations were higher in milk than in sow plasma; both γ-tocotrienol (Table 3) and traces of δ-tocopherol (results not shown) were detected in milk.

**Piglets’ plasma and tissue.** Plasma total α-tocopherol concentrations were very low at birth, had increased by d 4 (P = 0.0001) and decreased slowly until d 14 (P = 0.03; Fig. 5). Throughout the suckling period, the α-tocotrienol and γ-tocopherol concentrations were < 1/100 of the α-tocopherol concentrations, whereas γ-tocotrienol was not detected in the piglets’ plasma.

At birth, the variation in plasma vitamin E was high (as shown in Fig. 5); no vitamin E was detected in some plasma samples. In umbilical cord plasma, concentrations were also very low: d 0 α-tocopherol: 0.65 ± 0.16 μmol/L, α-tocotrienol: 0.0018 ± 0.0031 μmol/L, and γ-tocopherol: 0.0040 ± 0.0070 μmol/L.

At birth, total α-tocopherol concentrations were very low in lung, heart and muscle tissue, but by d 7 these had increased markedly (Fig. 3). In liver (P = 0.0001), muscle (P < 0.0001), and kidney (P < 0.044), unlabelled α-tocopherol concentrations were lower at d 21 than at d 7, whereas in adipose tissue (P < 0.03) and brain (P = 0.0001) the unlabelled α-tocopherol concentrations were higher at d 21 than at d 7 (Fig. 3). The unlabelled α-tocopherol concentrations in heart were unchanged (P = 0.14). As shown in Table 4, liver (P < 0.04), kidney (P < 0.001) and intestine (P = 0.03) γ-tocopherol concentrations decreased from d 7 to d 21, whereas those of the brain (P = 0.005) and heart (P < 0.003) increased. Except for an increase in the muscle concentration of γ-tocotrienol (P < 0.001), no statistically significant differences between d 7 and d 21 were observed.
and d 21 were found tissue α- and γ-tocotrienol concentrations.

DISCUSSION

In this study, the natural and synthetic forms of α-tocopherol were compared in sows' plasma and milk via an oral supplement of a 1:1 mixture of d3-RRR and d3-all-rac-α-tocopherol acetates. The concentrations of d3-α-tocopherol in plasma, colostrum and milk of the sows were significantly greater than those of d6-α-tocopherol, roughly 2:1.

The results also showed that the sow preferentially transferred d3-α-tocopherol into the milk, which showed a d3 to d6 α-tocopherol ratio of 2:1. The liver plays a critical role in the process of stereoselection between the natural and the synthetic forms of vitamin E, as a result of the process of stereoselection between the natural and the synthetic forms of vitamin E in plasma, colostrum and milk of the sows was significant.

Greater than those of d6-α-tocopherol, roughly 2:1. The liver plays a critical role in the stereoselection mechanism operates continuously on all tocopherols entering the liver (both newly absorbed and recirculated) and quickly establishes its maximum effect in plasma (9). α-TTP has not been reported in pigs, but in rats the expression of α-TTP in liver was low immediately after birth, increased steadily during the 2 wk of life and reached the adult level at 4 wk (31). Additionally, the presence of an α-TTP-like mechanism in the mammary gland cannot be excluded; mammary gland α-TTP could facilitate α-tocopherol secretion into milk. Jensen et al. (32) showed that the daily secretion of α-tocopherol into milk can be described using Michaelis-Menten kinetics, which applies for carrier-mediated transport across membranes and is independent of milk yield and milk fat content.

The retention of d3-RRR-α-tocopherol by the brain compared with other tissues from d 7–21 supports previous studies (33,34) in which the brain showed an extraordinary discrimination in favor of natural RRR-α-tocopherol. Brain α-TTP may be important in this regard (16). Compared with other tissues, the absolute concentration of labeled vitamin E accumulated in the brain was low; similarly a modest increase in rat brain α-tocopherol has also been reported (35). Amusquivar et al. (36) fed rat dam fish oil-containing diets with all-rac-α-tocopherol acetate at concentrations of 0.1 or 1 g/kg diet and then measured tissue α-tocopherol concentrations of the 21-

**TABLE 2**

| Organ weights and d0-, d3- and d6-α-tocopherol levels in piglets that consumed milk from sows fed from d−7 (d 108 of pregnancy) to d 7 of lactation of an equal mixture of d3-RRR and d6-all-rac-α-tocopherol acetates |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Organ weight    | d0              | d7              | d21             | d0              | d7              | d21              |
| g               | nmol            | nmol            | nmol            | nmol            | nmol            | nmol            |
| Brain           | 26.6 ± 1.2      | 33.6 ± 13.3     | 135.8 ± 34.4    | 33.6 ± 13.3     | 135.8 ± 34.4    | 33.6 ± 13.3     |
| Kidney3         | 5.2 ± 1.3       | 147.6 ± 27.1    | 170.5 ± 58.7    | 5.2 ± 1.3       | 147.6 ± 27.1    | 170.5 ± 58.7    |
| Heart           | 10.4 ± 2.1      | 421.5 ± 28.6    | 480.1 ± 190.0   | 10.4 ± 2.1      | 421.5 ± 28.6    | 480.1 ± 190.0   |
| Lung            | 21.1 ± 4.9      | 651.8 ± 124.8   | 847.3 ± 143.3   | 21.1 ± 4.9      | 651.8 ± 124.8   | 847.3 ± 143.3   |
| Liver           | 38.9 ± 11.4     | 1642.7 ± 365.8  | 2185 ± 1189     | 38.9 ± 11.4     | 1642.7 ± 365.8  | 2185 ± 1189     |

1 Average body weight gain per piglet from 0 to 21 d of age was 5.1 ± 1.2 kg.
2 Values are means ± SD, n = 9.
3 Values are from one kidney per piglet.

**FIGURE 4** Sow plasma α- (total) (SEM = 0.443 μmol/L) and γ-tocopherol (SEM = 0.026 μmol/L) and α-tocopherol (SEM = 0.0044 μmol/L) concentrations (μmol/L) after daily oral administration from d−7 (d 108 of pregnancy) to d 7 of lactation of an equal mixture of d3-RRR- and d6-all-rac-α-tocopherol acetates. Values are means, n = 3.
d-old suckling rats. Brain α-tocopherol concentrations were similar in both groups despite higher liver and plasma concentrations in those rats suckling from dams fed diets containing 10 times higher vitamin E concentrations. These data suggest that the brain has a mechanism to regulate α-tocopherol concentrations.

The accumulation of labeled vitamin E in the piglets increased in the following sequences: brain<kidney<heart<lung< liver (Table 3). This study shows that the porcine liver has a very high short-term storage capacity for vitamin E, as also described previously (37). The rapid loss of labeled vitamin E from the liver after cessation of supplementation in the sows at d 7 may be a result of export to other tissues.

Based on these results and in accordance with the conclusion of Mahan et al. (22), a conversion factor of 1.36 in applying the biological equivalence of all-rac-α-tocopheryl acetate to RRR-α-tocopheryl acetate is not appropriate for sows. If the 1.36 value had been correct, the plasma and milk RRR:all-rac ratios should have been 1.36:1. The bioactivity of the natural compared with the synthetic form of vitamin E is on the order 2:1 in favor of the RRR-form.

Plasma α-tocopherol concentrations in sows decreased from late gestation to parturition. The drop in the plasma at parturition is perhaps a consequence of a considerable amount of α-tocopherol partitioned into the colostrum (20) but may also be a decrease in lipoprotein output from the liver during labor. Tissues sampled from piglets killed before they had consumed colostrum had very low vitamin E concentrations (Fig. 3), suggesting that α-tocopherol crosses the placenta in very limited amounts, as was previously reported (19, 37). In our study as well as in the study by Farnworth et al. (38), the effect of the maternal dietary vitamin E supplementation during the last week of pregnancy seemed to be negligible because no labeled vitamin E was detected in the newborn piglets. However, a trend for higher tissue levels in piglets born to sows receiving higher levels of vitamin E in their gestation diets was reported by Hidiroglou et al. (21). Likewise, i.m. supplementation of 1.5 g α-tocopheryl acetate on d 7 and 2 before farrowing increased the vitamin E concentration in colostrum of sows and in the serum of piglets 2 and 5 d after birth (39). The ingestion of colostrum with its high α-tocopherol concentration, therefore, plays an important role in determining the plasma α-tocopherol concentrations, as well as vitamin E status of the newborn piglets. These data showed an approximate 83-fold increase in plasma α-tocopherol concentrations by d 4 (Fig. 2).

Despite relatively high concentrations of non-α-tocopherol vitamin E forms in the feed, sow plasma α-tocopherol and α-tocotrienol concentrations were much lower than α-tocopherol concentrations. In humans, all forms of vitamin E are absorbed, but the plasma becomes preferentially enriched in α-tocopherol as a result of α-TTP (40). The relatively low contributions of dietary γ-tocopherol and α-tocotrienol to plasma vitamin E status were expected from previous results in pigs (41).

Sow’s milk, γ-tocopherol and α-tocotrienol contributed almost the same percentage (2.3% to 5.2%) to the total vitamin E, whereas the contribution of γ-tocotrienol was lower but generally increased throughout the lactation period. However, the contribution of these derivatives to the piglets’ vitamin E status was negligible.

In conclusion, the bioactivity of synthetic all-rac-α-tocopherol is roughly one-half of that of natural RRR-α-tocopherol during pregnancy and lactation in sows, resulting in a 2:1 ratio of the natural and the synthetic vitamin E forms in milk and in the suckling progeny. The other vitamin E derivatives

### Table 4

<table>
<thead>
<tr>
<th>Tissue</th>
<th>α-tocotrienol</th>
<th>γ-tocopherol</th>
<th>γ-tocotrienol</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>d 1</td>
<td>d 7</td>
<td>d 21</td>
</tr>
<tr>
<td>Lung</td>
<td>0.023&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.077&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.061&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Liver</td>
<td>ND</td>
<td>0.200&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.104&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Heart</td>
<td>0.012&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.062&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.078&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Brain</td>
<td>ND</td>
<td>0.120</td>
<td>0.131</td>
</tr>
<tr>
<td>Kidney</td>
<td>ND</td>
<td>0.065</td>
<td>0.070</td>
</tr>
<tr>
<td>Muscle</td>
<td>0.001&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.329&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.412&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Intestine</td>
<td>ND</td>
<td>0.059</td>
<td>0.065</td>
</tr>
<tr>
<td>Adipose&lt;sup&gt;2&lt;/sup&gt;</td>
<td>—</td>
<td>0.391</td>
<td>0.242</td>
</tr>
</tbody>
</table>

1 Values are least-square means, n = 9. Means in a row for a variable not sharing a superscript differ, P < 0.05.
2 Adipose tissue could not be obtained at birth.
present in the diet only represented a minor contribution to the vitamin E status of the sows and the piglets.

ACKNOWLEDGMENTS

Scott W. Leonard, Angela Mastaloudis and Lars Bilde Gildberg are greatly acknowledged for their technical assistance.

LITERATURE CITED