ABSTRACT: Second-parity sows (n = 7) were fed diets containing organic or inorganic trace minerals, and their progeny (n = 68) were used to determine the Fe status of pigs at birth and nursing and postweaning phases. The experiment comprised 2 parts, in which the first experiment was a 2 × 2 factorial arrangement. Sow trace mineral (organic vs. inorganic) was the first factor evaluated, and the injection of Fe (0 or 200 mg) to neonatal pigs within litter was the second factor. In Exp. 2, half the pigs in each litter from each neonatal Fe injection group were injected with Fe (0 vs. 200 mg) at weaning as an added factor in a 2 × 2 × 2 factorial arrangement in a split-split-plot design. Weanling pigs were fed diets fortified with 90 mg/kg of Fe (sulfate), but the analyzed indigenous and fortified Fe content was 170 mg/kg. Pigs in both experiments were bled at periodic intervals to determine hemoglobin (Hb) concentration, percentage of hematocrit (Hct), and ceruloplasmin oxidase activity. Neonates and d-2 pigs from sows fed organic trace minerals had lower (P < 0.05) Hb concentrations compared with sows fed inorganic Fe. Blood Hb seemed to remain lower throughout the nursing period when sows were fed organic vs. inorganic Fe. Pigs without Fe injection had decreased ADG (P < 0.05) from 0 to 7 and 7 to 17 d than pigs injected with Fe. Although Hb values increased when neonatal pigs received Fe injection, they were somewhat lower when sows were fed the organic Fe. Ceruloplasmin oxidase activity was low at birth, increased to weaning in each treatment group, and was greater in pigs without Fe injection at d 13 (P < 0.05) and those from sows fed organic minerals at d 17 (P < 0.01). In Exp. 2, when the Fe-fortified diet was fed, BW and ADG responses were both greater (P < 0.01) to 28 d postweaning when neonates had received Fe injections. Neonates not injected with Fe at birth but injected at weaning had greater ADG, Hb, and Hct values, whereas pigs injected with Fe did not respond to Fe injection at weaning, which resulted in interactions (P < 0.05) in those criteria at most measurement periods. The results indicated a reduced Fe bioavailability when sows were fed the organic Fe source, but this may also have been due to the greater Fe need, lowered Fe status, or both, of the sow because of the greater number of pigs farrowed and heavier litter weights at parturition and weaning. The results also indicated that Fe injections at birth may be critical to achieving maximum pig growth response to weaning. There was no apparent advantage to injecting Fe at weaning when neonatal pigs received Fe injections.

Key words: anemia, iron, pig, reproduction, trace mineral

INTRODUCTION

Nursing pigs require 7 to 16 mg of Fe/d to support erythropoiesis and other metabolic activities associated with Fe (NRC, 1998). The young pig uses the 40 to 50 mg of its body stores that is transferred during gestation plus Fe supplied from sow milk to meet its Fe need, but these supplies become inadequate within 7 to 10 d of age, and the pig becomes anemic. Larger and faster growing pigs will exhibit signs of anemia sooner because of their increasing tissue growth and the corresponding need for a greater blood volume.

Attempts to increase neonatal Fe reserves (Pond et al., 1961) and milk Fe concentration (Venn et al., 1947;
Pond et al., 1965) have largely been unsuccessful. To prevent anemia in young pigs, an exogenous Fe source must be administered, with the most common method being an i.m. injection (Ullrey et al., 1959; Kernkamp et al., 1962). Nursing pigs have been reported to practice coprophagy and thus can absorb the Fe ingested from sow fecal excrement. However, with the use of slotted farrowing crates, this is not a dependable source of Fe for the young pig.

Reports have indicated that an organic Fe source fed to pregnant sows increases fetal Fe stores, lowers the number of stillbirths, increases pig birth weight, increases piglet blood hemoglobin (Hb), reduces postnatal pig mortalities, and results in heavier pig weaning weights (Close, 1999). Collectively, these results imply that organic Fe may be a potentially better source of Fe than the inorganic Fe salts currently fed to most reproducing sows.

This experiment evaluated the effect of feeding diets containing either an organic or inorganic Fe trace mineral source to reproducing sows on the subsequent Fe status of neonatal pigs. In addition, the effect of Fe administered to their pigs at birth and weaning on blood hematological measurements and postnatal growth performance was evaluated.

**MATERIALS AND METHODS**

The experimental use of animals and the procedures followed were approved by the College Animal Care Committee.

Second-parity sows (Yorkshire × Landrace) were used to evaluate the effect of dietary trace mineral source on the Fe status of their progeny at birth and then to investigate the subsequent carryover effects during the nursing and postweaning periods when pigs received various exogenous doses of Fe administered postnatally. Because pigs were continued from the nursing phase into the nursery phase, where additional treatments were imposed, the experiment was separated into 2 experiments.

**Exp. 1**

In Exp. 1, sows were selected (n = 7) from a larger subset from another experiment in which their diets contained either an organic or inorganic Fe trace mineral premix. Our first experiment was conducted as a 2 × 2 factorial arrangement in a split-plot design, with the first factor being the sow trace mineral source containing organic or inorganic Fe and the second factor being an i.m. injection of Fe to the neonate (0 or 200 mg) as Fe dextran. A total of 68 Yorkshire × Landrace × PIC (line 280) pigs originally born to those sows were the only pigs used for the blood hematological measurements in the experiment. Although pigs were cross-fostered to equalize lactation litter size, they were not used for blood measurements. Cross-fostered pigs were, however, included in the growth and gain data. Within each litter, 3 to 4 neonatal pigs were randomly selected and bled via cardiac puncture before the consumption of colostrum for the determination of initial hematological values.

Pigs were bled and weighed on d 2, 7, 9, 13, and 17 postpartum. Blood samples (2 to 3 mL) were obtained by cardiac puncture using 20-gauge, 3.8-cm-long needles and were collected into 3-mL heparinized (45 USP units of sodium heparin) vacutainer tubes (Becton Dickinson, Franklin Lakes, NJ) and placed on ice. After transportation to the laboratory, samples were analyzed for Hb concentration and percentage of hematocrit (Hct), as described below. The remaining blood was centrifuged (2,200 × g at 5°C for 15 min) and stored at 4°C, and ceruloplasmin oxidase activity was determined on individual plasma samples, as described below.

**Exp. 2**

At the time of weaning, pigs from Exp. 1 were allotted within each litter to 2 additional treatment groups. Half of the pigs in each litter from each neonatal Fe injection treatment group received either 0 or 200 mg of Fe (dextran) i.m. in the neck muscles at weaning. The postweaning pig experiment was thus conducted as a 2 × 2 × 2 factorial arrangement of treatments in a split-split-plot design. The original sow dietary trace mineral source (organic or inorganic) was the main plot, and the neonatal Fe injection (0 vs. 200 mg of Fe) and Fe injection at weaning (0 vs. 200 mg of Fe) were the sub-subplots. This phase of the experiment evaluated postweaning performance and also carryover responses from the prenatal and nursing phases.

Pigs in Exp. 2 were allotted to nursery pens (approximately 0.30 m² of floor space/pig) with 4 to 5 pigs/pen and 4 pens/treatment, based on their Fe injection at birth and BW. Each pen contained 1 stainless steel nipple waterer and a 4-hole, stainless steel feeder. Environmental temperatures were initially set at 28°C but were adjusted as needed to remain within the comfort zone of the pig.

Pigs were bled and weighed on 0, 7, 10, 14, 17, 21, and 28 d postweaning. Blood samples (2 to 3 mL) were collected into 3-mL heparinized vacutainer tubes via cardiac puncture, placed on ice, and transported to the laboratory for hematological determinations. The remaining blood was centrifuged and stored at 4°C, and ceruloplasmin oxidase activity was determined on individual plasma samples, as described below.

**Experimental Premixes and Diets**

The organic trace mineral premix fed to the sows contained a source of organic Fe, along with other essential trace minerals (Cu, Mn, and Zn) chelated to hydrolyzed soy protein (Bioplex, Alltech Inc., Nicholasville, KY). Selenium was added as a yeast source (Sel-Plex, Alltech Inc.). The inorganic trace minerals were salts
in the sulfate form, including Fe sulfate, except Se and Mn, which were added as Na selenite and Mn oxide, respectively. Chromium picolinate was added to the diets of both sow groups. Each organic or inorganic trace mineral premix contained 15 ppm Cu, 120 ppm Fe, 40 ppm Mn, 0.30 ppm Se, 120 ppm Zn, and 0.20 ppm Cr. Composition of the organic and inorganic trace mineral premixes and the diets fed to sows were previously reported (Peters and Mahan, 2008). The products were purchased from a commercial premix company (Akey, Lewisburg, OH). The trace mineral level added to the corn-soybean meal sow diets were considered industry standards, thus exceeding the NRC (1998) requirements. Composition of the organic and inorganic trace mineral premixes and the diets fed to the sows were previously reported (Peters and Mahan, 2008).

The dietary trace minerals were initially fed to gilts during the nursery period (Table 1). The trace mineral premix in the nursery diets contained inorganic trace minerals fortified with 90 mg of Fe (Fe sulfate), 8 mg of Cu (sulfate), 20 mg of Mn (oxide), 0.30 mg of Se (selenite), and 100 mg of Zn (sulfate)/kg of diet and provided on an as-fed basis. Analysis of the complete diets, including both the indigenous Fe in the feed grains and exogenous macromineral sources plus the supplemental 90 ppm Fe (sulfate), exceeded the NRC (1998) requirement for Fe. Nursery diets were formulated to a total Lys concentration of 1.55 and 1.45% during the 0 to 14-d and 14 to 28-d periods, respectively. Diets met or exceeded all NRC (1998) nutrient requirements.

### Analytical Methods

Total Hb concentration in whole blood was determined using the AOAC (2000) method by conversion of Hb and its derivatives to cyanmethemoglobin, and absorbance at 540 nm was determined. Blood samples were centrifuged (Micro Capillary Centrifuge, MB International Equipment Co., Boston, MA) to determine percentage of Hct using the microhematocrit method (INACG, 1985). The remaining blood was centrifuged at 2,200 x g at 5°C for 15 min, and plasma was collected and stored at 4°C for the determination of ceruloplasmin oxidase activity. Plasma ceruloplasmin oxidase activity analysis was performed the day after blood sample collection by spectrophotometry at room temperature using the method of Lehmman et al. (1974). Ceruloplasmin oxidase activity was calculated using the change in absorbance between tubes incubated for 5 and 15 min and the molar absorptivity of the substrate (o-dianisidine dihydrochloride; D-2757, Sigma Chemical Co., St. Louis, MO) consumed. Ceruloplasmin oxidase activity is expressed in international units per milliliter of plasma, where 1 IU equals activity oxidation rate decline of 200 µL of o-dianisidine from 50 µL of plasma.

Nursery diets were analyzed for trace mineral content using inductively coupled plasma equipment methodology (PS 3000, Leeman Labs Inc., Hudson, NH). Selenium was analyzed in the diets after they were wet-ashed in nitric and perchloric acid using the fluorometric method outlined by AOAC (2000).

Sow and pig performance and pig hematological data were analyzed as a split-plot design (Steel and Torrie, 1980) using the GLM procedure (SAS Inst. Inc., Cary, NC). In Exp. 1, sow trace mineral source was the main plot, and Fe injection of the neonate were the subplots. Litter was considered as the experimental unit during the nursing period. In Exp. 2, the sow and neonatal Fe injection responses were statistically analyzed as in Exp. 1, with pig considered as the subplot. The data were analyzed by using the GLM procedure of SAS. Because weanling pigs within litters were separated by BW and placed into different pens containing pigs from different litters, the pigs within each pen were used as the experimental unit in this phase of the study. Consequently, only gain data could be evaluated for perfor-

### Table 1. Composition of nursery diets (% as-fed basis)

<table>
<thead>
<tr>
<th>Days fed</th>
<th>0 to 14</th>
<th>14 to 28</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn, ground</td>
<td>28.40</td>
<td>22.15</td>
</tr>
<tr>
<td>Soybean meal, 48% CP</td>
<td>28.25</td>
<td>34.60</td>
</tr>
<tr>
<td>Dried whey</td>
<td>25.00</td>
<td>25.00</td>
</tr>
<tr>
<td>Dried blood plasma</td>
<td>4.00</td>
<td>4.00</td>
</tr>
<tr>
<td>Lactose</td>
<td>8.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Choice white grease</td>
<td>3.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.75</td>
<td>0.85</td>
</tr>
<tr>
<td>Se premix</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Trace mineral premix</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Vitamin premix</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Salt, iodized</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>dl-Lys·HCl</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>dl-Met</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Zinc O, 72% Zn</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Antibacterial agent</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

1 Formulated to 1.54% Lys (total), 0.85% Ca, and 0.71% P (total).
2 Formulated to 1.45% Lys (total), 0.86% Ca, and 0.68% P (total).
3 Sodium selenite in a limestone carrier provided 0.30 mg of Se/kg of diet.
4 Supplied the following per kilogram of nursery diet: 90 mg of Fe (ferrous sulfate); 8 mg of Cu (sulfate); 20 mg of Mn (oxide); and 100 mg of Zn (sulfate). The analyzed content (in mg/kg) was as follows: Cu = 10; Fe = 175; Mn = 21; Se = 0.38; and Zn = 125 in the diet fed during 0 to 14 d and Cu = 8; Fe = 145; Mn = 21; Se = 0.36; and Zn = 214 in the diet fed during 14 to 28 d.
5 Formulated to a total Lys concentration of 1.55 and 1.45% during the 0 to 14-d and 14 to 28-d periods, respectively. Diets met or exceeded all NRC (1998) nutrient requirements.
In Table 2 are generally consistent with the previous trace minerals of organic or inorganic origin. The sow not only in the Fe source but also the other essential or inorganic trace minerals, thus their diets differed study were fed the typical industry level of organic the Fe status of their progeny. The sows used in this experiment was conducted using a subset of the parity organic trace minerals (Peters and Mahan, 2008). This and had heavier litter birth weight than those fed in- minerals farrowed more pigs (total and live) per litter e numerically greater when sows were fed organic trace minerals farrowed more pigs (total and live) per litter ef-ect of the sow trace mineral source and Fe injections pigs were used for litter performance. When Fe was injected in the neonate, the Hb concentration increased in pigs from both sow groups, but the Hb concentration in pigs from sows fed inorganic trace minerals seemed to be somewhat greater than those from sows fed organic trace minerals. This resulted in a greater difference between the noninjected and injected pigs from sows fed the organic vs. the inorganic Fe source at 7 to 17 d. There were Fe injection × sow Fe source interactions (P < 0.05) at 7 and 13 d of age. These results indicate that the injected Fe source provided more Fe relative to the maternal Fe supply, particularly when sows were fed the organic trace mineral premix.

Hematocrit values showed the same general postna- tial trend as did Hb concentrations. A decline in per-centage of Hct by 2 d of age was observed in all pigs reg ardless of the sow trace mineral source. Percentage of Hct continued to decline throughout the nursery period in non-Fe injected pigs. When neonatal pigs from both sow trace mineral groups received 200 mg of Fe, per-centage of Hct steadily increased from 2 to 17 d of age. There were Fe injection × sow Fe source interactions (P < 0.05) at 7 and 13 d of age. These results indicate that the injected Fe source provided more Fe relative to the maternal Fe supply, particularly when sows were fed the organic trace mineral premix.

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RESULTS AND DISCUSSION

Our other report indicated that sows fed organic trace minerals farrowed more pigs (total and live) per litter and had heavier litter birth weight than those fed inorganic trace minerals (Peters and Mahan, 2008). This experiment was conducted using a subset of the parity 2 sows from that study to more thoroughly investigate the Fe status of their progeny. The sows used in this study were fed the typical industry level of organic or inorganic trace minerals, thus their diets differed not only in the Fe source but also the other essential trace minerals of organic or inorganic origin. The sow reproductive performances and pig responses reported in Table 2 are generally consistent with the previous report in which a greater number of sows were used (Peters and Mahan, 2008).

Prenatal and Preweaning Responses to Fe

Sow Trace Mineral Source and Neonatal Fe Injections. Pig birth weight was similar for pigs from both sow groups, but litter birth weights were numerically greater when sows were fed organic trace minerals due to the larger litter size (Table 2). The effect of the sow trace mineral source and Fe injections in neonatal pigs on their subsequent performance and hematological responses are presented in Table 3.

The progeny from sows fed the organic Fe source had lower Hb concentrations at birth (P < 0.05) and 2 d of age (P < 0.01) than piglets from sows fed inorganic Fe. From birth to 2 d of age, a decline in blood Hb concentration occurred in all pigs. This decline is attributed to the increase in postnatal circulatory fluid from the water in colostrum, thus diluting existing blood Hb concentrations in the neonate.

When Fe was injected in neonatal pigs within 24 h of birth, there was a greater (P < 0.05) growth rate from 0 to 7 d of age than noninjected pigs, indicating that Fe administration at this early period may have improved their growth response. A greater bioavailability of injected Fe within 24 h of birth compared with oral Fe administration has been demonstrated by Hill et al. (1999). The lowered growth rate of the noninjected pig group, compared with those injected with 200 mg of Fe, continued throughout the nursery period and resulted in decreased BW (P < 0.05) at 17 d of age and ADG (P < 0.01) from 7 to 17 d of age; responses were consistent with other reports (Barber et al., 1955; Ullrey et al., 1959; Zimmerman et al., 1959).

As postnatal growth rate increases, the need for Fe increases because of the greater volume of blood necessary to maintain the greater amount of tissue being formed. The increased production of blood cells, thus the corresponding greater need for Hb, increases the Fe needed by the young pig. Blood Hb concentration declined from 0 to 17 d (weaning) of age in noninjected pigs from both sow trace mineral groups but seemed to decline somewhat faster when sows were fed organic trace minerals.

When Fe was injected in the neonate, the Hb concentration increased in pigs from both sow groups, but the Hb concentration in pigs from sows fed inorganic trace minerals seemed to be somewhat greater than those from sows fed organic trace minerals. This resulted in a greater difference between the noninjected and injected pigs from sows fed the organic than those fed the inorganic Fe source at 7 to 17 d. There were Fe injection × sow Fe source interactions (P < 0.05) at 7 and 13 d of age. These results indicate that the injected Fe source provided more Fe relative to the maternal Fe supply, particularly when sows were fed the organic trace mineral premix.
concentrations and percentages of Hct with little or no apparent carryover effect of the sow trace mineral sources. Although the hematological differences in the neonatal pig indicated a greater bioavailability of Fe from the inorganic trace mineral source fed to pregnant and lactating sows, other factors may also have contributed to this response. For example, our other results indicated that sows fed the trace mineral premix containing organic Fe farrowed more pigs with heavier birth and litter weaning weights than sows fed inorganic trace minerals (Peters and Mahan, 2008). Sows fed organic trace minerals in this study farrowed more pigs/litter (i.e., 2.5) with greater litter birth weights (i.e., 4.49 kg) and greater litter weaning weights (i.e., 4.69 kg) than sows fed inorganic trace minerals (Table 2). The greater number of pigs born or nursed during lactation could have affected the amount of Fe transferred prenatally to individual fetuses and postnatally to the mammary glands for milk synthesis, thus affecting individual pig Hb and Hct values and potentially the body Fe stores of the sow. Previous results demonstrated that prolific sows have lower body contents of trace minerals, including Fe, than sows of decreased prolificacy (Mahan and Newton, 1995). No attempt was made to monitor the coprophagy of nursing pigs within farrowing crates, but obviously this did not prevent the decline in blood Hb concentration or percentage of Hct in the progeny of both sow treatment groups without Fe injection.

Ceruloplasmin oxidase activity was extremely low in the neonates from both sow trace mineral groups, being nondetectable in several neonatal pigs. Within 2 d of age, however, the activity of this oxidase enzyme increased in the plasma of pigs from both sow trace mineral groups. Ceruloplasmin oxidase activity continued to increase at each measurement period to weaning in pigs from both sow treatment groups and pig Fe injection groups. Although there was a somewhat

### Table 3. Effect of sow dietary trace mineral source and neonatal iron injections (0 or 200 mg) on nursing pig performance and blood measurements during the nursing period (Exp. 1)

<table>
<thead>
<tr>
<th>Item</th>
<th>Organic (n = 3 sows)</th>
<th>Inorganic (n = 4 sows)</th>
<th>SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 (n = 16 pigs)</td>
<td>200 (n = 15 pigs)</td>
<td></td>
</tr>
<tr>
<td>BW, kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 d (birth)</td>
<td>1.83</td>
<td>1.78</td>
<td>1.76</td>
</tr>
<tr>
<td>7 d</td>
<td>3.25</td>
<td>3.45</td>
<td>3.27</td>
</tr>
<tr>
<td>17 d (wean)¹</td>
<td>5.50</td>
<td>6.51</td>
<td>5.56</td>
</tr>
<tr>
<td>ADG, g</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 to 7 d</td>
<td>203</td>
<td>238</td>
<td>212</td>
</tr>
<tr>
<td>7 to 17 d²</td>
<td>216</td>
<td>329</td>
<td>228</td>
</tr>
<tr>
<td>0 to 17 d²</td>
<td>201</td>
<td>261</td>
<td>222</td>
</tr>
<tr>
<td>Hemoglobin, g/dL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 d</td>
<td>8.72</td>
<td>9.73</td>
<td>10.07</td>
</tr>
<tr>
<td>2 d</td>
<td>6.45</td>
<td>7.36</td>
<td>7.67</td>
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<tr>
<td>7 d</td>
<td>4.77</td>
<td>8.81</td>
<td>5.58</td>
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<td>9 d</td>
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<tr>
<td>13 d</td>
<td>3.35</td>
<td>9.66</td>
<td>4.20</td>
</tr>
<tr>
<td>17 d</td>
<td>3.89</td>
<td>12.03</td>
<td>4.29</td>
</tr>
<tr>
<td>Hematocrit, %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 d</td>
<td>33.4</td>
<td>37.2</td>
<td>38.0</td>
</tr>
<tr>
<td>2 d</td>
<td>24.0</td>
<td>27.5</td>
<td>27.6</td>
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<tr>
<td>7 d</td>
<td>19.7</td>
<td>35.7</td>
<td>22.6</td>
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<tr>
<td>9 d</td>
<td>18.1</td>
<td>36.3</td>
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<tr>
<td>13 d</td>
<td>16.0</td>
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<td>18.7</td>
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<tr>
<td>17 d</td>
<td>15.9</td>
<td>39.5</td>
<td>17.7</td>
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<tr>
<td>Ceruloplasmin oxidase activity,⁶ IU/mL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 d</td>
<td>0.001</td>
<td>0.007</td>
<td>0.004</td>
</tr>
<tr>
<td>2 d</td>
<td>0.026</td>
<td>0.026</td>
<td>0.027</td>
</tr>
<tr>
<td>7 d</td>
<td>0.087</td>
<td>0.132</td>
<td>0.169</td>
</tr>
<tr>
<td>9 d</td>
<td>0.101</td>
<td>0.114</td>
<td>0.109</td>
</tr>
<tr>
<td>13 d</td>
<td>0.121</td>
<td>0.112</td>
<td>0.117</td>
</tr>
<tr>
<td>17 d</td>
<td>0.135</td>
<td>0.134</td>
<td>0.112</td>
</tr>
</tbody>
</table>

¹Effect of Fe injection (P < 0.05).
²Effect of Fe injection (P < 0.01).
³Trace mineral source (P < 0.05).
⁴Trace mineral source (P < 0.01).
⁵Trace mineral source × Fe injection interaction (P < 0.05).
⁶Ceruloplasmin activity units = IU/mL of plasma.
greater ceruloplasmin oxidase activity in pigs not injected with Fe, its activity was greater \((P < 0.01)\) in pigs at weaning when sows had been fed organic trace minerals. There was, however, no consistent response throughout the nursing period in pigs from either sow trace mineral source or from neonatal Fe injections.

The results indicate that during an Fe-deficient state, the activity of this enzyme may be somewhat elevated, with its activity increasing as the nursing period commences, perhaps a biological attempt to compensate for the antioxidative activity from Fe.

Fe Effects During the Postweaning Period

Sow Trace Mineral Source and Neonatal Fe Injections. There were no 3-way interactions for the experimental variables. Therefore, each of the 2-way interaction responses is presented as least squares means in tabular form. The effect of sow trace mineral source \(\times\) neonatal Fe injection on subsequent pig postweaning performance and hematological responses are presented in Table 4. Although the nursery diet was supplemented with 90 ppm Fe from Fe sulfate, the total amount of analyzed Fe from both supplemental and indigenous Fe resulted in 175 and 163 mg/kg diet during the 0 to 14-d and 14 to 28-d periods, respectively, thus both nursery diets exceeded current NRC (1998) requirement estimates.

Neonatal pigs that had not initially received Fe injections had decreased \((P < 0.01)\) BW, Hb concentrations, and percentages of Hct values but greater \((P < 0.05)\) ceruloplasmin oxidase activities at weaning (17 d of age) than pigs injected with 200 mg of Fe. During the initial 0 to 7 d postweaning, there was no difference in ADG responses, but from 7 to 14 \((P < 0.01)\), 14 to 21 \((P < 0.01)\), 21 to 28 d \((P < 0.05)\), and for the overall 0 to 28 d \((P < 0.01)\), postweaning, ADG responses were greater when Fe was injected at birth in the pigs from both sow treatment groups, even though the nursery diet exceeded the NRC (1998) Fe requirement. There

### Table 4. Effect of sow dietary trace mineral source and neonatal iron injection (0 or 200 mg) on postweaning pig performance and blood measurements (Exp. 2)

<table>
<thead>
<tr>
<th>Item</th>
<th>Sow mineral source</th>
<th>SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Organic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inorganic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 (n = 16 pigs)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 (n = 15 pigs)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 (n = 19 pigs)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 (n = 18 pigs)</td>
<td></td>
</tr>
<tr>
<td>BW, kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 d (wean) (^1)</td>
<td>5.32</td>
<td>0.24</td>
</tr>
<tr>
<td>14 d (^1)</td>
<td>7.76</td>
<td>0.35</td>
</tr>
<tr>
<td>28 d (^1)</td>
<td>14.44</td>
<td>0.55</td>
</tr>
<tr>
<td>ADG, g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 to 7 d</td>
<td>25</td>
<td>18</td>
</tr>
<tr>
<td>7 to 14 d (^1)</td>
<td>324</td>
<td>16</td>
</tr>
<tr>
<td>14 to 21 d (^1)</td>
<td>436</td>
<td>18</td>
</tr>
<tr>
<td>21 to 28 d (^2)</td>
<td>518</td>
<td>26</td>
</tr>
<tr>
<td>14 to 28 d (^1)</td>
<td>477</td>
<td>18</td>
</tr>
<tr>
<td>0 to 28 d (^1)</td>
<td>326</td>
<td>15</td>
</tr>
<tr>
<td>Hemoglobin, g/dL</td>
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<td></td>
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<tr>
<td>0 d (^1)</td>
<td>3.57</td>
<td>0.28</td>
</tr>
<tr>
<td>7 d (^1)</td>
<td>6.65</td>
<td>0.29</td>
</tr>
<tr>
<td>14 d (^1)</td>
<td>7.64</td>
<td>0.19</td>
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<tr>
<td>17 d (^1)</td>
<td>9.14</td>
<td>0.21</td>
</tr>
<tr>
<td>21 d (^1)</td>
<td>9.78</td>
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<tr>
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<td>0 d (^1)</td>
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<tr>
<td>7 d (^1)</td>
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</tr>
<tr>
<td>14 d (^1)</td>
<td>30.5</td>
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</tr>
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<td>21 d (^1)</td>
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<td>0.60</td>
</tr>
<tr>
<td>28 d (^1)</td>
<td>37.2</td>
<td>0.43</td>
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<td>Ceruloplasmin oxidase activity, (^3) IU/mL</td>
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<td></td>
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<td>0 d (^2)</td>
<td>0.127</td>
<td>0.008</td>
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<tr>
<td>7 d</td>
<td>0.132</td>
<td>0.010</td>
</tr>
<tr>
<td>14 d</td>
<td>0.155</td>
<td>0.008</td>
</tr>
<tr>
<td>17 d</td>
<td>0.157</td>
<td>0.010</td>
</tr>
<tr>
<td>21 d</td>
<td>0.170</td>
<td>0.009</td>
</tr>
<tr>
<td>28 d</td>
<td>0.171</td>
<td>0.008</td>
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</table>

\(^1\)Effect of neonatal Fe injection \((P < 0.01)\).
\(^2\)Effect of neonatal Fe injection \((P < 0.05)\).
\(^3\)Ceruloplasmin activity units = IU/mL of plasma.
was no apparent effect of sow trace mineral sources or neonatal Fe injection responses in hematological measurements. Although blood Hb concentration and percentage of Hct for the pigs without neonatal Fe injection increased each week postweaning, they were lower when pigs had been injected with Fe at birth. However, differences between the 2 groups seemed to become closer with time after weaning. By 28 d postweaning, the BW of noninjected neonatal pigs remained lower (P < 0.01), and Hb concentrations and percentages of Hct values were still lower compared with neonatal pigs injected with Fe.

Ceruloplasmin oxidase activity was initially greater (P < 0.05) in the noninjected neonatal pig group at weaning. These values increased each week postweaning in each treatment group. The ceruloplasmin oxidase activity of neonatal pigs injected with Fe and those not injected with Fe was not different at any measurement period postweaning. These results indicate that postweaning diets containing a total of 170 ppm Fe (indigenous plus 90 ppm Fe sulfate) was insufficient to improve Fe-deficient pigs at weaning to achieve maximum pig growth or hematological normalcy by the end of a 28-d starter period. However, this dietary Fe level was adequate when pigs were injected with 200 mg of Fe at birth.

### Neonatal Fe Injections and Fe Injections at Weaning

The interaction effect of neonatal Fe injections and Fe injections at weaning on postweaning responses is presented in Table 5. Pigs not injected with Fe at birth had decreased ADG during the 7 to 14-, 14 to 21-, 21 to 28 (P < 0.05)-, and for the overall 0 to 28-d (P < 0.01) period. There were neonatal Fe injection × weaning Fe injection interactions (P < 0.05) during 7 to 14 and 14 to 21 d. Those pigs not injected with Fe

### Table 5. Effect of iron injections in neonatal pigs (0 or 200 mg) and weanling pigs (0 or 200 mg) on postweaning performance and blood measurements (Exp. 2)

<table>
<thead>
<tr>
<th>Item</th>
<th>0 (n = 13 pigs)</th>
<th>200 (n = 18 pigs)</th>
<th>0 (n = 19 pigs)</th>
<th>200 (n = 18 pigs)</th>
<th>SEM</th>
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<tbody>
<tr>
<td><strong>BW, kg</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 d (wean)&lt;sup&gt;1&lt;/sup&gt;</td>
<td>5.58</td>
<td>5.28</td>
<td>6.18</td>
<td>6.29</td>
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<td>7 d&lt;sup&gt;1&lt;/sup&gt;</td>
<td>5.85</td>
<td>5.71</td>
<td>6.72</td>
<td>6.73</td>
<td>0.27</td>
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<td>14 d&lt;sup&gt;1&lt;/sup&gt;</td>
<td>7.92</td>
<td>8.31</td>
<td>9.71</td>
<td>9.72</td>
<td>0.35</td>
</tr>
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<td>28 d&lt;sup&gt;1&lt;/sup&gt;</td>
<td>14.52</td>
<td>15.38</td>
<td>17.43</td>
<td>17.29</td>
<td>0.55</td>
</tr>
<tr>
<td><strong>ADG, g</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>0 to 7 d&lt;sup&gt;2&lt;/sup&gt;</td>
<td>39</td>
<td>61</td>
<td>76</td>
<td>63</td>
<td>18</td>
</tr>
<tr>
<td>7 to 14 d&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>295</td>
<td>371</td>
<td>428</td>
<td>427</td>
<td>17</td>
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<tr>
<td>14 to 21 d&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>413</td>
<td>470</td>
<td>519</td>
<td>489</td>
<td>18</td>
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<tr>
<td>21 to 28 d&lt;sup&gt;3&lt;/sup&gt;</td>
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<td>540</td>
<td>584</td>
<td>593</td>
<td>26</td>
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<tr>
<td>14 to 28 d&lt;sup&gt;1&lt;/sup&gt;</td>
<td>471</td>
<td>505</td>
<td>552</td>
<td>541</td>
<td>18</td>
</tr>
<tr>
<td>0 to 28 d&lt;sup&gt;1&lt;/sup&gt;</td>
<td>319</td>
<td>361</td>
<td>402</td>
<td>393</td>
<td>15</td>
</tr>
<tr>
<td><strong>Hemoglobin, g/dL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 d&lt;sup&gt;4,5&lt;/sup&gt;</td>
<td>3.85</td>
<td>4.02</td>
<td>10.24</td>
<td>11.02</td>
<td>0.28</td>
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<tr>
<td>7 d&lt;sup&gt;4,5&lt;/sup&gt;</td>
<td>5.16</td>
<td>8.48</td>
<td>11.90</td>
<td>12.48</td>
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<td>14 d&lt;sup&gt;4,5&lt;/sup&gt;</td>
<td>6.11</td>
<td>9.55</td>
<td>10.40</td>
<td>10.64</td>
<td>0.18</td>
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<tr>
<td>17 d&lt;sup&gt;4,5&lt;/sup&gt;</td>
<td>8.06</td>
<td>10.23</td>
<td>10.96</td>
<td>11.06</td>
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<tr>
<td>21 d&lt;sup&gt;4,5&lt;/sup&gt;</td>
<td>8.90</td>
<td>10.76</td>
<td>11.81</td>
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<td>0.23</td>
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<td>28 d&lt;sup&gt;3,6&lt;/sup&gt;</td>
<td>10.67</td>
<td>11.41</td>
<td>11.61</td>
<td>11.60</td>
<td>0.17</td>
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<tr>
<td><strong>Hematocrit, %</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 d&lt;sup&gt;4,5&lt;/sup&gt;</td>
<td>16.15</td>
<td>16.99</td>
<td>36.50</td>
<td>37.98</td>
<td>0.84</td>
</tr>
<tr>
<td>7 d&lt;sup&gt;4,5&lt;/sup&gt;</td>
<td>20.73</td>
<td>30.97</td>
<td>39.43</td>
<td>40.95</td>
<td>0.76</td>
</tr>
<tr>
<td>14 d&lt;sup&gt;4,5&lt;/sup&gt;</td>
<td>26.09</td>
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<td>36.56</td>
<td>37.69</td>
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<td>31.48</td>
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<td>38.73</td>
<td>38.35</td>
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<tr>
<td>21 d&lt;sup&gt;4,5&lt;/sup&gt;</td>
<td>34.19</td>
<td>38.14</td>
<td>40.12</td>
<td>39.57</td>
<td>0.60</td>
</tr>
<tr>
<td>28 d&lt;sup&gt;4,5&lt;/sup&gt;</td>
<td>36.92</td>
<td>38.45</td>
<td>39.91</td>
<td>39.09</td>
<td>0.43</td>
</tr>
<tr>
<td><strong>Ceruloplasmin activity,7 IU/mL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 d&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0.116</td>
<td>0.125</td>
<td>0.105</td>
<td>0.102</td>
<td>0.008</td>
</tr>
<tr>
<td>7 d&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0.134</td>
<td>0.131</td>
<td>0.116</td>
<td>0.138</td>
<td>0.010</td>
</tr>
<tr>
<td>14 d&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0.146</td>
<td>0.150</td>
<td>0.145</td>
<td>0.155</td>
<td>0.008</td>
</tr>
<tr>
<td>17 d&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0.152</td>
<td>0.161</td>
<td>0.163</td>
<td>0.16</td>
<td>0.010</td>
</tr>
<tr>
<td>21 d&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0.166</td>
<td>0.167</td>
<td>0.148</td>
<td>0.175</td>
<td>0.009</td>
</tr>
<tr>
<td>28 d&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0.165</td>
<td>0.166</td>
<td>0.154</td>
<td>0.159</td>
<td>0.008</td>
</tr>
</tbody>
</table>

1Effect of neonatal Fe injection (P < 0.01).
2Neonatal Fe and weaning Fe injection interaction (P < 0.05).
3Effect of neonatal Fe injection (P < 0.05).
4Neonatal Fe and weaning Fe injection interaction (P < 0.01).
5Effect of weaning Fe injection (P < 0.01).
6Effect of weaning Fe injection (P < 0.05).
7Ceruloplasmin activity units = IU/mL of plasma.
at birth seemed to respond more positively to the Fe injection at weaning, at least during the initial 21-d postweaning, than to the dietary supply of Fe. These pigs also had decreased BW, decreased blood Hb concentrations, and decreased percentages of Hct than neonatal pigs injected with Fe, which resulted in interactions (P<0.01) at 7, 14, 17, and 21 d for Hb and 7, 14, 17, 21, and 28 d postweaning for percentages of Hct, indicating that the Fe injection at birth was more critical for postnatal performances than the Fe administration at weaning. Both noninjected Fe neonatal pig groups increased their blood Hb concentrations and percentages of Hct from weaning to the end of the nursery period when fed the diets fortified with 90 ppm Fe.

Neonatal pigs injected with Fe at birth responded positively to the Fe injection at weaning in terms of ADG, Hb, and Hct, but their responses were not as great as those observed without Fe injection at birth. Ceruloplasmin oxidase activity in the plasma of weaned pigs increased from weaning to 28 d postweaning in all pig treatment groups, with no effect of neonatal or weaning pig Fe injection.

Hemoglobin and Hct values have been previously shown to decline when pigs are not administered Fe during the nursing period. Our results are consistent with those reports. The results of Rincker et al. (2004) indicated that postweaning diets containing a supplemental level of 150 mg of Fe (Fe sulfate) per kilogram of diet may be necessary to maintain blood hematological profile. Our data using 90 ppm Fe and the results of Rincker et al. (2004) using 150 ppm Fe indicate that supplementing the nursery diet with dietary concentrations of Fe sulfate >90 ppm may be necessary to maintain or increase blood Hb and Hct values, particularly when pigs are borderline anemic at weaning.

Our results indicated that feeding an inorganic Fe trace mineral to gestating sows results in greater Hb concentrations and percentages of Hct in their progeny at birth and perhaps at weaning. Although this indicates an increased bioavailability from the inorganic Fe source when fed to sows, there may also be other factors involved that make this conclusion questionable. Increased litter size at birth and milk productivity, which can result in a greater litter or pig weaning weight, may affect Fe status of the sow and therefore could have an effect on individual pigs. Pigs from larger litters at birth may have compromised hematological responses because of decreased Fe stores in the reproducing dam that might be available for transfer to the developing fetus or to the mammary tissue. Mature sows with variable body Fe stores may, therefore, affect the outcome of such studies and may help to explain the differences from the sow and progeny of this study compared with others (Close, 1999). Long-term sow studies would be meaningful to help fully understand the need for Fe for both the sow and progeny. Whether there are any long-term carryover effects from gestation and lactation cannot be directly ascertained from our experiment, but the results suggest that inorganic Fe salts resulted in greater hematological responses in their progeny, but the Fe status of the sow may also affect the growth and hematological responses of the progeny both pre- and postnatally.

In addition, our results clearly confirmed the need for an exogenous administration of Fe to young pigs during the initial days postpartum regardless of the Fe source fed to the dam. The results indicated that growth benefits occurred in young pigs during the early postnatal period from Fe injections. Although we did not test other injected amounts of Fe in neonatal pigs, the research of Hill et al. (1999) indicated that there was no advantage of injecting greater amounts of Fe in the neonatal pig or an additional injection of Fe at weaning was beneficial.

The results further indicated that young pigs at weaning do not readily overcome a previously induced Fe deficiency, even if injected with Fe at weaning, and although blood Hb concentrations and percentages of Hct respond positively to Fe-fortified nursery diets, the need for exogenous Fe at birth seems to be critical to achieve maximum postweaning response.

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