Anabolic effects of insulin and IGF-I in the ovine fetus are reduced by prolonged maternal fasting

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Anabolic effects of insulin and IGF-I in the ovine fetus are reduced by prolonged maternal fasting. Am J Physiol Endocrinol Metab 288: E907–E913, 2005. First published January 11, 2005; doi:10.1152/ajpendo.00551.2004.—Fetal nutritional stress may result in intrauterine growth restriction and postnatal insulin resistance. To determine whether insulin resistance can begin in utero, we subjected late-gestation (130–135 days) ewes to 120 h of complete fasting and compared the results with our previous work in fed ewes (38). We determined the effect of insulin and/or recombinant human (rh)IGF-I infusion on ovine fetal phenylalanine kinetics, protein synthesis, and phenylalanine accretion. Experimental infuses were 1) saline, 2) rhIGF-I plus a replacement dose of insulin (40 nmol IGF-I/h + 16 mIU insulin/h), 3) insulin (890 mIU/h), and 4) IGF-I plus insulin (40 nmol IGF-I/h + 890 mIU insulin/h). During hormone infusion, both glucose and amino acid concentrations were clamped at basal concentrations. Amino acid infusion was required during infusion of either hormone to maintain plasma concentrations constant. However, the amount required during insulin infusion was less than during IGF-I infusion and 40% less than the amount required during identical studies in nonfasted animals. Phenylalanine used for protein synthesis and accretion was increased compared with control animals but again less so than in the nonfasted animals. In contrast to nonfasted animals, neither hormone increased the fractional synthetic rate of skeletal muscle protein nor that of plasma albumin. These results indicate that a short but severe nutritional stress can significantly alter the fetal anabolic response to insulin even when both glucose and amino acid substrate supplies are restored. Therefore, adaptive responses characterized by insulin resistance begin in utero when the fetus is subjected to sufficient nutritional stress.

protein synthesis; skeletal muscle; phenylalanine kinetics; fetal programming

insulin and IGF-I are the major anabolic hormones in the fetus and neonate. However, in the case of either hormone, substrate supply is an important modulator of action. The major substrates for fetal growth and energy are glucose, glucose-derived lactate, and amino acids. These are all supplied in positive net quantities continuously to the fetus. Under normal circumstances, glucose is the major energy source, whereas amino acids provide substrate for both protein accretion and energy. When the ewe undergoes prolonged fasting, the relative uptake and utilization pathways change significantly, as glucose supply declines by ≤50%; amino acid supply remains relatively constant, but their ratio of utilization for protein synthesis and oxidation changes dramatically in favor of oxidation (15, 16, 24). Previous studies have suggested that glucose supply is the major factor causing this change (21, 23), whereas the role of alterations in hormone sensitivity has remained unclear (22).

Epidemiological work in humans has suggested that prenatal nutritional state may induce life-long changes in hormone sensitivity, especially for insulin (1, 30, 31). This has been documented also in several animal models (8, 43). Adaptive changes in hormone sensitivity in utero are now hypothesized to predispose the organism to postnatal diseases, including obesity, type 2 diabetes, and the metabolic syndrome. A better understanding of the acute changes in fetal hormone action during fetal nutritional stress may improve our understanding as to how in utero nutritional stresses predispose the adult to insulin resistance.

The present study was designed to investigate the changes in anabolic hormone sensitivity that occur in the ovine fetus after a prolonged, 120-h total fast by the ewe. This represents 3.5% of the total gestation in the sheep and is equivalent to 6 days of fasting in a human gestation. Either rhIGF-I, insulin, or both were infused at pharmacological doses to determine maximal tissue sensitivity as measured by either substrate utilization or rates of protein synthesis. The study design was identical to that of our previous study in normally fed animals, thereby enabling us to determine the distinct effects of prolonged fasting (38). Although substrate was naturally limited during the fasting period, both glucose and amino acid concentrations were clamped during the metabolic studies, thereby eliminating acute substrate supply and/or alterations in plasma concentrations as a factor. Phenylalanine kinetics and accretion as well as glucose utilization were studied under control conditions and during infusion of pharmacological doses of insulin, IGF-I, or combined insulin plus IGF-I. We have previously documented that the anabolic effects of insulin are mediated by signal transduction via the phosphatidylinositol 3-kinase-mammalian target of rapamycin pathway, whereas IGF-I anabolic effects are independent of this pathway (37). The overall hypothesis of the study was that the insulin-signaling pathway would be most responsive to nutritional stress; therefore, we expected to see greater alterations in amino acid kinetics and accretion during insulin than during IGF-I infusion.

MATERIALS AND METHODS

Animals and surgical procedures. Twenty-three ewes of 115–120 days of gestation were utilized for this study. Animal care was in strict compliance with National Institutes of Health guidelines within an American Association for Laboratory Animal Care-certified facility.

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and the study protocols were approved by the Institutional Animal Care and Use Committee.

Surgical procedures were performed aseptically while the animals were under general anesthesia. Anesthesia was induced with intravenous ketamine and maintained with isoflurane inhalation. Fetal catheters were placed in the inferior vena cava, umbilical vein, and abdominal aorta; maternal catheters were placed in the inferior vena cava and abdominal aorta. Catheters were exteriorized and irrigated daily with 0.9% saline containing 50 U heparin/ml. All ewes consumed ad libitum a diet consisting of hay and pelleted alfalfa and had constant access to water and a salt lick.

Study design. The animals were allowed a minimum of 5 days of recovery from operative stress before the study. Complete recovery and fetal health were assessed by monitoring maternal food intake, fetal and maternal glucose concentrations, and acid-base status. Food was then removed and the ewe fasted for 5 days. Water and salt lick were provided continuously.

On the day of the study, baseline blood samples were obtained for amino acid, glucose, and hormone concentration assays. Then, the fetus was infused with one of the following four infusates: 1) saline, 2) recombinant human (rh)IGF-I (gift of Eli Lilly Research Laboratories, Indianapolis, IN) plus a replacement dose of insulin (40 nmol IGF-I/h + 16 mLU insulin/h), 3) insulin (890 mLU/h), and 4) IGF-I plus insulin (40 nmol IGF-I/h + 890 mLU insulin/h). The infusions were into the fetal inferior vena cava and continued for the duration of the 420-min study. The infusion rates of insulin and IGF-I were identical to those of our previous work, have been shown to result in pharmacological concentrations of insulin and IGF-I, and have been shown to affect amino acid and protein kinetics in the ovine fetus (4, 7, 18, 20). The dose of insulin infused in treatment 2 was expected to maintain plasma insulin concentrations at the baseline level, counteracting the inhibition of insulin secretion during the rhIGF-I infusion. In addition, L-[ring-2H]phenylalanine (1.2 μmol/min), L-[3H]tyrosine (0.12 μmol/min), and L-[ring-2,6-3H]phenylalanine (0.66 μCi/min) were infused into the fetal inferior vena cava, and L-[1-13C]phenylalanine (3.6 μmol/min) was infused into the maternal inferior vena cava throughout the study.

During the hormone infusion, fetal whole blood glucose was clamped at the baseline level by frequent glucose concentration measurement with a glucose analyzer (YSI 2300; Yellow Springs Instrument, Yellow Spring, OH) and a variable infusion of 20% glucose. Likewise, the total fetal plasma branched-chain amino acid concentration was determined in duplicate with an automatic, direct reading by photometry (OSM-3; Radiometer, Copenhagen, Denmark). The within-animal coefficient of variation was 13% for arterial or venous oxygen contents. Phenylalanine and tyrosine isotopic enrichments were determined in plasma after derivatization to their tertiary butyldimethylsilyl (TBDMS) derivatives (36). These derivatives were injected into a Hewlett-Packard 5970 GC-MS (Hewlett-Packard, Palo Alto, CA) with electron impact ionization and selected ion monitoring of ions. Tracer-to-tracee ratios were calculated by the method of Rosenblatt and Wolfe (32).

Phenylalanine and tyrosine kinetics, including phenylalanine conversion to tyrosine, were estimated by the method of Clark and Bier (5), modified for the fetus as we have previously described (17, 18). Phenylalanine kinetic parameters estimated by this model include rate of appearance (Ra), phenylalanine irreversible disposal by hydroxylation, unidirectional flux of phenylalanine from maternal to fetal plasma (Fma), phenylalanine used for protein synthesis (FS), and phenylalanine appearance from protein breakdown (PBa). Muscle fractional protein synthetic rate was estimated by the ratio of specific activities of protein bound to plasma [1H]phenylalanine. Muscle tissue was obtained from fetal quadriceps at study completion immediately before euthanasia and snap-frozen in liquid nitrogen. Samples were homogenized and protein precipitated. The protein pellet was hydrolyzed, and radioactivity from phenylalanine was isolated by HPLC. Phenylalanine concentration in the hydrolysate was determined by AccQTag HPLC methodology (Waters, Milford, MA). Plasma phenylalanine concentration and tritium radioactivity were measured on a single sample after separation by HPLC. For determining plasma specific activity curves, additional blood samples were obtained at 10, 20, 40, 60, and 90 min after the beginning of the [1H]phenylalanine infusion. These data, in addition to the steady state, were fitted to a two-parameter exponential rise to maximum equation: f = a·(1 - e^{-k·t}), using SigmaPlot (SPSS, Chicago, IL). The area under the curve (AUC) of the resulting fitted equation was then determined. To determine the fractional synthetic rate, the specific activity of the skeletal muscle protein-bound fraction was divided by the plasma AUC. The results are expressed as %·day^{-1}.

Albumin fractional synthetic rate. Albumin was isolated by differential solubility in trichloroacetic acid-absolute alcohol (32, 50). The sample was dried by vacuum distillation and hydrolyzed by adding 1 ml of 4 N HCl into the dried albumin (40). Phenylalanine from albumin was enzymatically converted to phenylethylamine by L-tyrosine decarboxylase (9). TBDMS-phenylethylamine was formed, and the enrichment of TBDMS-[1H3]phenylethylamine was determined by electron impact ionization and selected ion monitoring. The time-dependent slope of the albumin enrichment was determined using SigmaPlot. The fractional synthetic rate of albumin was calculated by dividing the increase (slope) in the enrichment of [1H3]phenylalanine in albumin by the steady-state plasma [1H3]phenylalanine enrichment over the same period (52).

Statistical analysis. The data were analyzed by two-way ANOVA, using insulin and IGF-I as independent factors (JMP; SAS, Cary, NC). All values are expressed as means ± SE. Main effects were taken to be significantly different if the F-test resulted in a P value of ≤0.05. Tukey’s honestly significant difference method was used for post hoc analysis of group differences. In the tables, the results of the post hoc analysis are given by symbols *, †, ‡, §, denoting group differences as detected by post hoc analysis; groups connected by the same symbol are not significantly different.

RESULTS

The fetal weights, maternal and fetal glucose concentrations, and fetal oxygen concentrations are given in Table 1. There were no significant differences in fetal weights among the four groups. Maternal glucose concentration was slightly higher in the control studies. There were also slight variations in the fetal

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glucose concentrations, but all fetuses were clamped at glucose concentrations within the range normally observed in fasted animals (29). The physiological significance of these variations is unclear. There were no differences in fetal oxygen content or fetal oxygen consumption among studies.

Figure 1 shows the phenylalanine and leucine concentrations over the course of the study. There were no significant differences in concentrations of these amino acids from the first to the last sampling period; neither were there any significant differences in the mean concentrations between the control, insulin, and combined studies. The mean phenylalanine and leucine concentrations in the IGF-I study were significantly different from those in the other three studies.

Table 2 shows the concentrations of insulin, IGF-I, and IGF-II. The expected differences of insulin and IGF-I based on study design were observed. In particular, the small difference in mean insulin concentration between the control and IGF-I groups was not statistically significant. There was a statistically significant difference in insulin concentration between the insulin and combined groups. IGF-I concentrations were consistent with study design; saline and insulin groups were similar and differed significantly from IGF-I and combined groups; IGF-I and combined were not different from each other.

The infusion rates of glucose and phenylalanine necessary to maintain clamp conditions are shown in Fig. 2. The amount of glucose required was increased to a similar extent by both IGF-I and insulin alone. When hormones were given in combination, the amount of glucose required was equivalent to that required by IGF-I infusion alone; there was no synergistic effect, and in fact IGF-I may have attenuated the effect of insulin. As with glucose, the phenylalanine requirement was increased by both hormones. However, unlike glucose, the phenylalanine requirement was increased to a greater extent by IGF-I than by insulin. Again, no synergistic effect was seen, with the combined infusion equal to that of IGF-I alone.

Phenylalanine and tyrosine kinetics were determined for the whole fetal body. The Ra for phenylalanine and tyrosine are given in Table 3. Ra of phenylalanine and tyrosine are shown in Table 3. Ra of phenylalanine was higher during the insulin and combined infusions; Ra of tyrosine was lowest during IGF-I and highest during insulin infusion. Phenylalanine hydroxylation rates mirrored phenylalanine Ra. The flux of phenylalanine to the fetus from the placenta was greatest during insulin infusion, intermediate during IGF-I and combined infusion, and lowest during the control studies. The effects of insulin and IGF-I on phenylalanine balance, and by inference, protein balance, are shown in Fig. 3. Phenylalanine for protein synthesis was increased equally by insulin alone or by both hormones. IGF-I alone failed to increase protein synthesis. On the other hand, IGF-I alone decreased phenylalanine appearance from protein breakdown, whereas insulin, either alone or in combination with IGF-I, failed to decrease protein breakdown. The net effects of these changes were such that IGF-I, insulin, or both increased phenylalanine accretion rates to the same extent. No synergistic effect was found.

The fractional protein synthetic rates for skeletal muscle are shown in Fig. 4. Small, statistically insignificant changes were seen in fractional protein synthetic rates. Albumin fractional synthesis was also not increased to a statistically significantly extent during infusion of either hormone alone or in combination.

### Table 1. Fetal body weight and glucose and oxygen data

<table>
<thead>
<tr>
<th>Weight, g</th>
<th>Maternal Glucose, mM</th>
<th>Fetal Glucose, mM</th>
<th>Fetal O2, mM</th>
<th>O2 Uptake, μmol·kg⁻¹·min⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>4062 ± 266</td>
<td>1.96 ± 0.058*</td>
<td>0.486 ± 0.022†</td>
<td>0.835 ± 0.035</td>
</tr>
<tr>
<td>IGF-I</td>
<td>3404 ± 326</td>
<td>1.72 ± 0.047†</td>
<td>0.671 ± 0.017*</td>
<td>0.739 ± 0.026</td>
</tr>
<tr>
<td>Insulin</td>
<td>3599 ± 326</td>
<td>1.72 ± 0.064†</td>
<td>0.543 ± 0.022‡</td>
<td>0.889 ± 0.038</td>
</tr>
<tr>
<td>Both</td>
<td>3560 ± 302</td>
<td>1.68 ± 0.058†</td>
<td>0.426 ± 0.021‡</td>
<td>0.783 ± 0.033</td>
</tr>
</tbody>
</table>

Data are means ± SE. Means with different symbols *, †, ‡ are statistically different from one another (P < 0.05).

### Table 2. Insulin, IGF-I, and IGF-II plasma concentrations during experimental infusions

<table>
<thead>
<tr>
<th></th>
<th>Insulin, µU/ml</th>
<th>IGF-I, ng/ml</th>
<th>IGF-II, ng/ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.55 ± 4.67*</td>
<td>40.2 ± 20*</td>
<td>362 ± 33.8</td>
</tr>
<tr>
<td>IGF-I</td>
<td>2.05 ± 3.54*</td>
<td>316 ± 13.2†</td>
<td>414 ± 21.3</td>
</tr>
<tr>
<td>Insulin</td>
<td>38.5 ± 5.1†</td>
<td>38.8 ± 20.5*</td>
<td>419 ± 33</td>
</tr>
<tr>
<td>Both</td>
<td>73.8 ± 4.82†</td>
<td>292 ± 17.9†</td>
<td>432 ± 28.8</td>
</tr>
</tbody>
</table>

Data are means ± SE. Means with different symbols *, † are statistically different from each other (P < 0.05).
DISCUSSION

A major assumption of the “developmental origins of disease” paradigm is that the fetus responds to an adverse environment by downregulating growth, thereby sparing substrate and/or oxygen for vital life functions (9). The term “programming” is often used to indicate that essential fetal adaptations last beyond the fetal period, extending even into adulthood. Many of these adaptations involve alteration in metabolic response to anabolic hormones, especially insulin and IGF-I (41). Epidemiological studies have shown that insulin resistance, with its myriad complications, is a major risk to the organisms after experiencing intrauterine growth retardation (2, 30, 31). The present data demonstrate that resistance to the anabolic actions of insulin begins in utero when the fetus is sufficiently stressed.

Fig. 2. Amounts of glucose (A) and phenylalanine (B) required to be infused to maintain the respective fetal arterial substrate concentration at the basal level. Data are reported as means ± SE. *Differs from Control at P < 0.05; †differs from insulin and IGF-I at P < 0.05; ‡differs from IGF-I and Both at P < 0.05.

We and others have documented that regulation of fetal growth results from a complex interaction between substrate supply and the resulting hormonal milieu (17, 19, 22, 38, 39). Our previous studies have demonstrated that glucose concentration was a significant factor determining amino acid catabolism and accretion (21, 23). However, amino acid availability was not controlled in those studies. The present study, in which amino acid concentrations were clamped by variable infusion of a balanced amino acid solution, extend our studies of the effect of insulin on rates of fetal amino acid accretion.

Fig. 3. Rates of fetal whole body phenylalanine used for protein synthesis (A), phenylalanine derived from protein breakdown (B), and phenylalanine accretion (C). Data are reported as means ± SE. *Differs from Control at P < 0.05.

The major finding of interest in the present study is that, although hyperinsulinemia induces increases in protein synthesis and accretion above the basal rate, the magnitude of increase in accretion is less than in animals that have not been stressed by maternal fasting. Whole body rates of phenylalanine used for protein synthesis were 3.2 ± 0.18 μmol·kg⁻¹·min⁻¹, similar to fed animals studied under similar experimental protocols (38). However, protein synthesis in skeletal muscle was not

Table 3. $R_{\text{Phe}}$, $R_{\text{Tyr}}$, $Phe\rightarrow\text{Tyr}$, and (Ffm)

<table>
<thead>
<tr>
<th></th>
<th>$R_{\text{Phe}}$</th>
<th>$R_{\text{Tyr}}$</th>
<th>Phe→Tyr</th>
<th>Ffm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>2.94±0.16*</td>
<td>3.05±0.21†</td>
<td>0.361±0.023†</td>
<td>0.681±0.062†</td>
</tr>
<tr>
<td>IGF-I</td>
<td>2.55±0.11*</td>
<td>2.49±0.15†</td>
<td>0.333±0.016†</td>
<td>0.764±0.042†</td>
</tr>
<tr>
<td>Insulin</td>
<td>3.7±0.2†</td>
<td>3.55±0.27*</td>
<td>0.474±0.029*</td>
<td>1.027±0.091*</td>
</tr>
<tr>
<td>Both</td>
<td>3.78±0.2†</td>
<td>3.06±0.22*†</td>
<td>0.473±0.029*</td>
<td>0.852±0.084*†</td>
</tr>
</tbody>
</table>

Data are means ± SE in μmol·kg⁻¹·min⁻¹. $R_{\text{Phe}}$, $R_{\text{Tyr}}$, rates of appearance of phenylalanine and tyrosine; Phe→Tyr, phenylalanine irreversible conversion to tyrosine; Ffm, flux of phenylalanine from the maternal to fetal plasma compartment. Means with different symbols *, † are statistically different from each other (P < 0.05).

Fig. 3. Rates of fetal whole body phenylalanine used for protein synthesis (A), phenylalanine derived from protein breakdown (B), and phenylalanine accretion (C). Data are reported as means ± SE. *Differs from Control at P < 0.05.
increased, in sharp contrast to the fed animals. In addition, phenylalanine accretion was only 0.69 ± 0.17 μmol·kg⁻¹·min⁻¹, 30% less than that found in the fed studies.

Data from previous studies have indicated that the decrease in the magnitude to which insulin stimulates amino acid accretion during maternal fasting may simply be due to decreased substrate availability (22). However, the present study precludes this conclusion, as both amino acids and glucose were supplied as needed to maintain plasma concentrations constant. Therefore, the rates of infusion for glucose and amino acids during the studies reflect the degree to which insulin or IGF-I stimulated utilization rates. We (38) have previously published an experiment with identical experimental protocol but in ewes that had not been fasted. Insulin and IGF-I concentrations were similar in the two studies; glucose concentrations were lower and leucine/phenylalanine concentrations higher in the present experiment, consistent with the fasted state. Figure 5 shows the rates of glucose and phenylalanine infusion in the present study compared with those of our previously published study. Insulin stimulated glucose utilization to a comparable degree in both studies. However, phenylalanine utilization during insulin infusion was markedly diminished; during fasting, only 40% as much amino acid solution was required as during the fed studies. This difference cannot be attributed to insulin concentrations, as pharmacological doses were used in both experiments, and the concentrations achieved during fasting were greater than during the fed studies.

A second major finding of the present study was a reversal in the anabolic potency of IGF-I relative to insulin. In the fed experiments, both phenylalanine utilization and accretion were stimulated by both hormones but to a greater extent by insulin (38). These data were similar to studies in neonatal piglets, where exquisite sensitivity to insulin is seen, especially after feeding (28). There was also a suggestion of a synergistic effect when the hormones were coinfused. During fasting, IGF-I stimulated phenylalanine utilization to a greater extent than insulin and with twice the effectiveness as during the fed experiments. It was equal with insulin in effecting phenylalanine accretion, whereas in the fed experiments it had been less effective.

We also measured the fractional protein synthesis rates in skeletal muscle. As with whole body synthesis, insulin stimulated fractional protein synthesis rates in skeletal muscle to a lesser extent relative to the fed experiments. In fact, in skeletal muscle, the fractional protein synthesis rate was statistically unchanged from control during any of the experimental conditions. In the fed experiments, the fractional protein synthesis rate was increased by 50–100% during hormone infusion. Likewise, the plasma albumin fractional protein synthesis rate was unchanged during infusion of either hormone, although there was a nonsignificant trend toward increased synthesis.

![Graph 4: The fractional rate of skeletal muscle protein (top) and albumin (bottom) synthesis (FSR) during each of the experimental conditions. Data are means ± SE.](http://ajpendo.physiology.org/)

![Graph 5: Comparison of substrate utilization rates in fed and fasted states during hormone infusion. Fasted data are from the present study; fed data are from a previously published study (38). A: glucose infused to maintain the basal concentration. B: phenylalanine infused. A also shows insulin concentrations achieved during experimental infusions. Because these groups of studies (Fed and Fasted), although performed under identical study protocols, were conducted as separate experiments, no statistical comparisons have been performed.](http://ajpendo.physiology.org/)
This may be due to the comparatively large interanimal variance in albumin synthesis, with a resultant lack of power to detect changes. Therefore, at the level either the whole body or the individual organ, anabolic insulin resistance is induced by severe fetal nutritional stress.

Controversy exists as to whether the associations between intrauterine growth retardation and insulin resistance are primarily the result of genetic background or intrauterine stress (9). This has resulted in two paradigms: the “thrifty genotype,” in which genetic makeup is paramount (27), and the “thrifty phenotype,” in which fetal adaptive responses to nutritional stress are paramount (10). It is likely that considerable overlap exists between these alternative hypotheses. Most existing studies either are epidemiological or have been performed in small mammals such as rats (11–14, 25, 40, 43) or mice (6), where genetic diversity may be limited. The present studies were performed in a large animal, the sheep, with considerably larger genetic diversity. Other investigators have also used the growth-retarded sheep to demonstrate alterations in placental substrate transport (33, 42) and pulmonary development (26). However, to our knowledge, this is the first demonstration of decreased anabolic action of insulin. It is also the first to show that such changes may occur in a relatively short period of time, given a sufficient stress. Therefore, our finding of decreased anabolic action of insulin in these studies supports the hypothesis that nutritional stress per se induces insulin resistance.

It is interesting that the insulin resistance occurs only in relation to amino acid and protein metabolism. Insulin-stimulated glucose utilization remained normal compared with unstressed fetuses. This is important because glucose is the main oxidative fuel of the fetus (3). During fasting of the ewe, maternal and fetal glucose levels fall to very low levels (15, 16, 34, 35). Thus maintenance of normal glucose insulin sensitivity may be important for the fetus to be able to utilize the reduced but essential amounts of glucose yet available. On the other hand, by reducing the protein anabolic effects, amino acids are spared for use as an oxidative substrate.

In summary, the present study demonstrates that, during an acute severe nutritional stress, the ovine fetus adapts by decreasing the anabolic response to insulin even when amino acid substrates are supplied in adequate amounts. Glucose insulin sensitivity remains unchanged. The fetal anabolic response to IGF-I also remains largely unchanged. The net result of these adaptations allows the fetus to maintain oxidative metabolism but at the expense of growth. These adaptations are consistent with the hypothesis that undernutrition programs the fetus to develop insulin resistance later in life, when substrate availability is sufficient.

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