Regulation of mammary parenchymal growth by the fat pad in prepubertal dairy heifers: role of inflammation-related proteins

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Abstract

In prepubertal heifers, the mammary parenchyma consists of epithelial and myoepithelial cells growing within a mammary fat pad (MFP). The MFP produces IGF-I that stimulates epithelial cell proliferation. In other species, adipose tissue expansion induces inflammation-related proteins (IRP), such as tumor necrosis factor α (TNFα), interleukin (IL)-6, IL-1β transforming growth factor β, monocyte chemoattractant protein 1 (MCP-1), and plasminogen activator inhibitor-1 (PAI-1). The MFP production of IRP may influence mammary development because they impair not only insulin but also IGF-I actions. Moreover, the MFP expansion seen with development and increased nutrition coincides with reduced parenchymal growth. Our first objective was to identify IRP capable of altering proliferation of bovine mammary epithelial cells. TNFα, but neither IL-6, IL-1β MCP-1 nor PAI-1, inhibited basal and IGF-I-stimulated proliferation in MAC-T cells and primary cells isolated from heifers. Our second objective was to determine whether MFP expression of IRP changed in a manner consistent with inhibition of parenchymal growth. MFP expression was measured from 100 to 350 kg body weight (experiment 1) or at 240 kg body weight (experiment 2) in dairy heifers offered restricted or high planes of nutrition. In experiment 1, neither nutrition nor development altered MFP expression of TNFα. Nutrition increased MCP-1 and PAI-1 but only before MFP expansion and after cessation of allometric parenchymal growth. In experiment 2, nutrition increased TNFα and PAI-1, but not MCP-1. Thus, MFP expansion increases IRP production in cattle, but this is unlikely to contribute to reduced parenchymal growth observed with development or increased nutrition.

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Introduction

In rodents and humans, increased adiposity induces adipose tissue production of the proinflammatory cytokines tumor necrosis factor α (TNFα), interleukin (IL)-6, and IL-1β (Wellen & Hotamisligil 2005, Tilg & Moschen 2006). These cytokines interfere with insulin signaling in adipose tissue, liver, and muscle, leading to the development of whole-body insulin resistance (Wellen & Hotamisligil 2005, Shoelson et al. 2006). All three cytokines also impair insulin-like growth factor-1 (IGF-I)–stimulated proliferation of human mammary epithelial cells (Shen et al. 2002). Mechanistically, these inhibitory actions occur because inflammatory cytokines attenuate the activity and abundance of signaling elements shared by both insulin and IGF-I (e.g. insulin receptor substrate–proteins (IRS) proteins; Rui et al. 2002, Wellen & Hotamisligil 2005).

Adipose tissue expansion also induces the production of other proteins associated with inflammation, including transforming growth factor β (TGFB1), monocyte chemoattractant protein 1 (MCP-1), and plasminogen activator inhibitor-1 (PAI-1; Tilg & Moschen 2006). TGFB1 reduces serum-stimulated proliferation of bovine mammary epithelial cells (Woodward et al. 1995, Purup et al. 2000a). MCP-1 is a chemoattractant molecule that recruits monocytes to adipose tissue (Chen et al. 2005, Kanda et al. 2006). PAI-1 not only inhibits the activity of urokinase and tissue plasminogen activator proteins (uPA and tPA), which generate plasmin, but also modulates the biological activities of proteins such as vitronectin and IGF-I–binding protein 5 (Stefansson & Lawrence 1996, Maile et al. 2006, Sorrell et al. 2006). MCP-1 and PAI-1 have been shown to attenuate insulin signaling and cell growth in non-bovine systems (Lopez-Alemany et al. 2003, Kanda et al. 2006, Kortlever et al. 2006, Sell et al. 2006).

The ability of adipose tissue to produce inflammation-related proteins (IRP) could be relevant to the growth of the mammary parenchymal compartment of prepubertal dairy heifers. At this stage of development, the parenchyma consists of epithelial and myoepithelial cells growing as multi-layered duct-like structures within the mammary fat pad (MFP). This arrangement maximizes epithelial cell exposure to essential mitogens produced by the MFP, such as IGF-I (Wälde et al. 1998, Kleinberg et al. 2000, Meyer et al. 2006a, Connor et al. 2007). In theory, it would also facilitate growth inhibition if MFP expansion triggered the synthesis of IRP. This possibility is...
suggested by situations where indices of parenchymal and MFP growth are inversely related. Specifically, expansion of the MFP in rapidly growing dairy heifers is associated with decreased parenchymal growth when assessed at a similar body weight (Sejrsen et al. 1982, Capuco et al. 1995). Moreover, cessation of allometric parenchymal growth occurs near 300 kg body weight when the MFP has expanded significantly (Meyer et al. 2006b).

These observations raise the possibility that MFP expansion induces the synthesis of IRP, which then impairs mammary epithelial cell growth. Our first objective was to identify which IRP, previously shown to be produced by human or rodent adipose tissue, could inhibit proliferation of bovine mammary epithelial cells in vitro. Our second objective was to verify physiological relevance for the inhibitors identified in vitro. We did so by determining whether MFP expression of these factors was inversely related with indices of parenchymal growth in prepubertal dairy heifers.

Materials and Methods

[^3]H] thymidine incorporation in bovine mammary epithelial cells

The MAC-T bovine mammary epithelial cell line was established from primary bovine mammary alveolar cells by immortalization with the SV-40 large T antigen (Huynh et al. 1991). MAC-T cells were routinely grown at 37 °C with 5% CO2 in basal Dulbecco’s modified Eagle’s medium (DMEM with 4.5 g/l glucose containing 20 U/ml penicillin, 2.4 nM glutamine, 1 mg/l soybean trypsin inhibitor, 1 μg/ml selenium, 0.2% penicillin, and streptomycin antibiotic solution) supplemented with 10% fetal calf serum and 5 μg/ml insulin (Thorn et al. 2006). For proliferation assays, MAC-T cells were plated at 1 × 105 cells/cm2 into 48-well plates and cultured for 48 h. Cells were washed twice with PBS and incubated in basal DMEM for 24 h. After 24 h, the media was changed to basa DMEM supplemented with [methyl-3H] thymidine (1 μCi/well; MP Biomedicals, Irvine, CA, USA) and hormones for 18 h as indicated in figure legends.

Primary mammary epithelial cell (pMEC) organoids were obtained from two independent isolations by digestion of the parenchymal mammary compartment of prepubertal Friesian heifers, as described previously (Purup et al. 2001). Frozen stocks of pMEC were thawed as needed in basal medium 199 (M199 containing 2.6 g/l BSA, 5 mg/l transferrin, 1 mg/l reduced glutathione, 1 mg/l soybean trypsin inhibitor, 1 μg/ml selenium, 0.2% penicillin, and streptomycin antibiotic solution) and kept at 37 °C with 5% CO2. For cell proliferation assays, the two independent cell isolates were mixed and seeded in basal M199 supplemented with 10 μg/ml insulin (Sigma) into three-dimensional gels, as described previously (Weber et al. 1999). After 24 h, cells were incubated for 4 days with basal M199 supplemented with insulin and indicated hormones (see figure legends). Media were changed every 2 days and [methyl-3H] thymidine was added for the last 24 h of the culture period.

For both cell systems, all treatments were performed in triplicate. Thymidine incorporation was measured, as previously reported (Thorn et al. 2006). Human recombinant proteins tested were TNFα (PeproTech Ltd, Rocky Hill, NJ, USA), IL-6 (PeproTech), IL-1β (PeproTech), MCP-1 (PeproTech), the stable and constitutively active form of PAI-1 described by Czekay et al. (2003) (Calbiochem, San Diego, CA, USA), and IGF-I (National Institute of Diabetes & Digestive & Kidney Diseases, Bethesda, MA, USA for MAC-T; Austral Biologicals, San Ramon, CA, USA for pMEC).

Prepubertal heifer experiments

Mammary adipose tissue was obtained from two experiments performed in prepubertal dairy heifers. All experimental procedures were conducted with the approval of the local Institutional Animal Care and Use Committee (Cornell University or Danish Animal Experimentation Inspectorate). In the first experiment performed at Cornell University, Holstein dairy heifers were randomly assigned to a restricted (R) or high (H) plane of nutrition beginning at 10 days of age to attain an average daily gain (ADG) of 650 or 950 g/day respectively, as previously described (Meyer et al. 2006a). Heifers in each treatment group were killed at 100, 150, 200, 250, 300, and 350 kg body weight (n = 6 per group). In the second experiment performed at the Danish Institute of Agricultural Sciences, Holstein–Friesian dairy heifers were randomly allocated at 42 days of age to a R or H plane of nutrition (n = 12 per treatment) to attain an ADG of 700 or 1200 g/day respectively, as described previously (Thorn et al. 2006). Heifers in both treatments were killed at 240 kg body weight. In both experiments, mammary gland weights were recorded and MFP samples were collected and snap frozen in liquid nitrogen.

Measurement of cytokine gene expression

Representative samples (200 mg) of MFP tissue were homogenized with 1 ml Qiазol (Qiagen). Total RNA was isolated and purified using RNeasy Mini columns and on-column RNase-free DNase treatment (Qiagen) following the manufacturer’s protocol. Quantity and integrity of RNA was determined using the RNA Nano Lab Chip Kit (Agilent; Palo Alto, CA, USA). Reverse transcription reactions were performed with 2 μg RNA, 500 ng random primers (Invitrogen), and ImPromII reverse transcriptase (Promega) in a 20 μl volume.

Gene expression was measured by real-time PCR. TNFα transcripts were detected with a Taqman probe assay, whereas TGFβ1, MCP-1, PAI-1, and 18S transcripts were detected with a SYBR green assay (Table 1). A previously validated assay was used for leptin (Thorn et al. 2006). Reactions were performed in duplicate in a 25 μl volume using Perfect Real Time 2× Premix with supplied ROX dye (Takara; Madison, WI, USA) for leptin, 2× Universal Mix (Applied Biosystems Inc., Foster City, CA, USA) for TNFα, and Power SYBR Mix (Applied Biosystems Inc.) for other assays. Reactions contained 500 nM of each primer, 100 nM probe (for leptin and TNFα assays), and diluted cDNA (20 ng reverse-transcribed RNA, except 2 ng for 18S). The average s.d. for sample C1 was 0-10. To analyze the data, a relative standard
curve was generated for each transcript using pooled cDNA prepared from prepubertal mammary parenchyma and MFP. The relative standard curve consisted of six serial twofold dilutions of the pooled cDNA. Amplification was linear and efficient across the range of standards for each assay (efficiency for all assays was $0.9$, based on efficiency $= 10^{-1/\text{slope}} - 1$, where slope is obtained from regression of $C_T$ versus log input). Unknown sample expression was then determined from the standard curve, adjusted for 18S, and expressed as a fold difference as indicated in the figure legends.

Statistical analysis

Analyses were performed using SAS statistical software (SAS Institute, Cary, NC, USA). When testing a single dose, thymidine incorporation data from the MAC-T and pMEC experiments were analyzed separately with the fixed effects of IRP (TNFα, IL-6, IL-1β, MCP-1, or PAI-1), IGF-I, their interaction (INT), and experiment (block). For the dose–response experiments, thymidine incorporation data in basal and IGF-I-stimulated conditions were analyzed separately from the MAC-T and pMEC experiments. The model included the fixed effect of treatment dose and experiment (block). Treatment dose differences were detected using multiple comparison tests with a Tukey adjustment. Gene expression data were analyzed with a mixed model accounting for body weight at slaughter, and their INT in the first experiment, or only the effect of nutrition in the second experiment. Statistical significance was declared at $P<0.05$.

Results

Effect of IRP on the proliferation of bovine mammary epithelial cells

The effects of IRP were first evaluated in the transformed mammary epithelial cell line, MAC-T, using thymidine incorporation as an index of proliferation. These cells are responsive to IGF-I as evidenced by a two to threefold increase in proliferation ($P<0.001$, Fig. 1). Treatment of the MAC-T cells with 10 ng/ml TNFα-reduced proliferation by 50% under basal growth conditions and 70% in the presence of IGF-I (INT $P<0.001$, Fig. 1). In contrast, the proinflammatory cytokines IL-6 or IL-1β, the chemoattractant MCP-1, and the inhibitor of plasminogen activation PAI-1 did not alter thymidine incorporation under basal or IGF-I-stimulated growth conditions even if used at high concentrations (50–100 ng/ml, Fig. 1).

We also determined whether these IRP had similar effects on primary mammary epithelial cells isolated from prepubertal dairy heifers (pMEC cells). Proliferation in these cells is also IGF-I dependent, with an almost twofold increase in thymidine incorporation when incubated with IGF-I at the concentration of 10 ng/ml ($P<0.001$, Fig. 2). As seen with the MAC-T cells,
a 10 ng/ml dose of TNFα caused a 50% reduction in thymidine incorporation under both basal and IGF-I-stimulated conditions (P<0.001, Fig. 2), whereas 100 ng/ml doses of IL-6, IL-1β, PAI-1, and MCP-1 had no effect.

Next, we characterized the dose-dependent effect of TNFα treatment on proliferation. The MAC-T and pMEC cells were incubated with increasing concentrations of TNFα (0, 0.01, 0.1, 1, and 10 ng/ml) under basal and IGF-I-stimulated conditions. The minimally effective dose of TNFα in MAC-T cells was 1 ng/ml. This dose reduced basal and IGF-I-mediated thymidine incorporation by 30–35% (Fig. 3A). In pMEC, the minimally effective concentration was 10 ng/ml under basal conditions and 1 ng/ml in the presence of IGF-I (Fig. 3B). These results demonstrate that a low dose of TNFα is sufficient to attenuate IGF-I-stimulated mammary epithelial cell proliferation.

**Effects of development and nutrition on MFP production of IRP in prepubertal heifers**

To determine whether the expression of IRP with effects on cell proliferation varies in a manner consistent with diet-induced changes in mammary parenchymal mass, we measured the expression of these factors in the MFP of prepubertal heifers growing at a rate of 650 (R) or 950 g/day (H) (Meyer et al. 2006b). The mass of the MFP increased over eightfold in these heifers across the 100–350 kg body weight interval and was 60% higher in the H than in the R heifers at 350 kg body weight (1126 g in H versus 710 g in R heifers). The H heifers also had less DNA per unit of MFP mass than R heifers (Meyer et al. 2006b). TNFα expression in the MFP, however, was unaffected by plane of nutrition or body weight (Fig. 4). We also measured TGFβ1 expression because it is increased in the serum of rapidly growing heifers and has been shown to inhibit MAC-T and pMEC proliferation (Woodward et al. 1995, Purup et al. 2000a,b). TGFβ1 expression was not affected by development or nutrition (Fig. 4).

**Discussion**

In rodents, prepubertal expansion of the mammary epithelial compartment proceeds only in the presence of the MFP (Coulldrey et al. 2002). This requirement reflects in part the ability of the MFP to synthesize growth factors such as IGF-I, which then drive epithelial cell proliferation (Walden et al. 1998, Kleinberg et al. 2000). Consistent with this model,
prepubertal ductal growth is impaired in IGF-I null mice, but proceeds normally in mice retaining MFP IGF-I production even if deficient in plasma IGF-I (Ruan & Kleinberg 1999, Richards et al. 2004). Current evidence suggests a similar role for the MFP in prepubertal cattle. IGF-I in the mammary gland is produced in the MFP in response to systemic factors such as estrogen (Berry et al. 2003, Meyer et al. 2006). Furthermore, the highest density of proliferating epithelial cells is found at the interface with the MFP (Ellis et al. 2000, Capuco et al. 2002). Recent data in rodents and humans have also shown that adipose tissue produces potent inhibitors of IGF-I action such as TNFα, IL-6, and IL-1β and other factors that could modulate IGF-I action such as MCP-1 and PAI-1 (Shen et al. 2002, Lopez-Alemany et al. 2003, Wellen & Hotamisligil 2005, Sell et al. 2006). TGFβ1 is also

**Figure 3** TNFα dose–response in bovine mammary epithelial cells. (A) MAC-T were plated and grown in complete media for 48 h and then washed and incubated in basal media for 24 h. pMEC were plated and incubated in basal media supplemented with insulin for 24 h. Cells were incubated in basal media supplemented with 0, 0.01, 0.1, 1.0, and 10 ng/ml of TNFα in the absence of presence of IGF-I (10 ng/ml). For MAC-T cells, hormone treatments and [3H] thymidine were added for 18 h. (B) For pMEC, cells were incubated with hormone treatments for 4 day with a media change every 2 day, and [3H] thymidine was added for the last 24 h of the culture period. Mean ± S.E.M. is shown for each treatment. Data are representative of two to four experiments. *P < 0.05 compared with cells grown in basal media alone. **P < 0.05 compared with cells grown in the presence of IGF-I alone.

**Figure 4** Effect of nutrition and body weight on the mRNA abundance of inflammation-related proteins and leptin in the mammary fat pad of prepubertal dairy heifers. Dairy heifers were offered a restricted (R) or high (H) plane nutrition between 10 days of age and slaughter at 50 kg intervals from 100 to 350 kg body weight (six animals per treatment). Total RNA was extracted from the mammary fat pad and analyzed by real-time PCR for the abundance of TNFα, TGFβ1, MCP-1, PAI-1, and leptin. Results are expressed relative to the mean expression level in the MFP of the 100 kg group on the R plane of nutrition. The effects of nutrition (NUTR), body weight (BW), and their interaction (INT) are reported when significant. Mean ± S.E.M. is shown for each treatment.
expressed in adipose tissue and serum levels are increased in rapidly growing heifers (Purup et al. 2006b). TGFβ1 has been shown to inhibit bovine mammary epithelial cell proliferation (Woodward et al. 1995, Purup et al. 2000a).

Consistent with the possibility that an IRP could modulate IGF-I-dependent parenchymal growth in dairy heifers, we found that a low dose of TNFα reduced basal and IGF-I-stimulated proliferation in both MAC-T and pMEC cells. TNFα has previously been reported to reduce serum-stimulated proliferation in mammary epithelial cells (Okada et al. 1999). Our results suggest that at least a portion of this effect of TNFα is due to the inhibition of IGF-I actions. Our results are also consistent with those showing that TNFα inhibited basal and IGF-I-mediated proliferation in human mammary epithelial cells (Shen et al. 2004). Unlike others, however, we found that high doses of IL-6 and IL-1β (50 and 100 ng/ml respectively) did not affect basal or IGF-I-stimulated proliferation of bovine mammary cells. These results are not likely to reflect a lack of activity of human IL-6 and IL-1β in bovine cells or their use at sub-effective concentrations. Identical or even lower doses of each treatment are expressed relative to the mean expression level in the MFP of the R heifers. Mean ± S.E.M. is shown for each treatment. *P<0.05 relative to expression in R heifers.

Figure 5 Effect of nutrition on the mRNA abundance of inflammation-related proteins in the mammary fat pad of prepubertal dairy heifers. Dairy heifers were offered a restricted (R) or high (H) plane nutrition between 42 days of age and slaughter at 240 kg (12 animals per treatment). Total RNA was extracted from the mammary fat pad and analyzed by real-time PCR for the abundance of TNFα, TGFβ1, MCP-1, and PAI-1. Results are expressed relative to the mean abundance of GAPDH. Relative levels of TNFα, TGFβ1, MCP-1, and PAI-1, respectively: R heifers mean expression levels were 1.0, 1.0, 0.8, and 0.6 relative to expression in H heifers. Mean ± S.E.M. is shown for each treatment. *P<0.05 relative to expression in R heifers.

In dairy heifers, development and nutrition have been shown to impact indices of mammary parenchymal growth. Specifically, the parenchyma grows allometrically for most of the prepubertal period until heifers reach ~300 kg of body weight when growth slows to an isometric rate (Meyer et al. 2006c). In the case of nutrition, diets supporting daily growth rates in excess of 700 g/day are associated with reduced parenchymal mass when assessed in heifers at a similar body weight (Capuco et al. 1995, Sejrsen et al. 2000, Meyer et al. 2006b). Meyer et al. (2006b,c) showed that increased nutrient intake reduced mammary parenchymal mass predominantly by shortening the period of allometric growth. This finding did not exclude the possibility of other negative effects, such as inhibition of IGF-I-mediated cell proliferation by MFP-derived IRP. Indeed, adipose tissue expansion in humans and rodents results in increased production of TNFα, IL-6, TGFβ1, MCP-1, and PAI-1 (Wöllhen & Hotamisligil 2005, Tilg & Moschen 2006). All of these proteins have been shown to reduce insulin or IGF-I actions (Shen et al. 2002, Lopez-Alemany et al. 2003, Sartipy & Loskutoff 2003, Sell et al. 2006). This may explain why indices of mammary parenchymal growth are reduced with development and increased nutrient intake, even though the MFP IGF-I expression is unchanged when these reductions are detected (Meyer et al. 2007). Our in vivo data, however, offer little support for such a mechanism. Specifically, neither TNFα nor TGFβ1 expression was affected by development or nutrition in the first experiment. Increased nutrient intake did increase MCP-1 and PAI-1 expression, but in a manner that is inconsistent with the hypothesis. The H heifers had increased expression of MCP-1 and PAI-1 at 100 kg body weight in the absence of MFP expansion and in conjunction with a higher rate of epithelial cell proliferation than R heifers, and again at 350 kg body weight when epithelial cell proliferation was unaffected by nutrient intake (Meyer et al. 2006b,c). Moreover, MCP-1 and PAI-1 expression did not increase at 300 kg body weight when allometric growth ceased (Meyer et al. 2006c). Significant increases in TNFα and PAI-1, but not TGFβ1 or MCP-1, were observed in the second experiment, where the MFP had a greater degree of expansion in response to increased nutrient intake. Overall, these data show that MFP expansion does increase the production of IRP in dairy cattle, but give little support to the idea that these factors contribute to the reduced parenchymal growth observed with development or increased nutrient intake.

It is interesting to compare these results with those obtained with leptin, another cytokine hypothesized to mediate the negative effects of the expanding MFP on mammary parenchymal growth (Silva et al. 2002). Leptin expression in the MFP increases with development and nutrient intake. Quantitative real-time PCR assays have shown that the signaling form of the leptin receptor (Ob-Rb) is undetectable in MAC-T and pMEC cells and negligible in mammary parenchyma when compared with the hypothalamus, a recognized leptin target tissue (Thorn et al. 2006, 2007). Moreover, leptin is unable to induce signaling events or alter basal and IGF-I-stimulated proliferation in cultured bovine mammary epithelial cells (Thorn et al. 2006). Thus, despite an expression profile in the MFP that is consistent with modulation of parenchymal growth, leptin is unable to do so by acting directly on epithelial cells. In contrast, TNFα and TGFβ1 are potent inhibitors of IGF-I-mediated proliferation in vitro, but are unlikely to explain...
reduced parenchymal growth because neither development nor nutrition consistently altered their expression in the MFP.

In conclusion, TNFα has potent inhibitory effects on mammary epithelial cell proliferation in vitro. MFP expression of TNFα, TGFβ1, MCP-1, and PAI-1 was static around the time when allometric parenchymal growth ceases. Moreover, increased nutrient intake reduced mammary parenchymal mass in both the absence and the presence of increased TNFα and PAI-1 expressions. Overall, these data suggest that MFP and PAI-1 expressions are dynamic. Reduced parenchymal growth because neither development nor nutrition consistently altered their expression in the MFP.

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