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PROTEIN AND ENERGY NUTRITION DURING LACTATION

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INTRODUCTION

According to pediatric expert committees, breast feeding is the preferred method of feeding infants in all countries (111). This is particularly true in most developing countries, for reasons well-summarized elsewhere (11, 45).

In spite of the importance of breast feeding in developing countries, it is known that undernourished mothers often secrete less milk than do well-

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nourished mothers, although the reasons for this are not well-understood (45). Waterlow & Thomson (123) pointed out that growth of infants in developing countries frequently falters by the age of three months; they associated this with breast milk supply failing to keep up with the protein and energy demands of the growing infant. Whitehead & Paul (125, 126) recently emphasized individual variation and suggested that it is difficult to identify a single age when breast feeding becomes inadequate as the sole source of food. By comparing breast milk output and composition to the theoretical protein and energy requirements of infants, Waterlow & Thomson (123) suggested that energy is the limiting nutrient. However, more recently, Waterlow (119) suggested that protein may be at least as limiting as energy and that there may be an additional protein requirement for linear growth beyond that required for nitrogen retention.

The major public health problems that involve nutrition in developing countries are (*a*) high rates of infant and preschool mortality, and (*b*) growth stunting which, in many cases, affects half of the surviving children (120). The diets in these countries are typically marginal in energy, but the importance of protein, both in quantity and quality, should not be ignored (42, 107). The effects of protein and energy deficits on protein synthesis and degradation in growing and adult humans and experimental animals were recently summarized in considerable detail (121, 122). However, protein metabolism during lactation is not discussed in either of these extensive reviews.

This review emphasizes protein and energy nutrition as they pertain to human lactation; studies in experimental and domestic animals are reviewed as they concern this focus. We do not cover lactation in dairy ruminants such as cows and goats except in a few cases where specific mechanisms are involved. For more general reviews on lactation and breast feeding, the reader is referred elsewhere (1, 11, 45, 50, 52).

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PROTEIN AND ENERGY REQUIREMENTS FOR LACTATION

The joint FAO/WHO Ad Hoc Expert Committee on protein and energy requirements (27) estimated that the increase in the energy requirement during the first six months of lactation is 550 kcal/day. This is a 25% increase in the energy requirement associated with lactation based on the estimated requirement of 2200 kcal/day for a moderately active adult woman. The increased energy required for lactation was based on an estimated milk secretion of 850 ml/day containing 600 kcal. It was also assumed that the calorie efficiency of milk synthesis and secretion is 80% and that roughly 200 kcal/day would be available from mobilization of body fat deposited during pregnancy. The total energy requirement during lactation for a moderately active woman thus would be 2750 kcal/day. The Food and Nutrition Board (76) estimated the energy allowance during lactation at 2500 kcal/day, an increase of 25% over the allowance for nonpregnant, nonlactating adult women.

Whitehead et al (127) evaluated the recommended dietary allowance for energy during lactation in 25 presumably well-nourished British women. Energy intake increased during lactation but was still 450 kcal lower than the United Kingdom's recommendation. Milk output did not vary with energy intake when more than 2000 kcal/day were consumed, and averaged 775 g/day. Below this level of energy consumption, milk output was significantly reduced to a level of 455 g/day. At the levels of energy intake measured, the apparent efficiency in energy utilization for milk production was 127%, an obviously impossible figure. It would appear that substantial compensatory alterations in maternal energy metabolism were being made, but these are yet to be elucidated.

The estimated safe level of intake of egg or milk protein for a moderately active adult woman was estimated to be 29 g/day (0.52 g/Kg), or 41 g/day of protein with a net protein utilization (NPU) of 70 (27). Based on the amount of protein in breast milk, the FAO/WHO Expert Group recommended an additional 17 g of egg or milk protein per day during the first six months of lactation. Thus the increase in the protein requirement would be 24 g/day for protein with an NPU of 70. This is an increase of 60% over the requirement for nonpregnant, nonlactating adult women, which is considerably more than the 25% increase estimated for the energy requirement. In the United States, the Food and Nutrition Board (76) estimated the protein allowance during lactation at 66 g/day, an increase of 45% over the requirement for a nonpregnant, nonlactating woman. Protein quality-quantity relationships and/or amino acid requirements during human lactation remain to be investigated.

PROTEIN AND ENERGY METABOLISM DURING LACTATION

Maternal protein synthesis in lactating mammary tissue and in the whole body is essential for milk secretion. Roberts et al (97) inhibited maternal protein synthesis by injecting cycloheximide into lactating rats and observed that milk delivery to suckling pups was completely blocked 4 hours later. Mammary tissue must synthesize protein both for export in milk and for maintenance of mammary structural and enzymatic protein necessary for production of milk lipid, carbohydrate, and protein. As in other secretory tissues, mammary proteins that undergo posttranslational modification, i.e. milk proteins, are synthesized on mammary bound ribosomes. Proteins that are not subject to such modifications, such as intracellular proteins, are synthesized on mammary free polysomes (65). Mammary protein metabolism has been reviewed by Blaxter (10) and Larson & Jorgensen (51). Recent reviews and reports on

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mammary protein synthesis have focused on endocrinology and molecular biology (19, 22, 31, 108, 109, 114). The effects of maternal intake of protein and energy on mammary protein synthesis and the role of mammary protein synthesis in regulating milk secretion have received little attention.

Protein turnover requires a significant expenditure of metabolic energy (66). Liver, gut, heart and mammary tissue of the rat increase significantly in weight during lactation (129). The same is true for liver, gut, and mammary tissue of dairy cows (5). Canas et al (14) attributed the increase in weight of liver, gut and heart in lactating rats to increased food consumption during lactation. They concluded that the 25% increase in the maintenance energy requirement for the lactating rat was due at least in part to the increased weight and metabolic activity of these organs. Increases in organ weight and activity must involve increased protein synthesis and turnover. Baldwin et al (5) estimated that protein turnover represents 10–15% of the total maintenance energy expenditure in lactating dairy cows. Those authors suggested that, in theory, maintenance energy requirements for lactating dairy cows could be significantly reduced by genetic selection of animals with high milk yields and minimal increases in organ weight during lactation.

Hasan et al (38) reported that 55% of casein synthesized by rabbit mammary glands in culture was degraded within 2 hours of synthesis. This observation has not been verified in vivo, but there is evidence that degradation of a significant fraction of newly synthesized export protein is a common feature of secretory tissues (9). Russell et al (102) suggested that lactating mammary tissue and other secretory tissues may use posttranslational catabolism of protein to regulate secretion of export proteins. The possibility that significant amounts of milk proteins are degraded before secretion raises several intriguing questions. Does turnover of milk protein, which would increase the metabolic cost of lactation, impart some advantage to the maternal or nursing organism? Does maternal intake of protein and energy affect the extent of degradation? Halban & Wollheim (33) demonstrated that degradation of insulin varied inversely with glucose concentration in cultured β-cells from rat pancreas. Can the efficiency of maternal energy metabolism during lactation vary depending on the extent of protein degradation? Baldwin et al (5) observed that growth and milk secretion in dairy cows theoretically could be improved by decreasing total body protein turnover, although they noted that because turnover serves an adaptive function (e.g. induction of new hepatic enzymes when diet is altered), protein turnover could not be eliminated without deleterious consequences. An extension of this suggestion is that it may be possible to increase milk output by inhibiting degradation of newly synthesized mammary protein. With or without milk protein turnover, total body protein synthesis and turnover associated with lactation require a significant expenditure of energy by the lactating organism.

Maternal protein and energy metabolism undergo regulated changes during lactation to support secretion of milk. Bauman & Currie (6) have described

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such orchestrated changes in metabolism "homeorhesis," defined as "the coordination of metabolism in various tissues to support an altered physiological state." Naismith and coworkers have documented homeorhetic changes in protein and lipid metabolism of rats during pregnancy and lactation. During the first two weeks of gestation, protein and lipid stores accumulate in the maternal carcass. In contrast, during the final week of gestation, carcass protein is mobilized to support growth of the fetal mass (71, 72, 74). Of lipid deposited during gestation in well-nourished rats, one third is stored subcutaneously while the remaining two thirds are stored in central depots. (75). Naismith et al (75) fed previously well-nourished lactating rats diets that contained 11% or 25% protein and observed that both groups lost 60% of body fat during lactation, even though the 11% group ate less, lost body protein, and secreted significantly less milk than did the 25% group. The authors concluded that mobilization of maternal stores of lipid in the lactating rat is under hormonal, not dietary, control. They suggested that in the rat, energy available from lipid mobilization during lactation makes a major contribution to the energy cost of lactation, which permits optimum use of dietary protein for milk production. Rats fed the 25% protein diet in this study underwent no net change in carcass protein during lactation, whereas rats fed the 11% diet lost carcass protein during lactation and produced one-third as much milk as the 25% group.

Using food intake, initial and final body weights, and diet composition data as input, Romero et al (99) developed a deterministic model of energy transformations in the lactating rat. The model predicted that: (*a*) The efficiency of conversion of body to milk energy is 83%; (*b*) the gross and net efficiencies of milk production are 57% and 80%, respectively; (*c*) maintenance energy requirements vary with food intake. Gross efficiency was defined as the conversion of food energy to milk energy, and net efficiency as the conversion of food energy above maintenance to milk energy.

The above considerations suggest that in well-nourished females, carbohydrate and lipid are stored in the maternal carcass during gestation and are mobilized to provide energy and anabolic substrates for milk secretion during lactation. Rasmussen & Warman (92) allowed rats that had been fed 50% of ad libitum consumption during gestation to have free access to food during lactation. Underfeeding presumably impaired deposition of lipid and protein during gestation. In spite of this, pup weights at day 14 of lactation from dams underfed during gestation were similar to those from dams that were fed ad libitum throughout gestation and lactation. Similarly, Mahan & Mangan (61) observed that sows that had been protein-malnourished during gestation but given adequate rations during lactation produced normal litters. Similar results, discussed below, have been obtained in other studies with lactating sows. These observations suggest that stores of lipid and protein accumulated during gestation are not mandatory for successful lactation if a high-quality diet is available in adequate amounts during lactation.

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DIETARY PROTEIN AND ENERGY: MATERNAL BODY WEIGHT AND COMPOSITION

In considering the issue of protein and energy nutrition during lactation in humans, a major concern has been over diminished lactation in developing countries, where protein and energy intakes are typically low. What is remarkable, however, is that breast milk output is as high as it appears to be, in the face of dietary intakes that are well below the suggested allowances for lactation. Clearly, adjustments in maternal energy metabolism are being made that have not yet been clarified. Before discussing the studies that have been carried out in humans, it is instructive to examine certain animal models for potential mechanisms. The animal studies most pertinent to human lactation are those carried out on laboratory rats and swine.

Animal Studies

Kanto & Clawson (48) fed a corn-soy diet formulated to meet National Research Council (NRC) requirements to rats ad libitum (H) during pregnancy and lactation or at 60% of ad libitum intake (L). All dams lost body weight during lactation. The reduction in body fat during lactation was greater than the loss of body weight, especially in L dams in which body fat was reduced to 2.4% regardless of what intake level had been fed during lactation. Body fat during pregnancy increased significantly in H dams and decreased significantly in L dams, but body protein changes during lactation were minimal.

Emery et al (26) had previously concluded on the basis of rat studies that high-fat diets and exogenous glucocorticoids each augment prolonged lactation. Morgan & Naismith (68) reported that body fat deposition during pregnancy was greatly increased in rats fed a high-protein diet during pregnancy, as compared to those fed a low-protein diet, as a result of consumption of 18% more food and 81% more protein.

The amino acid requirements for lactation in swine have recently been summarized by Baker & Speer (3). Mahan & Grifo (60) reported that in sows fed an 8% corn protein diet during pregnancy, weight loss during lactation was minimized by increasing the protein level and quality of the diet during lactation. When the lactation diet contained 18% protein from corn and soy, sow weight loss was prevented independent of the protein level fed during gestation. In later studies (58, 59), Mahan recommended feeding a 14% protein diet throughout gestation and lactation as the most convenient way to minimize sow weight loss and optimize milk production.

The effect of energy intake on reproduction in swine has also been studied. Frobish et al (29) fed sows corn-soy diets through three reproductive cycles. During lactation, a 16% protein diet was fed at metabolizable energy (ME) levels of 3.0–7.5 Mcal/day. Sows gained weight during lactation at all levels

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fed, with the largest gain at the highest energy level. However, the number of animals completing the three cycles was lowest at the highest energy level, as was the number of pups farrowed. The authors recommended a ME level of 4.5–5.0 Mcal/day as desirable. More recently Reese et al (95, 96) investigated the influence of energy intake during lactation on weight changes during lactation and the postweaning performance of sows. In these experiments, all sows were fed equal amounts of protein during lactation, but the ME level was either 8, 12, or 16 Mcal/day. The sows fed the lowest energy level lost the most weight and back fat during lactation. Fewer sows fed the lowest energy level expressed estrus at seven days than did the sows fed at the higher energy levels. However, energy intake during lactation did not affect sow weight loss during a subsequent lactation period.

Human Studies

Nitrogen balance during lactation in human subjects has apparently not been investigated extensively. However, Edozien (24) reported that four Nigerian mothers were in negative nitrogen balance while consuming 25 g protein/day, but were in positive balance while consuming 50 g/day.

Several studies on the effect of energy intake on energy balance during lactation in humans have been made. Prentice et al (91) reported on the long-term energy balance during lactation in Gambian women. Energy intakes were 1662 ± 16 and 1413 ± 37 kcal/day during the dry and wet seasons, respectively. The mothers gained body weight during the dry season (+0.6 kg/month) and lost weight during the wet season (−0.7 kg/month). These weight changes, however, were closely similar to the seasonal changes seen in nonpregnant, nonlactating women, and maternal nutritional status did not deteriorate with increasing parity. As will be discussed below, milk production was surprisingly high, especially during the dry season, on these low energy intakes. In a study carried out in India, Prema and co-workers (85) reported that maternal weight loss during 18–24 months of lactation averaged only 2 kg in spite of energy intakes of only 1100 kcal/day. In this study, the energy intakes in lactating women were not different from the intakes in nonpregnant, nonlactating women. It has been reported that Bangladesh women maintain body weight through 30 months of lactation (41). Additional information on energy intakes during lactation has been summarized by Whitehead (125) and by Aebi & Whitehead (1).

Rates of energy expenditures and food intakes of Guatemalan women during lactation were studied by Schutz et al (106). Consistent with the other reports discussed above, energy intakes were not increased during lactation over that observed for the nonlactating condition. Lactating and nonlactating women consumed 1929 ± 360 and 1876 ± 40 kcal/day, respectively. Rates of energy expenditure, measured with a heart rate monitor, were similar in the two groups, and both were judged moderately active. Weight loss during lactation, 369 g/month, was ten times greater than in the nonlactating group. The authors suggested that the energy costs of lactation were met to a greater extent by fat loss than by either increased energy intake or reduced energy expediture, or both.

In The Gambia, the effects of a nutritional supplement on maternal nutritional status and lactational performance have been studied (88, 90). The nutritional supplement, consisting of groundnut biscuits and a vitamin-fortified tea, was supplied for one year to 130 lactating women. Maternal energy intake increased on the average from 1568 ± 15 to 2291 ± 14 kcal/day, considering the entire 12-month period. Protein intake during the supplementation period was 131% and 146% of the FAO/WHO standard (27) during the wet and dry seasons, respectively. The supplement resulted in a net body gain of 1.8 kg but, as will be discussed below, milk secretion was not increased. The authors suggested that much of the additional energy supplied by the supplement was converted to increased physical activity or was wasted because of decreased metabolic efficiency.

Energy and protein consumption of well-nourished North American women as related to postpartum weight changes and body composition has been studied by Manning-Dalton & Allen (62). Weight loss increased as energy intake decreased. Adequacy of lactation correlated with energy intake, and the women who secreted the most milk consumed the most dietary energy and lost the least weight. In this study, lactation did not promote weight loss in well-nourished women. A normal physiological cycle of fat retention during early pregnancy followed by fat mobilization during late pregnancy helps to explain the fact that women typically do not increase food intake during late pregnancy when the metabolic demands are high (23, 73).

Body weight changes during the first three months of breast feeding and food intake during lactation were both found to be related to weight gain during pregnancy (73). The mothers with the highest gains during pregnancy lost more weight and ate less food during lactation than did the mothers who gained the least weight during pregnancy. This relationship between weight gain during pregnancy and weight loss and food intake during lactation was also observed in British women by Whitehead et al (127) and in Gambian women by Paul et al (81). There is little doubt that metabolic events in lactation are influenced by pregnancy and that pronounced alterations in energy metabolism occur during lactation.

DIETARY PROTEIN AND ENERGY: PROTEIN SYNTHESIS

The effect of dietary protein and energy during lactation on protein synthesis in maternal tissues has received little attention, in spite of the fact that protein

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synthesis is required for secretion of milk (97) and is metabolically costly to the mother (6). Sampson & Jansen (103a,c) measured protein synthesis rates in mammary gland, liver, and muscle of lactating rats fed diets differing in protein quality and level of intake. Rates of protein synthesis were measured at mid-lactation from incorporation of ^{3}H-phenylalanine into tissue proteins following injection of a flooding dose of radiolabeled phenylalanine (30). Diets in these studies contained 25% protein supplied by wheat gluten (WG), wheat gluten supplemented with lysine and threonine (WGLT), or casein (C). In the first study rats were pair-fed throughout gestation and lactation to 100% or 85% of the consumption of rats fed the gluten diet ad libitum (PF100 and PF85, respectively). At PF100, rates of mammary protein synthesis were three times higher in rats fed the high-quality diets (WGLT at 1171 ± 164 mg/day and C at 894 ± 104 mg/day) compared to values in rats fed the poor-quality gluten diet (C at 326 ± 69 mg/day). At the more restricted feeding level (PF85), surprisingly, supplementation of gluten with lysine and threonine did not increase mammary protein synthesis, although rates were two times higher in C-fed rats compared to WG-fed rats (531 ± 101 mg/day, 660 ± 133 mg/day, and 1048 ± 67 mg/day, respectively, for WG, WGLT, and C).

In a second study, dams fed stock diet during pregnancy were switched at parturition to diets, fed ad libitum, in which the protein was supplied by wheat gluten (G) or casein (C-AL) (103c). In addition, casein was pair-fed to the consumption level of the WG group (C-PF). Improvement of protein quality (C-PF vs WG) did not increase mammary protein synthesis when food intake was held constant. However, when both protein quality and feeding level increased (C-AL vs WG), mammary protein synthesis rates increased threefold (584 ± 60 mg/day, 663 ± 58 mg/day, and 1743 ± 148 mg/day, respectively, for WG, C-PF, and C-AL). In liver, improvement in protein quality increased rates of protein synthesis, from 469 ± 46 mg/day in rats fed wheat gluten to 702 ± 62 mg/day in rats pair-fed casein to the consumption level of the gluten-fed rats, and to 970 ± 72 mg/day in rats fed casein ad libitum. In muscle, rates of protein synthesis were two times higher in rats fed casein ad libitum than in those that were fed wheat gluten or that were pair-fed casein (6.7 ± 1.0 percent per day vs 3.4 ± 0.5 percent per day, and 4.0 ± 0.8 percent per day, respectively), although the differences were not statistically different ($P > 0.05$). These observations are consistent with reports on nonlactating laboratory animals, which have shown that deficiencies in dietary protein and/or total food intake depress protein synthesis rates in liver and muscle (121). No circadian variation in rates of protein synthesis was observed in mammary gland, liver, or muscle in rats fed the poor-quality gluten diet, or in those fed the high-quality casein diet pair-fed to gluten consumption levels, or in those fed ad libitum. This is in contrast to synthesis of lactose and lipid in the mammary gland, both of which undergo circadian variations that are diet-sensitive (15, 69).

DIETARY PROTEIN AND ENERGY: MILK SECRETION

Animal Studies

In the laboratory rat, the influence of dietary protein and energy on milk secretion has generally been inferred from pup weight gain, which is strongly correlated with milk output (99, 103b). The primary effect of dietary deficiencies in protein and/or energy is reduction in milk volume, although a reduction in nitrogen and an increase in fat in milk from dams fed a low-protein diet have also been observed (20). In either case, offspring weight gain is the combined result of milk quantity, which has the greater effect, and milk quality, which has the lesser effect.

Jansen & Chase (43) fed unsupplemented white bread or bread supplemented with lysine and threonine to rats from conception until weaning. In spite of the relatively low (13%) protein level fed, 21-day weaning weights were increased from 17.0 ± 1.9 g to 39.8 ± 3.1 g by the addition of lysine and threonine to the bread, compared to 42.8 ± 3.8 g for the casein control group. Kwong & Barnes (49) also observed an increase in weaning weights when lysine and threonine were added to wheat gluten fed to rats at a 25% dietary protein level from conception until weaning. Surprisingly, in this study the weaning weights of pups from dams fed 12% wheat gluten were comparable to the weights of pups from dams fed 12% casein; no response to lysine and threonine was noted. The reason for this is not clear, since protein quality differences are generally greater at lower dietary protein levels. More recently Sasaki et al (104) reported that weaning weights were 59 ± 4.5 g when dams were fed 18% casein, compared to 27 ± 4.8 g. when the dams were fed 10% casein. Weaning weights were not further increased when 36% casein was fed.

The influence of protein quality, dietary energy and the protein-energy interaction on milk yields and pup gains have been studied by Jansen and co-workers. In the first study (44), pregnant rats were fed from conception until weaning diets in which protein was supplied at a 13% level by white bread (B), bread supplemented with lysine and threonine (BLT), or casein (C). These diets were fed either ad libitum or at 100%, 85% or 75% of the ad libitum intake of the group fed unsupplemented white bread. Increases in weaning weights with increases in protein quality in the maternal diet were consistent with the findings of the earlier study (43). Increased weaning weights, and, inferentially, increased milk yields were observed with improvements in protein quality, even when food intake was restricted. When the BLT and C groups were pair-fed to 70% of the ad libitum consumption of B, weaning weights were 28.8 ± 0.3 g and 27.2 ± 0.2 g, respectively, compared to 16.8 ± 0.4 g in the ad libitum white bread group, even though the former groups consumed 15% less protein and energy than did the latter group.

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In a more recent study, Sampson & Jansen (103a) measured milk yields in dams fed wheat gluten, gluten supplemented with lysine and threonine, or gluten supplemented with casein, from conception until day 15 of lactation. Diets contained 25% protein. Milk yields were calculated from pup weight and weight gain data, as described by Sampson & Jansen (103b). Milk yields were 22.0 ± 0.6 and 18.0 ± 0.6 g/day in dams pair-fed casein at 100% or 85% of the ad libitum consumption rate of the wheat gluten group, compared to 14.0 ± 0.7 g/day in the ad libitum gluten group and 30.0 ± 1.2 g/day in the ad libitum casein group. These results are consistent with those obtained earlier (44) and confirm that increases in protein quality or feeding level increase milk secretion in lactating rats. They further confirm that even when 15% less dietary protein and energy are consumed, milk secretion is significantly higher when casein rather than wheat gluten is fed. In this study and the other conducted by Sampson & Jansen (103c), improvements in maternal protein quality and/or energy intake increased milk output but did not always produce parallel increases in rates of mammary protein synthesis. For instance, rats fed a 25% casein diet at the intake level of rats fed a 25% gluten diet during lactation produced 50% more milk at mid-lactation than the gluten-fed rats (25.8 ± .5 g/day vs 17.2 ± .3 g/day) but had rates of mammary protein synthesis similar to those in the gluten-fed group (about 600 mg/day). The reason for the disassociation of milk yield and protein synthesis in dams fed restricted diets is not understood at present. In dams fed wheat gluten or casein ad libitum, milk yield was highly correlated with protein synthesis ($r^2 = 0.72$, $p < 0.001$). Naismith et al (25) also reported that milk secretion in rats was higher with a high-protein diet.

The effects of dietary protein and energy on lactation have been studied in swine. A variety of protein sequences during gestation and lactation were evaluated by Mahan (58, 60). In general, increasing the protein level fed during lactation increased milk secretion to the greatest extent when a low-protein level was fed during gestation. A corn-soy diet supplying protein at 14% during pregnancy and lactation was considered optimal. At the Rowett Research Institute, it was found that the weaning weight of pigs was greatest when a barley-soy diet supplying protein at 13% was fed throughout gestation and lactation (32).

Human Studies

Picciano (83) and Whitehead (124) recently summarized data on the volume and composition of human milk. Clearly, both vary with many factors including time of day and frequency of suckling. The volume of milk secreted by well-nourished mothers remains somewhat uncertain, with volumes in the range of 600–700 ml/day most commonly cited. Although a figure of 850 ml/day has been used by some in the past to calculate nutrient intakes by breast-fed infants, Picciano (83) suggests that a value of 650 ml/day would be more appropriate. More recently, Butte et al (13) estimated milk secretion in healthy, well-nourished mothers in Texas at 878 ± 188 ml/day, and Rattigan et al (93) estimated breast milk production in Australian women at 880 to 1187 g/day during 15 months of lactation. We still lack a clear picture of normal human milk production because of the many variables involved and the difficulty of making the measurement.

MILK COMPOSITION As summarized by Picciano (83), mature human milk, after the first two weeks of lactation during which time nitrogen content decreases considerably, contains 0.8–0.9 g "true protein" per 100 ml. Earlier estimates based on Kjeldahl analysis for nitrogen were that human milk contained 1.1 g "protein" per 100 ml, with the difference between the two estimates representing nonprotein nitrogen. However, in studies many years ago with infants fed cows' milk, Snyderman et al (110) showed that nonprotein nitrogen is the limiting factor for growth of infants on cows' milk protein. The infant uses amino acids and nitrogen donors rather than protein for growth; thus, the argument over the "true protein" content of milk appears to be relatively unimportant because one needs to account for efficiency in nitrogen, not protein, utilization. As far as the remaining energy nutrients are concerned, fat is the most variable, ranging from 1.5–5.0 g per 100 ml. Lactose is the least variable, with concentrations measured in the range of 6.0–7.4 g per 100 ml. The reason for this latter constancy is that lactose, because of its osmotic properties, appears to be a major determinant of milk volume (40, 56).

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In an earlier review of human milk composition in poorly nourished communities, it was concluded that protein and lactose levels in the milk were near normal; but the fat content, and hence calorie content, was quite commonly reduced (46). In a study of lactation in Burmese mothers, Naing et al (70) found no significant differences in the proximate composition of breast milk between malnourished and well-nourished mothers. Lauber & Reinhardt (53) reported little change in the proximate composition of breast milk during a 23-month study of lactation in a rural Ivory Coast community. Lonnerdal et al (57) and Svanberg et al (113) reported no significant differences among the lactose, nitrogen, protein, and free amino acid levels in breast milk from underprivileged Ethiopian women and well-nourished Swedish women. Chavalittamrong et al (17) also reported that the total amino acid levels in milk from Thai mothers were similar to values reported for American and Scottish mothers, and Butte & Calloway (12) reported that protein, lactose, and lipid levels were normal in breast milk from suboptimally nourished Navajo women. Wurtman & Fernstrom (131) reported that the concentrations of free lysine and tryptophan in milk from Guatemalan mothers consuming a corn-bean diet were approximately 25% lower than levels in samples from American women.

However, since free amino acids represent a small part of the total amino acid content of breast milk, the nutritional significance of this observation is not immediately apparent. In an extensive study of long-term variations in the lipid content of breast milk from women in The Gambia, a mean milk fat concentration of 3.93 g per 100 ml was observed (86). From seasonal changes in body fat stores and energy intake, it was concluded that breast milk fat concentration did not correlate with dietary energy intake or breast milk output, but rather correlated directly with the amount of subcutaneous fat. Prentice (87) reported that the fat content of breast milk was 4.36 ± 0.25 g per 100 ml and 3.45 ± 0.22 g per 100 ml during the dry and wet seasons, respectively. In contrast, protein content did not vary as a function of season.

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MILK VOLUME Since debate continues over the normal volume of milk secretion for well-nourished women, it is not surprising that it has been difficult to establish the extent to which milk secretion has been adversely affected by nutritional and socioeconomic factors in developing countries. Jelliffe & Jelliffe (46) reviewed the available data up to 1978 on the volume of human milk secreted by mothers in poorly nourished communities. Milk secretion rates ranged from 400–700 ml/day during the first six months of lactation, to 300–700 ml/day during the second six months, to 100–600 ml/day during the second year. Whitehead (124) reported volumes varying from 300–600 ml/day for 3–12 months of lactation with no clearly discernable pattern of variation. Other investigators have observed twofold variation in milk volume for similar lactation periods (124). Lonnerdal et al (57) compared milk volume in privileged and nonprivileged Ethiopian mothers to milk volume in well-nourished Swedish women using an electric pump on both breasts after an overnight fast. These workers observed no significant differences in volume among the three groups under these conditions. However, in the study of Burmese mothers already discussed, Naing et al (70) reported that mothers weighing more than 95% of standard weight for height secreted 934 ± 49 ml/day compared to 767 ± 25 ml/day in mothers weighing less than 75% of standard weight for height.

In The Gambia, energy intakes during pregnancy ranged from 1374 to 1652 kcal/day and protein intakes ranged from 41.6 to 53.8 g/day (81). Comparable figures for energy intake during lactation were 1184 to 2129 kcal/day and for protein, 34.8 to 72.1 g/day. In spite of the low energy consumption, milk secretion in this study was 720 g/day during the heavy farming period and 640 g/day during the rest of the year. Both energy intake and milk output were significantly higher during the dry season (87). It has also been observed that measured 12-hour breast milk intakes for infants with high birth weights were significantly greater during the first six months of life than intakes of infants with birth weights below average (101). This suggests that in addition to promoting storage of body fat and growth of mammary tissue, adequate nutrition during pregnancy is important for lactation, resulting in infants with larger birth weights and presumably stronger sucking stimuli.

SUPPLEMENTATION STUDIES In view of the relatively poor growth of infants in developing countries, the somewhat reduced volume of milk secretion by their mothers, and the marginal maternal intakes of protein and energy, it appears that milk output should be enhanced by increasing the dietary intake of protein and/or energy. As reviewed above, this has been the case in laboratory and domestic animals. Unfortunately, a beneficial effect of protein/energy supplements on milk secretion in marginally nourished lactating women has not been observed consistently. In fact, this response has to date been the exception, not the rule (124).

An early, successful attempt to "feed the nursing mother, thereby the infant" was made by Sosa et al (112) in Guatemala. A low-income woman consuming a corn-based diet in an amount estimated at 800 kcal/day was nursing a 3-month-old male infant who was failing to thrive. Over a period of 45 days, eggs, cheese, meat, and grain were provided to increase maternal calorie intake to 2200 kcal/day and to provide generous amounts of high-quality protein. Milk obtained from the breast one hour after feeding increased from 0.1 ml the first day to 14 ml by the 15th day of supplementation and remained at this high level. The infant's weight increased at a rate of 19 g/day but remained below the third percentile, and the mother gained only 130 g during the 45-day supplementation period.

Several other more extensive studies have failed to confirm that a food supplement has a beneficial effect on milk secretion. On the basis of a two-year longitudinal study in Mexico, Chavez et al (18) reported that a food supplement supplying 300 kcal and 20 g protein/day given from the 45th day of pregnancy through lactation increased milk volume 15%. However, milk from the supplemented mothers was more dilute, and the total solids secreted were not significantly different from those observed in nonsupplemented mothers. In The Gambia, a food supplement supplied to lactating mothers increased measured energy intake from 1568 ± 15 kcal/day to 2291 ± 14 kcal/day, with protein intake during supplementation higher than the FAO/WHO standard (89). Over a 12-month period, the supplement had no significant effect on milk volume or energy content at any stage of lactation or season of year, although a 7% increase in milk protein concentration was observed. As already discussed, maternal weight gain in lactating women averaged 1.8 kg during the year (88). The reasons for the lack of effect of the supplement on milk volume in this population are not understood but, as the authors suggest, these observations illustrate the complexity of the diet-lactation interaction. The authors did note desirable changes in maternal attitudes and behavior as a result of supplementation, although these are difficult to quantify (124).

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The effects of protein supplementation specifically on milk volume have been evaluated. Edozien et al (25) increased the protein intake of lactating mothers in Nigeria from 50 g/day to 100 g/day, keeping energy intake constant at 60 kcal per kg body weight per day. During the fourth week of the study, milk production was 742 ± 16 g/day in the lower protein group, compared to 872 ± 32 g/day in the higher protein group; infants' weight gains were 30.4 ± 3.6 g/day and 45.7 ± 2.0 g/day, respectively. Belavady (8) reported an increase in milk yield in six Indian women from 400 g to 510 g/day when protein was increased from 60 g to 100 g/day. In a more recent study with three healthy Swedish mothers in full lactation, Forsum & Lonnerdal (28) found that milk volume and total nitrogen secreted in milk were significantly increased by increasing the protein content of the diet. With a protein intake of 46 g/day (8% of energy intake), milk volume and total nitrogen were 857 ± 91 g/day and 1.46 ± 0.07 g/day, respectively. The corresponding values for milk volume and total nitrogen were 956 ± 72 g/day and 1.88 ± 0.12 g/day in mothers consuming 134 g/day of protein (20% of energy intake). These increases were observed in well-nourished mothers secreting high volumes of milk and in spite of the fact that even the low-protein group consumed protein in an amount equal to the FAO/WHO (27) suggested requirement (uncorrected for score). Whitehead (124) has suggested that protein deficiency may be at least as important as energy deficiency in reducing milk secretion, because lactation appears to be more seriously compromised in countries where kwashiorkor is the dominant form of preschool malnutrition as compared to countries where marasmus is dominant.

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POTENTIAL MECHANISMS OF IMPAIRED MILK SECRETION

The mechanisms by which milk secretion may be altered as a result of changes in maternal intake of protein and energy have not been established. Such mechanisms are of basic scientific interest with regard to effects of nutrition on regulation of metabolism. Knowledge of such mechanisms may also be of practical value by suggesting how best to correct impairment of milk secretion caused by undernutrition or other environmental conditions. Control points for regulation of milk secretion that will be considered here have either been shown to respond to maternal diet or seem likely to be diet-sensitive.

Blood Concentrations of Hormones and Substrates

Blood concentrations affect mammary metabolism because they determine amounts of hormones and substrates at apical borders, which mammary epithelial cells must respond to (in the case of hormones) or transfer into the cells' interior (in the case of substrates). Bauman & Currie (6) suggested that much of the current knowledge of mammary metabolism rests on putative relations between serum hormone concentrations and metabolic activity of mammary tissue. However, changes in blood concentrations of hormones and substrates caused by maternal intake of protein and energy should be interpreted with caution. Rook (100) noted that "only in a few instances has a close relationship been demonstrated between plasma concentration of a nutrient and the rate at which it is used by the mammary gland." For hormones and substrates, uptake by mammary tissue is influenced by blood flow and tissue extraction rates, as well as by blood concentrations (6, 55). For hormones, receptor number and affinity also affect tissue response. At parturition, uptake of glucose by goat mammary gland increased fivefold, whereas blood glucose concentration remained unchanged (21). During short-term starvation, blood concentration of glucose was stable in the lactating rat, whereas uptake of glucose by mammary tissue dropped significantly (98). Blood concentrations should be viewed as only one of several parameters related to tissue uptake of hormones and substrates; they do not by themselves yield cause-and-effect information about mammary metabolism.

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Mammary Gland Size and Cellularity

In the lactating rat, the mass of mammary tissue increases from 6.6% to 8.6% of body weight between days 5 and 15 of lactation (36). Mammary mass nearly doubles, from 13 to 24g, between days 1 and 12 of lactation (129). Moon (67) reported that mammary tissue from dams nursing large litters contained more DNA than tissue from dams nursing small litters. The increase in mammary size under these conditions is associated with increased secretion of milk that occurs in the rat as lactation progresses. A number of investigators have demonstrated that maternal intake of protein and energy during lactation has a pronounced effect on mammary size and cellularity in the rat. Turner (115) observed that mammary wet weights were significantly lower in rats fed 8% casein diets during lactation than in rats fed 25% casein diets. Yang & Baldwin (132) reported that a 32% restriction in intake of stock diet in lactating rats depressed mammary wet weights by 45% and pup weight gains by 34%. Ravi & Ganguli (94) found that feeding rats 5% casein diets through gestation and lactation decreased mammary gland wet weight and DNA content at day 14 of lactation. Sampson & Jansen (103c) observed that at day 15 of lactation, mammary gland wet weights and DNA content of previously well-nourished rats that were fed poor-protein-quality diets (25% wheat gluten diet) during lactation were only two thirds as large as values from rats fed a 25% casein diet. They also reported that if the poor-quality diet was fed during both gestation and lactation, mammary wet weight, DNA content, and milk yields were reduced to half of control values (103a). Pau & Milner (80) observed that feeding arginine-deficient diets or feeding control diets at 50% of ad libitum

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intake decreased mammary weights and DNA content of near-term rats. These studies suggest that underfeeding protein and/or energy during pregnancy and/or lactation depresses milk output in rats by decreasing mammary gland mass and cellularity. However, there is evidence that maternal intake of protein and energy affects unit activity of mammary tissue as well as mammary cellularity. In addition to decreases in mammary wet weight and DNA content, rats fed a 25% wheat gluten diet had less than half the mammary gland protein synthesis per mg of mammary DNA of rats fed a 25% casein diet (103a). When the wheat gluten diet was supplemented with lysine and threonine without increasing energy intake, mammary protein synthesis per mg of mammary DNA was increased threefold (103a). These observations suggest that maternal intake of protein and energy can affect both mammary cellularity and protein synthetic activity per cell. It is not known whether intake of maternal protein and energy affects mammary cellularity in humans in the same manner as it does in rats. The experiments discussed above, in which malnourished pigs and rats that were fed adequately during lactation were observed to lactate normally, suggest that deficits in mammary cellularity caused by underfeeding may be reversible or at least may be overcome if adequate food is available during lactation.

Cellular Uptake of Substrates

Uptake is defined as the product of blood flow and arterio-venous (A-V) difference for the compound under study (55). Substrate uptake is influenced by changes in blood flow or A-V differences. A-V differences in turn are affected by tissue transport systems. Both blood flow and transport are considered in the following discussion.

Various investigators have demonstrated that deficiencies of amino acids or glucose limit milk production in production and experimental animals. Schingoethe et al (105) demonstrated that deletion of any essential amino acid depressed milk protein synthesis in cultured rat mammary cells. The near-total extraction of methionine, phenylalanine, and leucine from mammary arterial blood led Mepham (63) to suggest that delivery of those amino acids may limit milk protein synthesis in goat mammary gland. The A-V difference data of Vina et al (117) indicated that rat mammary tissue extracts 26–58% of arterial essential amino acids at peak lactation—a range of values considerably below that for the lactating goat. Park & Chandler (79) demonstrated that casein synthesis fell steadily in response to decreasing total amino acid concentrations in the medium of cultured mammary cells from lactating rats. Glucose availability affects mammary anabolism in all milk-producing species that have been studied. Ruminants use glucose primarily for lactose production, while nonruminants utilize it for production of lactose, milk fat, and mammary energy (47). Wilde & Kuhn (128) concluded that glucose uptake is rate-limiting for lactose

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synthesis in acini prepared from lactating-rat mammary tissue. It has been postulated that lactose secretion regulates milk volume and composition as a result of its osmotic properties (40, 56). If this is true, maternal intake of energy may affect milk output via uptake of glucose by mammary tissue for lactose synthesis. Baldwin & Cheng (4) suggested that glucose availability to mammary tissue may become rate-limiting for milk secretion at the peak of lactation in the rat. There is little information available for any species on the effects of maternal protein and energy intake deficits on uptake of amino acids and glucose by lactating tissue. Athanasiou & Phillips (2) reported that a 36-hour fast depressed serum glucose concentrations from 60–45 mg/dl in lactating dairy cows, although they did not measure mammary glucose uptake. Taken together, these studies suggest that uptake of amino acids and glucose by lactating mammary tissue may affect milk production, especially if the maternal diet is limited in protein and energy.

Blood flow, one of the two parameters that determine substrate uptake, is a potential regulatory site for lactation that may be affected by diet. In the goat, mammary blood flow rises fourfold at parturition (64). Between days 1 and 5 of lactation, blood flow rose from 40 to 70 ml per 100 g mammary tissue per min; between days 5 and 15, mammary gland mass increased by 30% with a constant rate of blood flow per g of tissue (36). Mammary blood flow is positively correlated with milk yield in ruminants (55), rats (34, 35), and rabbits (77), although the degree of correlation is not always high. For instance, Mepham (64) observed that between weeks 18 and 23 of lactation, milk output in one goat declined 75%, while mammary blood flow declined by only 25%. It has been postulated that mammary secretory cells autoregulate blood flow to mammary tissue by release of vasodilatory substances (37, 55). According to this scheme, mammary secretory activity drives mammary blood flow, not vice versa. However, Hanwell & Linzell (35) demonstrated that cardiac output in lactating rats that had been separated from their litters for 24 hours rose significantly after administration of prolactin. This suggests that mammary blood flow may be regulated by at least two mechanisms: vasodilators from the mammary tissue itself, and prolactin released in response to suckling. If the second component of this putative regulatory scheme, release of prolactin, is diminished by inadequate maternal intake of protein and energy, then milk production may be impaired in part by decreased delivery of substrates and hormones to mammary tissue, caused by decreased mammary blood flow. In goats, a 16-hour fast decreased mammary blood flow twofold (55); after a 48-hour fast, mammary blood flow was 35% of control values (16). It is not possible to determine whether decreased blood flow under these conditions is a cause of decreased mammary secretory activity or a result of it. Effects of other forms of undernutrition on mammary blood flow have not been studied, nor have there been any reports dealing with mammary blood flow and human milk secretion. Decreased mammary blood flow under conditions of maternal undernutrition, whether a cause or an effect of impaired mammary metabolism, would affect interpretation of blood substrate and hormone concentrations (6).

A-V differences, the second component affecting mammary substrate uptake, have been studied in lactating cows, goats, pigs, and rats (47, 55, 98, 118). Hawkins & Williamson (39) reported that fasting lactating rats for 16 hours increased mammary A-V differences for β-hydroxybutyrate and acetoacetate, decreased A-V differences for glucose and triglycerides, and did not affect A-V differences for free fatty acids. Gamma-glutamyltranspeptidase (EC 2.3.2.2.) has been implicated in amino acid and glutathione transport into mammary tissue of rats (84, 116, 117) and cows (7). In the lactating rat, activity of γ-glutamyltranspeptidase increased threefold at parturition (84) and appears to play a role in transport of glutamine, methionine, cysteine, and alanine (116, 117). To date, effects of maternal protein and energy intake on mammary amino acid transport have not been reported.

Substrate uptake is another potential diet-sensitive regulatory site for mammary metabolism, but measurements of blood flow and A-V differences have not been made under conditions in which maternal intake of protein and energy have been varied. Laboratory animals are difficult to use for such experiments because of the ralatively small size of mammary blood vessels and the number of vessels supplying mammary tissue (54). Williamson and co-workers (78, 130) have shown that increased levels of ketone bodies in the blood of fasting rats depress mammary uptake of glucose. Other forms of protein and energy undernutrition may elicit analogous alterations in uptake of mammary substrates. Alterations in the hormonal control of lactation in response to dietary factors are clearly important possibilities, but this subject is beyond the scope of this review.

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CONCLUSIONS

Although a large body of information exists on effects of protein and energy intake on lactation in animals and humans, we are far from a comprehensive understanding of the basic principles involved. Protein synthesis in mammary tissue increases when nutritional status is improved, but milk output can apparently increase under conditions where mammary protein synthesis does not always increase. Observations in animals confirm that dietary protein and energy interact in affecting nitrogen utilization; improvement of dietary protein quality increases mammary protein synthesis when dietary energy is supplied in adequate amounts, but not always when energy intake is restricted. In contrast, milk output is increased by improving the net protein value of the diet, even when food energy is supplied in inadequate amounts.

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The extent to which milk production in human populations may be responsive to nutritional status is not completely understood. Gambian women at times produced amounts of milk comparable to those produced by well-nourished European and North American women, even though the Gambian women were consuming only 1700 kcal/day. If food intake of lactating rats is restricted to 70% of ad libitum consumption, milk production drops by 25%. Yet Gambian women consuming 1700 kcal/day, 62% of the energy intake for lactation recommended by the WHO, apparently produce milk at a level comparable to that of well-nourished Western women.

The effects of protein and energy intake on metabolic efficiency during lactation also are not clear. In rats, increasing food intake from moderately restricted to adequate levels results in significantly increased milk output. In humans, effects of food supplements on milk output in undernourished populations have not been established. In most instances, the increases in milk output reported in human supplementation studies have been small or nonexistent. However, it has been observed that nutritional status, if not nutritional supplementation, does affect milk production in humans. When food intake fell from 1700 to 1200 kcal/day during the rainy season, milk output in The Gambia dropped 40%, from 400 to 250 g over 12 hours. The decline in milk output paralleled the decline in food intake, with a two-month lag between the nadirs in intake and output. Some reports have shown substantial increases in milk output in lactating women given nutritional supplements. Weight gain of nursing infants rose from 30 to 46 g/day when Nigerian women consuming energy-adequate diets increased their protein intake from 50 to 100 g/day. There are indications that undernourished women given supplements during lactation partition the extra energy into increased activity or fat stores, rather than into milk. Beneficial effects of supplementation in the behavioral domain have also been observed. Nutritional supplements may also decrease the high metabolic efficiency of undernourished women during lactation. Peel et al (82) reported that administration of exogenous growth hormone to dairy cows in late lactation resulted in a 31% increase in milk output with a concomitant 16% decrease in food intake. The dairy cow is not the best model for human lactation, since it is a ruminant that has been selectively bred for high milk production. However, the increased efficiency of nutrient utilization for milk production observed in dairy cows under these conditions may reflect the same capacity to adapt metabolic efficiency during lactation to protein and energy intakes that is manifest in undernourished humans who secrete normal volumes of milk while consuming seemingly inadequate amounts of food. A fruitful area for future research will be to document the plasticity of maternal metabolic efficiency during lactation and to determine mechanisms by which intake of protein, energy, and other nutrients affect the efficiency of milk production.

Study of nutrient-endocrine relationships would be of considerable interest in this regard.

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Literature Cited

Annu. Rev. Nutr. 1984.4:43-67. Downloaded from www.annualreviews.org
by Texas State University - San Marcos on 01/04/12. For personal use only.

1. Aebi, H., Whitehead, R., eds. 1980. *Maternal Nutrition During Pregnancy and Lactation*. Bern: Hans Huber. 354 pp.
2. Athanasiou, V. N., Phillips, R. W. 1978. Effect of fasting on plasma metabolites and hormones in lactating dairy cows. *Am. J. Vet. Res.* 39:957–960
3. Baker, D. H., Speer, V. C. 1983. Protein and amino acid nutrition of non-ruminant animals with emphasis on the pig: Past, present, and future. *J. Anim. Sci.* 57 (Suppl. 2):284–299
4. Baldwin, R. L., Cheng, W. 1969. Metabolite changes associated with initiation and maintenance of lactation in rats and cows. *J. Dairy Sci.* 52:523–28
5. Baldwin, R. L., Smith, N. E., Taylor, J., Sharp, M. 1980. Manipulating metabolic parameters to improve growth rate and milk secretion. *J. Anim. Sci.* 51:1416–28
6. Bauman, D. E., Currie, W. B. 1980. Partitioning of nutrients during pregnancy and lactation: a review of mechanisms involving homeostasis and homeorhesis. *J. Dairy Sci.* 63:1514–29
7. Baumrucker, C.R., Pocius, P. A., Riss, T. L. 1981. Glutathione utilization by lactating bovine mammary secretory tissue in vitro. *Biochem. J.* 198:243–46
8. Belavady, B. 1980. Dietary supplementation and improvements in the lactation performance of Indian women. See Ref. 1, pp. 264–73
9. Bienkowski, R. S. 1983. Intracellular degradation of newly synthesized secretory proteins. *Biochem. J.* 214:1–10
10. Blaxter, K. L. 1964. Protein metabolism and requirements in pregnancy and lactation. In *Mammalian Protein Metabolism*, ed. H. N. Munro, J. B. Allison, 2:173–223. New York: Academic
11. Bond, J. T., Filer, L. J. Jr., Leveille, G. A., Thomson, A., Weil, W. B., eds. 1981. *Infant and Child Feeding*. New York: Academic. 502 pp.
12. Butte, N. F., Calloway, D. H. 1981. Evaluation of lactational performance of Navajo women. *Am. J. Clin. Nutr.* 34: 2210–15
13. Butte, N. F., Garza, C., Smith, E. O., Nichols, B. L. 1983. Evaluation of the deuterium dilution technique against the test weighing procedure for the determination of breast milk intake. *Am. J. Clin. Nutr.* 37:996–1003
14. Canas, R., Romero, J. J., Baldwin, R. L. 1982. Maintenance energy requirements during lactation in rats. *J. Nutrition* 112:1876–80
15. Carrick, D. T., Kuhn, N. J. 1978. Diurnal variation and response to food withdrawal of lactose synthesis in lactating rats. *Biochem. J.* 174:319–25
16. Chaiyabutr, N., Faulkner, A., Peaker, M. 1980. Effects of starvation on cardiovascular function (including the mammary circulation) and water balance in pregnant goats. *Q. J. Exper. Physiol.* 65:207–216
17. Chavalittamrong, B., Suanpan, S., Boonvisut, S., Chatranon, W., Gershoff, S. N. 1981. Protein and animo acids of breast milk from Thai mothers. *Am. J. Clin. Nutr.* 34:1126–30
18. Chavez, A., Martinez, C., Bourges, H. 1975. Role of lactation in the nutrition of low socioeconomic groups. *Ecol. Food Nutr.* 4:159–69
19. Craig, R. K., Campbell, P. N. 1978. Molecular aspects of milk protein synthesis. In *Lactation*, ed. B. L. Larson, 4:387–404. New York: Academic
20. Crnic, L. S., Chase, H. P. 1978. Models of infantile undernutrition in rats: Effects on milk. *J. Nutr.* 108:1755–60
21. Davis, A. J., Fleet, I. R., Goode, J. A., Hamon, M. H., Maule-Walker, F. M., Peaker, M. 1979. Changes in mammary function at the onset of lactation in the goat: correlation with hormonal changes. *J. Physiol.* 288:33–44
22. Djiane, J., Houdebine, L.-M., Kelly, P. A. 1982. Correlation between prolactin-

Annu. Rev. Nutr. 1984.4:43-67. Downloaded from www.annualreviews.org
by Texas State University - San Marcos on 01/04/12. For personal use only.

receptor interaction, down-regulation of receptors, and stimulation of casein and deoxyribonucleic acid biosynthesis in rabbit mammary gland explants. *Endocrinology* 110:791–95

23. Dobbing, J. 1981. Maternal nutrition in pregnancy—eating for two? *Early Human Develop.* 5:113–15
24. Edozien, J. 1980. Dietary influences on human lactation performance. See Ref. 1, pp. 203–221
25. Edozien, J. C., Khan, M. A. R., Waslien, C. I. 1976. Human protein deficiency: results of a Nigerian village study. *J. Nutr.* 106:312–28
26. Emery, R. S., Benson, J. D., Tucker, H. A. 1971. Dietary and hormonal effects on extended lactation and lipid metabolism in rats. *J. Nutr.* 101:831–38
27. FAO/WHO. 1973. Energy and protein requirements. *Report of a Joint FAO/WHO Ad Hoc Expert Committee. WHO Technical Report Series No. 522.* Geneva: WHO. 117 pp.
28. Forsum, E., Lonnerdal, B. 1980. Effect of protein intake on protein and nitrogen composition of breast milk. *Am. J. Clin. Nutr.* 33:1809–13
29. Frobish, L. T., Steele, N. C., Davey, R. J. 1973. Long-term effects of energy intake on reproductive performance of swine. *J. Anim. Sci.* 36:293–97
30. Garlick, P. J., McNurlan, M. A., Preedy, V. R. 1980. A rapid and convenient technique for measuring the rate of protein synthesis by injection of [^{3}H]phenylalanine. *Biochem. J.* 192: 719–23
31. Goodman, G. T., Akers, R. M., Friderici, K. H., Tucker, H. A. 1983. Hormonal regulation of α-lactalbumin secretion from bovine mammary tissue cultured in vitro. *Endocrinology* 112:1324–29
32. Greenhalgh, J. F. D., Elsley, F. W. H., Grubb, D. A., Lightfoot, A. L., Saul, D. W. 1977. Coordinated trials on the protein requirements of sows. 1. A comparison of four levels of dietary protein in gestation and two in lactation. *Anim. Prod. 24:307–21*
33. Halban, P. A., Wollheim, C. B. 1980. Intracellular degradation of insulin stores by rat pancreatic islets in vitro. *J. Biol. Chem.* 255:6003–6
34. Hanwell, A., Linzell, J. L. 1972. A simple technique for measuring the rate of milk secretion in the rat. *Comp. Biochem. Physiol.* 43A:259–70
35. Hanwell, A., Linzell, J. L. 1973. The effects of engorgement with milk and of suckling on mammary blood flow in the rat. *J. Physiol.* 233:111–25
36. Hanwell, A., Linzell, J. L. 1973. The time-course of cardiovascular changes in lactation in the rat. *J. Physiol.* 233:93–109
37. Hanwell, A., Peaker, M. 1977. Physiological effects of lactation on the mother. In *Comparative Aspects of Lactation, Symposium of the Zoological Society of London,* ed. M. Peaker, 41:297–312. London: Academic
38. Hasan, H. R., White, D. A., Mayer, R. J. 1982. Extensive destruction of newly synthesized casein in mammary explants in organ culture. *Biochem. J.* 202:133–38
39. Hawkins, R. A., Williamson, D. H. 1972. Measurement of substrate uptake by mammary gland of the rat. *Biochem. J.* 128:1171–73
40. Holt, C. 1983. Swelling of golgi vesicles in mammary secretory cells and its relation to the yield and quantitative composition of milk. *J. Theor. Biol.* 101: 247–61
41. Huffman, S., Chowdhury, A. K. M. A., Chakraborty, J., Simpson, N. K. 1980. Breast feeding patterns in rural Bangladesh. *Am. J. Clin. Nutr.* 33:144–54
42. Jansen, G. R. 1979. The importance of protein quality in human nutrition. In *Soy Protein and Human Nutrition,* ed. H. L. Wilcke, D. T. Hopkins, D. H. Waggle, pp. 149–70. New York: Academic
43. Jansen, G. R., Chase, H. P. 1976. Effect of feeding lysine and threonine fortified bread during gestation and lactation on growth of the offspring in rats. *J. Nutr.* 106:33–40
44. Jansen, G. R., Monte, W. C. 1977. Amino acid fortification of bread fed at varying levels during gestation and lactation in rats. *J. Nutr.* 107:300–9
45. Jelliffe, D. B., Jelliffe, E. F. P. 1978. *Human Milk in the Modern World.* New York: Academic. 500 pp.
46. Jelliffe, D. B., Jelliffe, E. F. P. 1978. The volume and composition of human milk in poorly-nourished communities. A review. *Am. J. Clin. Nutr.* 31:492–515
47. Jones, C. S., Parker, D. S. 1978. Uptake of substrates for milk-fat synthesis by lactating-rabbit mammary gland. *Biochem. J.* 174:291–96
48. Kanto, U., Clawson, A. J. 1980. Effect of energy intake during pregnancy and lactation on body composition in rats. *J. Nutr.* 110:1829–39
49. Kwong, E., Barnes, R. H. 1977. Comparative contributions of dietary protein quality and quantity to growth during gestation, lactation, and postweaning in the rat. *J. Nutr.* 107:420–25
50. Larson, B. L., ed. 1978. *Lactation,* Vol. 4. New York: Academic. 595 pp.

Annu. Rev. Nutr. 1984.4:43-67. Downloaded from www.annualreviews.org
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51. Larson, B. L., Jorgensen, G. N. 1974. Biosynthesis of milk protein. In *Lactation*, ed. B. L. Larson, V. R. Smith, 2:115–146. New York: Academic
52. Larson, B. L., Smith, V. R., eds. 1974. *Lactation*, Vols. 1–3. New York: Academic. 595 pp.
53. Lauber, E., Reinhardt, M. 1979. Studies on the quality of breast milk during 23 months of lactation in a rural community of the Ivory Coast. *Am. J. Clin. Nutr.* 32:1159–73
54. Linzell, J. L. 1953. The blood and nerve supply to the mammary gland of the rat and other laboratory animals. *Br. Vet. J.* 109:427–33
55. Linzell, J. L. 1974. Mammary blood flow and methods of identifying and measuring precursors of milk. In *Lactation*, ed. B. L. Larson, W. R. Smith, 1:143–225. New York: Academic
56. Linzell, J. L., Peaker, M. 1971. Mechanism of milk secretion. *Physiol. Rev.* 51: 564–97
57. Lonnerdal, B., Forsum, E., Gebre-Medhin, M., Hambraeus, L. 1976. Breast milk composition in Ethiopian and Swedish mothers. II. Lactose, nitrogen, and protein contents. *Am. J. Clin. Nutr.* 29:1134–41
58. Mahan, D. C. 1977. Effect of feeding various gestation and lactation dietary protein sequences on long-term reproductive performance in swine. *J. Anim. Sci.* 45:1061–72
59. Mahan, D. C. 1979. Effect of dietary protein sequence on long-term sow reproductive performance. *J. Anim. Sci.* 49:514–21
60. Mahan, D. C., Grifo, A. P. Jr. 1975. Effects of dietary protein levels during lactation to first-litter sows fed a fortified corn gestation diet. *J. Anim. Sci.* 41: 1362–67
61. Mahan, D. C., Mangan, L. T. 1975. Evaluation of various protein sequences on the nutritional carry-over from gestation to lactation with first-litter sows. *J. Nutr.* 105:1291–98
62. Manning-Dalton, C., Allen, L. H. 1983. The effects of lactation on energy and protein consumption, post-partum weight change, and body composition of well-nourished North American women. *Nutr. Res.* 3:293–308
63. Mepham, T. B. 1971. Amino acid utilization by the lactating mammary gland. In *Lactation*, ed. I. R. Falconer, pp. 297–315. University Park, Penn.: Penn. State Univ. Press
64. Mepham, T. B. 1982. Amino acid utilization by lactating mammary gland. *J. Dairy Sci.* 65:287–98
65. Mercier, J. C., Gaye, P. 1980. Early events in secretion of main milk proteins: occurrence of precursors. *J. Dairy Sci.* 65:299–316
66. Moe, P. W. 1981. Energy metabolism of dairy cattle. *J. Dairy Sci.* 64:1120–39
67. Moon, R. 1969. Mammary growth and milk yield as related to litter size. *Proc. Soc. Exp. Biol. Med.* 130:1126–28
68. Morgan, B. L. G., Naismith, D. J. 1977. Effects on the products of conception of protein supplementation of the diets of rats. *J. Nutr.* 107:1590–94
69. Munday, M. R., Williamson, D. H. 1983. Diurnal variations in food intake and in lipogenesis in mammary gland and liver of lactating rats. *Biochem. J.* 214:183–87
70. Naing, K. M., Oo, T. T., Theim, K. 1980. Study on lactation performance of Burmese mothers. *Am. J. Clin. Nutr.* 33:2665–68
71. Naismith, D. J. 1966. The requirement for protein, and the utilization of protein and calclium during pregnancy. *Metabolism* 15:582–95
72. Naismith, D. J. 1969. The foetus as a parasite. *Proc. Nutr. Soc.* 28:25–31
73. Naismith, D. J. 1980. Maternal nutrition and the outcome of pregnancy—a critical appraisal. *Proc. Nutr. Soc.* 39:1–11
74. Naismith, D. J., Morgan, B. L. G. 1976. The biphasic nature of protein metabolism during pregnancy in the rat. *Br. J. Nutr.* 36:563–66
75. Naismith, D. J., Richardson, D. P., Pritchard, A. E. 1982. The utilization of protein and energy during lactation in the rat, with particular regard to the use of fat accumulated in pregnancy. *Brit. J. Nutr.* 48:433–41
76. National Academy of Sciences, National Research Council. 1980. *Recommended Dietary Allowances*. Washington DC: Natl. Acad. Sci. 186 pp. 9th ed.
77. Ota, K., Peaker, M. 1979. Lactation in the rabbit: mammary blood flow and cardiac output. *Q. J. Exper. Physiol.* 64: 225–38
78. Page, M. A., Williamson, D. H. 1972. Lactating mammary gland of the rat: a potential major site of ketone body utilization. *Biochem. J.* 128:459–60
79. Park, C. S., Chandler, P. T. 1976. Response to labelled precursor amino acids, varying cell density, and graded amino acid complement for protein synthesis in mammary cell cultures. *J. Dairy Sci.* 59:216–23
80. Pau, M., Milner, J. A. 1982. Effect of arginine deficiency on mammary gland development in the rat. *J. Nutr.* 112: 1827–33

Annu. Rev. Nutr. 1984.4:43-67. Downloaded from www.annualreviews.org
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81. Paul, A. A., Muller, E. M., Whitehead, R. G. 1979. The quantitative effects of maternal dietary energy on pregnancy and lactation in rural Gambian women. *Trans. R. Soc. Trop. Med. Hyg.* 73:686–92
82. Peel, C. J., Fronk, T. J., Bauman, D. E., Gorewit, R. C. 1983. Effect of exogenous growth hormone in early and late lactation on lactational performance of dairy cows. *J. Dairy Sci.* 66:776–82
83. Picciano, M. F. 1981. The volume and composition of human milk. In *Infant and Child Nutrition*, ed. J. T. Bond, L. J. Filer, Jr., G. A. Leveille, A. Thomson, W. B. Weil, pp. 47–62. New York: Academic. 502 pp.
84. Pocius, P. A., Baumrucker, C. R., McNamara, J. P., Bauman, D. E. 1980. γ-Glutamyl transpeptidase in rat mammary tissue. Activity during lactogenesis and regulation by prolactin. *Biochem. J.* 188:565–68
85. Prema, K., Madhavapeddi, R., Ramalakshmi, B. A. 1981. Changes in anthropometric indices of nutritional status in lactating women. *Nutr. Reports Int.* 24:893–900
86. Prentice, A., Prentice, A. M., Whitehead, R. G. 1981. Breast-milk fat concentrations of rural African women. 2. Long-term variations within a community. *Brit. J. Nutr.* 45:495–503
87. Prentice, A. M. 1980. Variation in maternal dietary intake, birthweight and breast-milk output in The Gambia. See Ref. 1, pp. 167–183
88. Prentice, A. M., Lunn, P. G., Watkinson, M., Whitehead, R. G. 1983. Dietary supplementation of lactating Gambian women. II. Effect on maternal health, nutritional status, and biochemistry. *Hum. Nutr.: Clin. Nutr.* 37C:65–74
89. Prentice, A. M., Roberts, S. B., Prentice, A., Paul, A. A., Watkinson, M. 1983. Dietary supplementation of lactating Gambian women. I. Effect on breast milk volume and quality. *Hum. Nutr.: Clin. Nutr.* 37C:53–64
90. Prentice, A. M., Roberts, S. B., Watkinson, M., Whitehead, R. G., Paul, A. A. 1980. Dietary supplementation of Gambian nursing mothers and lactational performance. *Lancet* 2:886–87
91. Prentice, A. M., Whitehead, R. G., Roberts, S. B., Paul, A. A. 1981. Long-term energy balance in child-bearing Gambian women. *Am. J. Clin. Nutr.* 34: 2790–99
92. Rasmussen, K., Warman, N. L. 1983. Effect of maternal malnutrition during the reproductive cycle on growth and nutritional status of suckling rat pups. *Am. J. Clin. Nutr.* 38:77–83
93. Rattigan, S., Ghisalberti, A. V., Hartmann, P. E. 1981. Breast-milk production in Australian women. *Brit. J. Nutr.* 45:243–49
94. Ravi, R. T., Ganguli, N. C. 1980. Effect of dietary protein restriction on chromatin proteins of rat mammary gland. *J. Nutr.* 110:1144–51
95. Reese, D. E., Moser, B. D., Peo, E. R. Jr., Lewis, A. J., Zimmerman, D. R. 1982. Influence of energy intake during lactation on the interval from weaning to firstestrus in sows. *J. Anim. Sci.* 55:590–98
96. Reese, D. E., Moser, B. D., Peo, E. R. Jr., Lewis, A. J., Zimmerman, D. R. 1982. Influence of energy intake during lactation on subsequent gestation, lactation, and postweaning performance of sows. *J. Anim. Sci.* 55:867–72
97. Roberts, A. F. C., Vina, J. R., Munday, M. R., Farrell, R., Williamson, D. H. 1982. Effects of inhibition of protein synthesis by cycloheximide on lipogenesis in mammary gland and liver of lactating rats. *Biochem. J.* 204:417–23
98. Robinson, A. M., Williamson, D. H. 1977. Comparison of glucose metabolism in the lactating mammary gland of the rat in vivo and in vitro. *Biochem. J.* 164:153–59
99. Romero, J. J., Canas, R., Baldwin, R. L., Koong, L. J. 1976. Lactational efficiency complex of rats: provisional model for interpretation of energy balance data. *J. Dairy Sci.* 59:57–67
100. Rook, J. A. F. 1971. Discussion on nutrient utilization by the lactating mammary gland. See Ref. 19, pp. 333–338
101. Rowland, M. G. M., Paul, A. A. 1981. Factors affecting lactation capacity: implications for developing countries. See Ref. 11, pp. 63–75
102. Russell, S. M., Wilde, C. J., White, D.A., Hasan, H. R., Mayer, R. J. 1981. Characteristics of protein degradation in liver and mammary gland. *Acta Biol. Med. Germ.* 40:1397–1406

103a. Sampson, D. A., Jansen, G. R. 1983. The effect of dietary protein quality and feeding level on milk secretion mammary protein synthesis. Submitted for publication.

103b. Sampson, D. A., Jansen, G. R. 1983. Measurement of milk yield in the lactating rat from pup weight and weight gain. *J. Pediatr. Gastroenterol. Nutr.* In press

103c. Sampson, D. A., Jansen, G. R. 1983. Protein synthesis in mammary gland, liver and muscle during lactation: no circadian variation in rats fed diets varying in protein quality and level of intake. Submitted for publication.

104. Sasaki, A., Makagawa, I., Kajimoto, L.

Annu. Rev. Nutr. 1984.4:43-67. Downloaded from www.annualreviews.org
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1982. Effect of protein nutrition throughout gestation and lactation on growth, morbidity and life span of rat progeny. *J. Nutr. Sci. Vitaminol.* 28:543–55

105. Schingoethe, D. J., Hageman, E. C., Larson, B. L. 1967. Essential amino acids for milk protein synthesis in the in vitro secretory cell and stimulation by elevated levels. *Biochem. Biophys. Acta* 148:469–74
106. Schutz, Y., Lechtig, A., Bradfield, R. B. 1980. Energy expenditures and food intakes of lactating women in Guatemala. *Am. J. Clin. Nutr.* 33:892–902
107. Scrimshaw, N. S. 1977. Through a glass darkly: discerning the practical implications of human dietary protein-energy interrelationships. *Nutr. Rev.* 35:321–37
108. Servely, J.-L., Teyssot, B., Houdebine, L.-M., Delouis, C., Djiane, J. 1982. Evidence that the activation of casein gene expression in the rabbit mammary gland can be elicited by a low amount of prolactin firmly retained on its receptors. *Biochimie* 64:133–40
109. Skarda, J., Urbanova, E., Houdebine, L. M., Delouis, C., Bilek, J. 1983. Hormonal control of casein synthesis in mammary explants from pregnant goats. *Endokrinologie* 79:301–7
110. Snyderman, S. E., Holt, L. E. Jr., Dancis, J., Roitman, E., Boyer, A. 1962. Unessential nitrogen: A limiting factor for human growth. *J. Nutr.* 78:57–67
111. Society for Pediatric Research. 1982. Promotion of breast feeding: recommendations of the Councils of the Society for Pediatric Research (SPR) and American Pediatric Society (PAS) and of the American Academy of Pediatrics (AAP). *Pediatr. Res.* 16:264–65
112. Sosa, R., Klaus, M., Urrutia, J. J. 1976. Feed the nursing mother, thereby the infant. *J. Pediat.* 88:668–70
113. Svanberg, U., Gebre-Medhin, M., Ljungqvist, B., Olsson, M. 1977. Breast milk composition in Ethiopian and Swedish mothers. III. Amino acids and other nitrogenous substances. *Am. J. Clin. Nutr.* 30:499–507
114. Topper, Y. J., Freeman, C. S. 1980. Multiple hormone interactions in the developmental biology of the mammary gland. *Physiol. Rev.* 60:1049–1106
115. Turner, M. R. 1973. Perinatal mortality, growth, and survival to weaning in offspring of rats reared on diets moderately deficient in protein. *Br. J. Nutr.* 29:139–47
116. Vina, J., Puertes, I. R., Estrela, J. M., Vina, J. R., Galbis, J. L. 1981. Involvement of γ-glutamyltransferase in amino acid uptake by the lactating mammary gland of the rat. *Biochem. J.* 194:99–102
117. Vina, J., Puertes, I. R., Saez, G. T., Vina, J. R. 1981. Role of prolactin in amino acid uptake by the lactating mammary gland of the rat. *FEBS Lett.* 126:250–52
118. Vina, J. R., Puertes, I., Vina, R. 1981. Effect of premature weaning on amino acid uptake by the mammary gland of lactating rats. *Biochem. J.* 200:705–8
119. Waterlow, J. C. 1981. Observations on the suckling's dilemma—a personal view. *J. Human Nutr.* 35:85–98
120. Waterlow, J. C. 1981. Crisis for nutrition. Sixth Boyd Orr Memorial Lecture. *Proc. Nutr. Soc.* 40:195–207
121. Waterlow, J. C., Garlick, P. J., Millward, D. J. 1978. *Protein Turnover in Mammalian Tissues and in the Whole Body.* New York: North Holland. 804 pp.
122. Waterlow, J. C., Stephen, J. M. L., eds. 1981. *Nitrogen Metabolism in Man.* London: Applied Science. 558 pp.
123. Waterlow, J. C., Thomson, A. M. 1979. Observations on the adequacy of breast feeding. *Lancet* 2:238–42
124. Whitehead, R. G. 1983. *Maternal Diet, Breast Feeding Capacity, and Lactational Infertility. Food and Nutrition Bulletin Supplement* 6. Tokyo: United Nations Univ. 107 pp.
125. Whitehead, R. G. 1983. Nutritional aspects of human lactation. *Lancet* 1: 167–69
126. Whitehead, R. G., Paul, A. A. 1981. Infant growth and human milk requirements. A fresh approach. *Lancet* 2:161–63
127. Whitehead, R. G., Paul, A. A., Black, A. E., Wiles, S. G. 1981. Recommended dietary amounts of energy for pregnancy and lactation in the United Kingdom. In *Protein-Energy Requirements of Developing Countries: Evaluation of New Data,* ed. B. Torun, V. R. Young, W. M. Rand, pp. 259–65. Tokyo: United Nations Univ.
128. Wilde, C. J., Kuhn, N. J. 1981. Lactose synthesis and the utilization of glucose by rat mammary acini. *Int. J. Biochem.* 13:311–16
129. Williamson, D. H. 1980. Integration of metabolism in tissues of the lactating rat. *FEBS Lett.* 117:K93–K105
130. Williamson, D. H., Robinson, A. M. 1977. Control of glucose metabolism in lactating rat mammary gland: effects of other substrates, insulin, and starvation. *Biochem. Soc. Trans.* 5:829–33
131. Wurtman, J. T., Fernstrom, J. D. 1979. Free amino acid, protein, and fat contents of breast milk from Guatemalan mothers consuming a corn-based diet. *Early Hum. Develop.* 3:67–77
132. Yang, Y. T., Baldwin, R. L. 1976. Effect of adrenalectomy on rat mammary metabolism. *J. Dairy Sci.* 59:620–26.