Optimizing nutrient ratios in milk replacers for calves less than five weeks of age

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ABSTRACT

In trials 1A and 1B, the objective was to determine whether crude protein (CP) concentration could be lowered from 27% CP if Lys and Met were held constant. Forty-five calves per trial were fed milk replacer (MR) powders that contained 23, 25, or 27% CP (dry matter basis) from whey protein. Each MR powder contained 17% fat, 2.44% Lys, 0.75% Met, and 1.56% Thr by adding L-Lys, DL-Met, and L-Thr, and were fed at 0.681 kg/d. In trial 2, the objective was to estimate an optimal CP-to-energy ratio for 2 different amounts of MR fed. Ninety-six calves were fed 1 of 8 MR powders (dry matter basis): 1) 23% CP fed at 0.545 kg/d, 2) 25% CP fed at 0.545 kg/d, 3) 27% CP fed at 0.545 kg/d, 4) 29% CP fed at 0.545 kg/d, 5) 23% CP fed at 0.654 kg/d, 6) 25% CP fed at 0.654 kg/d, 7) 27% CP fed at 0.654 kg/d, and 8) 29% CP fed at 0.654 kg/d. In each MR, L-Lys and DL-Met were added to achieve a Lys:CP ratio of 0.09 and a Met:Lys ratio of 0.31. Holstein calves initially 2 to 3 d old and 43 ± 1 kg of body weight (BW) from 1 farm were fed MR until weaning at 28 d and were monitored for a total of 56 d. Calves were fed an 18% CP starter and water free choice from d 1 and were housed in individual pens bedded with straw in a naturally ventilated nursery with no added heat. Trials 1A and 1B were analyzed individually as completely randomized designs with repeated measures in a mixed model. Trial 2 was analyzed as a completely randomized block design with a factorial arrangement of 2 rates and 4 CP concentrations with repeated measures in a mixed model. In trials 1A and 1B, preweaning average daily gain (ADG) and feed efficiency declined as CP declined. Postweaning performance did not differ among treatments. In trial 2, preweaning ADG was greater and starter intake was lower at the high MR compared with the low MR feeding rate. Pre- and postweaning and overall ADG increased quadratically as CP increased. Preweaning MR rate interacted with CP; thus, at the low MR rate, providing 3.26 Mcal of metabolizable en-

ergy (ME)/d (0.0656 Mcal/kg of BW daily), 51.5 g of CP/Mcal of ME was the optimal ratio in the MR (25% CP, 17% fat, 2.26% Lys, and 0.68% Met) to maximize ADG. At the high ME intake, providing 3.71 Mcal/d (0.0743 Mcal/kg of BW daily), 55.0 g of CP/Mcal of ME was the optimal ratio in the MR (27% CP, 17% fat, 2.44% Lys, 0.75% Met) to maximize ADG.

Key words: calf, milk replacer, protein, energy

INTRODUCTION

It is well documented that ADG is increased with increased CP intake when energy is not limiting in calves fed only milk replacer (MR) and no starter (Donnelly and Hutton, 1976; Blome et al., 2003; Bartlett et al., 2006) and in calves fed MR and starter (Hill et al., 2006a,b). These studies were conducted by formulating the MR for CP without optimizing the MR formulas for AA. Recently, Hill et al. (2008b) reported an optimal concentration of AA in MR fed to calves under 5 wk old. They reported greater than 15% increases in ADG and feed efficiency to formulation for the concentration of Lys and Met in the MR and suggested a requirement for CP and Lys and for the ratios of Met and Thr to Lys. Their work suggested that other essential AA were adequate as supplied by the milk protein-based 27% CP replacers fed at 0.65 kg/calf daily and the starter feed consumed.

Information on the CP- and Lys-to-energy ratio in calves fed MR and starter is limited. Optimal ratios of CP to energy are important to maximize ADG and structural growth while not overfattening the animal. The optimal CP-to-energy ratios have been estimated in 60 kg of BW just-weaned calves (63 g of CP/Mcal of ME; Hill et al., 2008a), 95 kg of BW calves (52 to 59 g of CP/Mcal of ME; Hill et al., 2008a), and 150 kg of BW heifers (59 g of CP/Mcal of ME; Gabler and Heinrichs, 2003). The dairy NRC (2001) predicts calf ADG based on the limiting nutrients, either protein or energy, but AA are not considered. Blome et al. (2003) and Bartlett et al. (2006) questioned the accuracy of the equations in the dairy NRC (2001) based on their estimates of dietary nutrients transferred to the tissues of milk-fed calves, and they documented the impact of

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CP-to-energy ratios on ADG and protein deposition. A weakness of equations and predictions based on calves fed only MR is that different results can be obtained if calves are fed starter with the MR because of different enzyme systems (i.e., lactase or amylase) and efficiencies for digesting milk and plant nutrients (NRC, 2001). Additionally, as nutrient intake increases from the MR, starter intake, feed efficiency, and starter digestion decreases, negating the changes in ADG (Kuehn et al., 1994; Hill et al., 2006a,b; Terre et al., 2007) anticipated from increasing the MR fed. This interaction of MR fed with starter intake and digestion questions whether the optimal ratio of nutrients in MR-only diets is similar to or different from the ratio when starter is fed with MR. Although providing excellent information, previous trials by Donnelly and Hutton (1976), Blome et al. (2003), and Bartlett et al. (2006) used calves that were more than 14 d old when treatments began, with trial periods that were 35 to 49 d.

The current trials had 2 objectives. The first was to determine whether CP concentration of the MR powder fed at 0.654 kg/d could be lowered from the reported optimal 27% CP and 17% fat (Hill et al., 2008b) when Lys, Met, and Thr were held constant at 2.44% Lys, 0.75% Met, and 1.56% Thr. In the report by Hill et al. (2008b), the Lys, Met, and Thr concentrations were in a ratio with CP and declined as CP declined. If the requirement were only for Lys, Met, and Thr, lower CP concentrations might support similar ADG. The second objective was to estimate the optimal ratio of CP to energy in a MR powder fed at either 0.568 or 0.681 kg/d. Calves were less than a month of age and were fed starter under management similar to that in commercial settings.

MATERIALS AND METHODS

General

Holstein bull calves (43 ± 1 kg of BW) from a single dairy farm were received midday at 2 to 3 d of age after a 3-h transit. Their first MR was fed at the p.m. feeding. The day after arrival at approximately noon, the calves were weighed and randomly assigned to treatment (d 0, initial BW). Blood was sampled intravenously, serum was separated by centrifugation, and serum protein was estimated using an optical refractometer (Atago USA Inc., Bellevue, WA). General calf management; health protocols; and measurements of BW, starter intake, fecal scoring, body condition scoring, serum analysis for albumin, alkaline phosphatase, amylase, creatinine, glucose, total protein, and urea-N, and nutrient analysis of feeds (all methods for feed analysis were from AOAC, 2000) were conducted as described in Hill et al.

(2007a, 2008b). Specifically, AA were determined after acid hydrolysis [AOAC method 982.30 E(a)]. Total sulfur AA were determined after performic acid oxidation and then acid hydrolysis [AOAC method 982.30 E(b)]. Tryptophan content was determined after alkaline hydrolysis [AOAC method 982.30 E(c)].

Calves were housed in a curtain-sided, naturally ventilated nursery with no added heat in 1.2×2.4 m pens bedded with straw. Calves had access to clean, fresh water and starter at all times. All animals were cared for as described in the Guide for the Care and Use of Agricultural Animals in Agricultural Research and Teaching (FASS, 1999).

In each trial, calves were weaned at 28 d on study and measurements were made until d 56. Calves were weighed initially and every 7 d. Hip widths of the calves were measured initially and every 14 d. Starter intake offered and refused was measured daily. Feces were scored daily (1 to 5 scale; 1 = firm, normal; 5 = watery). A 17% fat MR powder was fed at no more than 0.681 kg of powder per day to all calves because this fat concentration and rate had been shown to improve ADG over a conventional 20% CP and 20% fat MR powder while not depressing starter intake or postweaning ADG when CP was more than 25% CP (Hill et al., 2006b). The MR was divided into 2 equal meals on d 0 to 25. On d 26 to 28, calves were fed half their daily amount of MR in the a.m. to facilitate weaning. All calves consumed the amount of MR offered. The MR were manufactured (Akey, Lewisburg, OH) by altering the concentrations of whey, whey protein concentrate (78% CP, as-fed basis), L-Lys, and DL-Met (Tables 1 and 2). The added fat was from lard and vegetable oils. A 20% CP starter formulated according to the guidelines of Hill et al. (2007b) was fed beginning on d 1. The starter contained 37% rolled corn, 35% protein pellets (71% soybean meal, 14% wheat middlings, and 15% minerals, vitamins, and decoquinate), 25% whole oats, and 3% molasses (Akey; Tables 1 and 2).

Trial 1A

Forty-five bull calves were fed 3 MR treatments (15 calves/treatment). The treatments were feeding calves 0.654 kg of DM/d of MR powder that contained 1) 23% CP, 2) 25% CP, or 3) 27% CP from whey protein, and each MR contained 2.44% Lys, 0.75% Met, and 1.56% Thr by adding L-Lys, DL-Met, and L-Thr (DM basis; Table 1). The MR were reconstituted at a rate of 148 g of powder/L of warm water and fed at 4.2 L/calf daily to provide 0.681 kg (as fed) of powder. For the first 7 d of the trial, all calves were fed MR 1 to establish a baseline value for serum sampling. On d 8 to 28, calves were fed their randomly assigned MR treat-

Table 1. Analyzed nutrient concentration of milk replacer powders¹ containing similar concentrations of Lys, Met, and Thr but different concentrations of CP and starters² fed in trials 1A and 1B

Item	Trial 1A				Trial 1B			
	23% CP	25% CP	27% CP	Starter	23% CP	25% CP	27% CP	Starter
Analyzed, % as fed								
DM	96.2	96.1	96.2	87.2	96.0	96.2	96.3	87.3
Analyzed, % of DM								
CP	23.1	25.1	27.3	20.7	23.3	25.2	27.1	20.8
Crude fat	17.8	18.0	17.7	4.3	18.1	18.0	17.9	4.2
Ash	6.8	6.7	6.7	6.3	6.6	6.8	6.6	6.4
Ca	0.81	0.82	0.82	0.91	0.83	0.84	0.84	0.85
P	0.62	0.65	0.64	0.58	0.65	0.63	0.62	0.61
AA								
Lys	2.40	2.41	2.41	1.06	2.45	2.45	2.45	1.07
Met	0.76	0.75	0.77	0.33	0.75	0.75	0.76	0.36
Cys	0.23	0.26	0.28	0.36	0.24	0.25	0.27	0.37
Thr	1.58	1.56	1.59	1.43	1.60	1.60	1.61	1.40
Arg	0.59	0.65	0.71	1.34	0.60	0.65	0.73	1.32
Glu	3.91	4.25	4.59	3.65	3.98	4.31	4.62	3.68
His	0.61	0.67	0.64	0.54	0.57	0.62	0.66	0.56
Ile	1.43	1.51	1.59	0.84	1.43	1.51	1.61	0.82
Leu	2.37	2.63	2.79	1.58	2.39	2.61	2.77	1.67
Phe	0.69	0.80	0.87	0.99	0.68	0.77	0.84	1.00
Trp	0.35	0.39	0.43	0.26	0.36	0.38	0.42	0.25
Tyr	0.53	0.67	0.72	1.96	0.56	0.70	0.76	1.89
Val	1.39	1.49	1.57	0.89	1.43	1.50	1.58	0.93
Calculated								
Digestible energy, ³ Mcal/kg	5.02	5.08	5.12	3.81	5.03	5.07	5.12	3.80
ME, ³ Mcal/kg	4.82	4.87	4.92	3.35	4.83	4.86	4.91	3.34
g of CP/Mcal of ME	47.8	51.5	55.6	61.7	48.3	51.7	55.2	62.3

¹Added concentrations (calculated): 8 mg of Cu/kg, 0.1 mg of Co/kg, 68 mg of Fe/kg, 0.7 mg of I/kg, 27 mg of Mn/kg, 0.2 mg of Se/kg, 34 mg of Zn/kg, 24 kIU of vitamin A/kg, 5 kIU of vitamin D/kg, 100 IU of vitamin E/kg, 15,500 µg of ascorbic acid/kg, 14 µg of biotin/kg, 3 µg of cobalamin/kg, 1,868 µg of choline/kg, 70 µg of folic acid/kg, 3,753 µg of niacin/kg, 1,876 µg of pantothenic acid/kg, 938 µg of pyridoxine/kg, 938 µg of riboflavin/kg, 938 µg of thiamin/kg, and 7 µg of decoquinat/kg.

²Added concentrations (calculated): 16 mg of Cu/kg, 1.2 mg of Co/kg, 94 mg of Fe/kg, 1.2 mg of I/kg, 54 mg of Mn/kg, 0.3 mg of Se/kg, 67 mg of Zn/kg, 8.5 kIU of vitamin A/kg, 2.8 kIU of vitamin D/kg, 72 IU of vitamin E/kg, 27 µg of biotin/kg, 6 µg of cobalamin/kg, 86 µg of folic acid/kg, 3,678 µg of niacin/kg, 2,747 µg of pantothenic acid/kg, 488 µg of pyridoxine/kg, 611 µg of riboflavin/kg, 611 µg of thiamin/kg, and 7 µg of decoquinat/kg.

³Using NRC (2001) equations.

ments. Jugular blood samples were taken on d 7, 14, and 21 at 90 min after the morning MR feeding, and the serum was separated by centrifugation. The average nursery temperature was -5°C and ranged from -21 to 10°C based on hourly measurements.

Statistical Analysis. Data for trial 1A were analyzed using MIXED procedures (version 8, SAS Institute Inc., Cary, NC) as repeated measures in a completely randomized design. Data from the first 7 d were averaged and used as covariates for the statistical analyses. The linear mixed model used was $Y_{ijk} = \mu + \beta X_{ij} + T_i + \rho_{ijk} + \epsilon_{ijk}$, where Y_{ijk} is the k th response of animal j on treatment i for repeated measurements 1 through k ; μ is the overall population mean; X_{ij} is the covariate variable and β is the coefficient on the covariate variable; T_i is the fixed effect of treatment i ; the random effect, ρ_{ijk} , is the correlation among k repeated measurements of animal j on treatment i ; and ϵ_{ijk} is the residual error term. Investigations using Akaike's information criteria indicated that the relationship among repeated

measures of Y_{ijk} could best be modeled using an autoregressive type 1 covariance structure within 28-d periods pre- or postweaning and the entire 56-d feeding period. When the overall F -test for treatments was significant ($P < 0.05$), orthogonal polynomial linear and quadratic contrasts were used to further characterize the treatment means. The experimental unit was the calf.

Trial 1B

Trial 1B was a repeat of the 3 treatments for trial 1A using 45 different bull calves (15 calves/treatment). However, there was no initial 7-d period in which all calves received MR 1, and blood was sampled only on d 21 at 90 min after the morning MR feeding. The average nursery temperature was 25°C and ranged from 11 to 37°C based on hourly measurements.

Statistical Analysis. Data for trial 1B were analyzed using MIXED procedures (version 9.1.3, SAS Institute Inc., Cary, NC) as repeated measures in a completely

Table 2. Analyzed nutrient concentration of milk replacer powders containing 23, 25, 27, or 29% CP and fed at either 0.545 or 0.654 kg of milk replacer powder¹ per day and starters² fed in trial 2

Item	23% CP	25% CP	27% CP	29% CP	Starter
Analyzed, % as-fed					
DM	96.5	96.4	96.8	96.1	87.5
Analyzed, % of DM					
CP	23.1	25.0	26.9	29.4	20.8
Crude fat	17.9	17.7	17.9	17.7	4.3
Ash	6.7	6.7	6.7	6.7	6.5
Ca	0.83	0.85	0.83	0.86	0.86
P	0.64	0.62	0.64	0.66	0.61
AA					
Lys	2.06	2.26	2.41	2.64	1.02
Met	0.63	0.68	0.75	0.82	0.37
Cys	0.24	0.25	0.26	0.29	0.34
Thr	1.36	1.47	1.63	1.77	1.44
Arg	0.61	0.65	0.71	0.78	1.31
Glu	3.84	4.20	4.56	4.95	3.68
His	0.49	0.52	0.56	0.59	0.51
Ile	1.27	1.46	1.55	1.70	0.80
Leu	2.30	2.58	2.76	2.97	1.61
Phe	0.69	0.78	0.85	0.89	0.97
Trp	0.36	0.43	0.44	0.49	0.23
Tyr	0.53	0.68	0.73	0.81	1.93
Val	1.36	1.46	1.55	1.71	0.94
Calculated					
Digestible energy, ³ Mcal/kg	5.01	5.06	5.09	5.17	3.79
ME, ³ Mcal/kg	4.81	4.85	4.89	4.96	3.34
g of CP/Mcal of ME	48.1	51.5	55.0	59.3	62.5

¹Added concentrations (calculated): 8 mg of Cu/kg, 0.1 mg of Co/kg, 68 mg of Fe/kg, 0.7 mg of I/kg, 27 mg of Mn/kg, 0.2 mg of Se/kg, 34 mg of Zn/kg, 24 kIU of vitamin A/kg, 5 kIU of vitamin D/kg, 100 IU of vitamin E/kg, 15,500 µg of ascorbic acid/kg, 14 µg of biotin/kg, 3 µg of cobalamin/kg, 1,868 µg of choline/kg, 70 µg of folic acid/kg, 3,753 µg of niacin/kg, 1,876 µg of pantothenic acid/kg, 938 µg of pyridoxine/kg, 938 µg of riboflavin/kg, 938 µg of thiamin/kg, and 7 µg of decoquinatone/kg.

²Added concentrations (calculated): 16 mg of Cu/kg, 1.2 mg of Co/kg, 94 mg of Fe/kg, 1.2 mg of I/kg, 54 mg of Mn/kg, 0.3 mg of Se/kg, 67 mg of Zn/kg, 8.5 kIU of vitamin A/kg, 2.8 kIU of vitamin D/kg, 72 IU of vitamin E/kg, 27 µg of biotin/kg, 6 µg of cobalamin/kg, 86 µg of folic acid/kg, 3,678 µg of niacin/kg, 2,747 µg of pantothenic acid/kg, 488 µg of pyridoxine/kg, 611 µg of riboflavin/kg, 611 µg of thiamin/kg, and 7 µg of decoquinatone/kg.

³Using NRC (2001) equations.

randomized design. The linear mixed model used was $Y_{ijk} = \mu + T_i + \rho_{ijk} + \varepsilon_{ijk}$, where Y_{ijk} is the k th response of animal j on treatment i for repeated measurements 1 through k ; μ is the overall population mean; T_i is the fixed effect of treatment i ; the random effect, ρ_{ijk} , is the correlation among k repeated measurements of animal j on treatment i ; and ε_{ijk} is the residual error term. The repeated measures were modeled using an autoregressive type 1 covariance structure selected as described previously. When the overall F -test for treatments was significant ($P < 0.05$), orthogonal polynomial linear and quadratic contrasts were used to further characterize the treatment means. The experimental unit was the calf.

Trial 2

Two blocks (48 calves/block) of bull calves were fed 1 of 8 MR treatments arranged as a 2×4 factorial.

Factors were total MR powder fed (0.545 and 0.654 kg of DM/d) and CP concentration of the MR powder (23, 25, 27, and 29%). The treatments (12 calves/treatment) were 1) 23% CP powder fed at 0.545 kg/d, 2) 25% CP powder fed at 0.545 kg/d, 3) 26% CP powder fed at 0.545 kg/d, 4) 29% CP powder fed at 0.545 kg/d, 5) 23% CP powder fed at 0.654 kg/d, 6) 25% CP powder fed at 0.654 kg/d, 7) 27% CP powder fed at 0.654 kg/d, and 8) 29% CP powder fed at 0.654 kg/d (DM basis; Table 2). The MR were reconstituted at a rate of 148 g of powder/L of warm water. Thus, 3.8 L of reconstituted MR of treatments 1, 2, 3, and 4 was fed to provide 0.568 kg of powder (as fed) per calf daily and 4.2 L of reconstituted MR of treatments 5, 6, 7, and 8 was fed to provide 0.681 kg of powder (as fed) per calf daily. In each MR, L-Lys and DL-Met were added to achieve a Lys:CP ratio of 0.09 and a Met:Lys ratio of 0.31, similar to the ratios defined in Hill et al. (2008b). Blood was sampled on d 21 at 90 min after the

Table 3. Intake and growth measurements and serum concentrations of selected constituents of calves fed milk replacer powders containing similar concentrations of Lys, Met, and Thr but either 23, 25, or 27% CP fed for 0 to 28 d preweaning in trial 1A

Item	23% CP	25% CP	27% CP	SEM	Linear <i>P</i> -value	Quadratic <i>P</i> -value
Calves, n	15	15	15	—	—	—
Initial serum protein, g/L	53	51	49	2.3	0.67	0.98
Initial BW, kg	43	43	42	1.4	0.46	0.96
28-d BW, kg	55	55	56	1.6	0.18	0.87
ADG, kg/d	0.44	0.46	0.48	0.023	0.05	0.97
Starter intake, kg/d	0.19	0.22	0.21	0.029	0.31	0.51
Milk replacer intake, kg/d	0.62	0.62	0.62	—	—	—
CP intake, kg/d	0.18	0.20	0.21	0.011	0.01	0.58
Lys intake, g/d	17	17	17	0.94	0.43	0.89
Met intake, g/d	5.4	5.4	5.5	0.31	0.48	0.93
Thr intake, g/d	13	13	13	0.70	0.52	0.84
ME intake, Mcal/d	4	4	4	0.29	0.38	0.95
g of CP/Mcal of ME	50.4	52.6	54.9	2.6	0.01	0.63
Feed efficiency, ¹ g/g	0.51	0.51	0.55	0.024	0.02	0.71
Initial hip width, cm	19	20	20	0.23	0.45	0.89
Hip width change, cm	1.4	1.6	1.6	0.18	0.19	0.62
Serum concentration						
Urea-N, mmol/L	2.7	2.8	3.2	0.23	0.01	0.45
Creatinine, μ mol/L	72	73	82	5.7	0.14	0.77
Alkaline phosphatase, units/L	253	248	245	35	0.29	0.82
Albumin, g/L	14	14	14	0.57	0.57	0.97
Total protein, g/L	56	57	58	1.7	0.14	0.91
Amylase, units/L	43	47	48	6.3	0.42	0.66
Glucose, mmol/L	5.6	5.5	5.4	0.32	0.38	0.76

¹BW gain divided by milk replacer plus starter intake.

morning MR feeding. The trial lasted 56 d. The average nursery temperature was 1°C and ranged from −13 to 25°C based on hourly measurements.

Statistical Analysis. Data for trial 2 were analyzed using the MIXED procedures of SAS as repeated measures from a randomized complete block design. The statistical model used was $Y_{ijklm} = \mu + b_i + R_j + P_k + RP_{jk} + \rho_{ijklm} + \varepsilon_{ijklm}$, where Y_{ijklm} is the m th response of animal l in block i fed rate j and CP level k for repeated measurements 1 through m ; μ is the overall population mean; b_i is the random effect of block i ; R_j is the fixed effect of feeding rate j ; P_k is the fixed effect of CP level k ; RP_{jk} is the interaction of feeding rate j and protein concentration k ; the random effect, ρ_{ijklm} , is the correlation among m repeated measurements of Y_{ijkl} ; and ε_{ijklm} is the residual error term. The repeated measures were modeled using an autoregressive type 1 covariance structure selected as described previously. When the overall F -test for CP level was significant ($P < 0.05$), orthogonal polynomial linear, quadratic, and cubic contrasts were used to characterize the treatment means. The experimental unit was the calf.

RESULTS

There were no differences in the initial measurements of serum protein concentrations, BW, and hip widths

in any of the trials. Target nutrient concentrations of the various MR powders were achieved (Tables 1 and 2).

Trial 1A

Prewaning intake of CP increased linearly ($P < 0.05$) as CP concentration of the MR increased. Intakes of starter and total ME were not different among treatments ($P > 0.05$; Table 3). Prewaning ADG and feed efficiency increased linearly ($P < 0.05$) as CP concentration of the MR increased. Serum concentration of urea-N increased linearly ($P < 0.05$) as CP concentration of the MR increased. Serum concentrations of creatinine, alkaline phosphatase, albumin, total protein, amylase, and glucose were not different among treatments ($P > 0.05$). Calves fed the 27% CP powder with a ratio of 57.8 g of CP/Mcal of ME had a ratio of 54.9 g of CP/Mcal of ME for the total dietary intake of MR and starter.

Postweaning and overall measurements were not tabulated. Postweaning ADG (0.749 ± 0.032 kg/d), starter intake (1.975 ± 0.045 kg/d), feed efficiency (0.381 ± 0.013), and hip width change (2.5 ± 0.4 cm) did not differ among treatments ($P > 0.05$). Overall (0- to 56-d) ADG responded linearly ($P < 0.05$) to CP concentration and were 0.596, 0.607, and 0.617

Table 4. Intake and growth measurements and serum concentrations of selected constituents of calves fed milk replacer powders containing similar concentrations of Lys, Met, and Thr but either 23, 25, or 27% CP fed for 0 to 28 d preweaning in trial 1B

Item	23% CP	25% CP	27% CP	SEM	Linear <i>P</i> -value	Quadratic <i>P</i> -value
Calves, n	15	15	15	—	—	—
Initial serum protein, mg/dL	52	54	52	1.4	0.70	0.29
Initial BW, kg	43	42	43	1.2	0.34	0.39
28-d BW, kg	51	53	54	1.3	0.05	0.32
ADG, kg/d	0.32	0.40	0.41	0.028	0.03	0.20
Starter intake, kg/d	0.09	0.11	0.13	0.014	0.04	0.97
Milk replacer intake, kg/d	0.62	0.62	0.62	—	—	—
CP intake, kg/d	0.16	0.18	0.20	0.007	0.01	0.26
Lys intake, g/d	16	16	17	0.5	0.46	0.83
Met intake, g/d	4.9	5.0	5.1	0.2	0.37	0.74
Thr intake, g/d	11	11	12	0.3	0.41	0.86
ME intake, Mcal/d	3.3	3.4	3.5	0.26	0.19	0.39
g of CP/Mcal of ME	49.5	52.7	56.0	1.9	0.01	0.28
Feed efficiency, ¹ g/g	0.43	0.52	0.51	0.025	0.04	0.22
Initial hip width, cm	18	18	18	0.3	0.20	0.77
Hip width change, cm	1.1	1.5	1.5	0.1	0.05	0.19
Serum concentration						
Urea-N, mmol/L	2.7	3.8	4.0	0.5	0.04	0.18
Creatinine, μ mol/L	106	116	119	6	0.11	0.21
Alkaline phosphatase, units/L	239	286	277	15	0.08	0.16
Albumin, g/L	17	17	17	1.0	0.89	0.99
Total protein, g/L	57	56	56	1.8	0.81	0.95
Amylase, units/L	36	46	47	2.9	0.01	0.15
Glucose, mmol/L	7.5	6.0	4.9	0.6	0.01	0.32

¹BW gain divided by milk replacer plus starter intake.

kg/d (SEM = 0.027 kg/d). Overall feed efficiencies responded linearly ($P < 0.05$) to CP concentration and were 0.445, 0.449, and 0.463 kg/d (SEM = 0.015 kg/d). Other overall measurements did not differ ($P > 0.05$) among treatments.

Trial 1B

Intake of CP increased linearly ($P < 0.05$) as CP concentration of the MR increased. Intake of total ME was not different among treatments ($P > 0.05$; Table 4). Preweaning ADG, starter intake, feed efficiency, and hip width change increased linearly ($P < 0.05$) as CP concentration of the MR increased. Serum concentration of urea-N and amylase increased linearly ($P < 0.05$), whereas concentration of glucose declined linearly ($P < 0.05$) as CP concentration of the MR increased. Serum concentrations of creatinine, alkaline phosphatase, albumin, and total protein were not different among treatments ($P > 0.05$). Calves fed the 27% CP powder with a ratio of 57.2 g of CP/Mcal of ME had a ratio of 56.0 g of CP/Mcal of ME for the total dietary intake of MR and starter.

Postweaning and overall measurements were not tabulated. Postweaning ADG (0.721 ± 0.040 kg/d), starter intake (1.821 ± 0.049 kg/d), feed efficiency (0.395 ± 0.031), and hip width change (2.0 ± 0.2 cm) did not differ among treatments ($P > 0.05$). Overall (0- to 56-d) ADG responded linearly ($P < 0.05$) to

CP concentration and were 0.520, 0.559, and 0.565 kg/d (SEM = 0.032 kg/d). Overall feed efficiencies responded linearly ($P < 0.05$) to CP concentration and were 0.412, 0.420, and 0.455 kg/d (SEM = 0.028 kg/d). Other overall measurements did not differ ($P > 0.05$) among treatments.

Trial 2

There was an interaction of MR feeding rate and CP concentration in the MR during the preweaning period for ADG and change in hip width ($P < 0.05$). Calf ADG and change in hip width changed quadratically ($P < 0.05$) with CP concentration in MR, with ADG being lowest for calves fed the 23% CP MR (Table 5). In calves fed 0.545 kg of MR, the ADG and hip width change were maximized with the 25% CP MR containing 51.5 g of CP/Mcal of ME, corresponding to 54.0 g of CP/Mcal of ME total dietary intake. In calves fed 0.654 kg of MR, the ADG and hip width change were maximized with the 27% CP MR containing 55.0 g of CP/Mcal of ME or 56.3 g of CP/Mcal of ME total dietary intake.

During the preweaning period, starter intake was less ($P < 0.05$) for calves fed 0.654 kg of MR than with calves fed 0.545 kg of MR (Table 5). Intakes of ME and CP were greater ($P < 0.05$) for calves fed 0.654 kg of MR than for calves fed 0.545 kg of MR (Table 6). The calf ADG and hip width change were greater ($P < 0.05$)

Table 5. Intake and growth measurements of calves fed milk replacer powders containing 23, 25, 27, or 29% CP and fed at either 0.545 or 0.654 kg of milk replacer powder per day in trial 2

Item	0.545 kg of DM/d				0.654 kg of DM/d				SEM	<i>P</i> -value for main effects			<i>P</i> -value for CP effects		
	23% CP	25% CP	27% CP	29% CP	23% CP	25% CP	27% CP	29% CP		Rate	CP	Rate × CP	Linear	Quad	Cubic
Calves, n	12	12	12	12	12	12	12	12	—	—	—	—	—	—	—
Initial serum protein, mg/dL	4.9	5.2	5.3	5.4	5.0	5.3	5.5	5.2	0.10	0.67	0.09	0.44	0.06	0.16	0.88
Initial BW, kg	42.7	43.2	43.0	42.9	42.6	43.9	42.9	41.2	0.85	0.78	0.55	0.23	0.61	0.39	0.78
28-d BW, kg	54.9	56.4	56.1	56.0	55.2	57.9	57.7	55.9	0.98	0.58	0.03	0.21	0.04	0.05	0.30
56-d BW, kg	77.3	78.6	78.6	78.9	76.1	82.0	80.8	77.1	1.12	0.47	0.05	0.24	0.04	0.05	0.39
ADG, kg/d															
0 to 28 d	0.44	0.47	0.47	0.47	0.45	0.50	0.53	0.52	0.016	0.03	0.02	0.05	0.03	0.04	0.90
29 to 56 d	0.80	0.80	0.80	0.82	0.75	0.86	0.82	0.76	0.017	0.82	0.02	0.15	0.02	0.03	0.68
0 to 56 d	0.62	0.63	0.64	0.64	0.60	0.68	0.68	0.64	0.015	0.44	0.03	0.14	0.04	0.05	0.71
Starter intake, kg of DM/d															
0 to 28 d	0.24	0.22	0.24	0.24	0.17	0.21	0.20	0.19	0.017	0.03	0.58	0.46	0.77	0.71	0.88
29 to 56 d	1.78	1.79	1.83	1.85	1.72	1.83	1.82	1.76	0.051	0.58	0.37	0.49	0.45	0.43	0.97
0 to 56 d	1.01	1.01	1.03	1.04	0.95	1.02	1.01	0.97	0.032	0.29	0.42	0.67	0.49	0.45	0.94
Milk replacer intake, kg of DM/d															
0 to 28 d	0.52	0.52	0.52	0.52	0.62	0.62	0.62	0.62	—	—	—	—	—	—	—
29 to 56 d	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0 to 56 d	0.26	0.26	0.26	0.26	0.31	0.31	0.31	0.31	—	—	—	—	—	—	—
Feed efficiency, ¹ kg/kg															
0 to 28 d	0.574	0.634	0.619	0.621	0.564	0.601	0.643	0.644	0.016	0.55	0.05	0.06	0.05	0.07	0.88
29 to 56 d	0.450	0.445	0.439	0.442	0.434	0.469	0.452	0.432	0.0085	0.91	0.38	0.21	0.62	0.33	0.97
0 to 56 d	0.487	0.500	0.491	0.494	0.476	0.511	0.512	0.499	0.0065	0.31	0.32	0.35	0.26	0.12	0.94
Hip width, cm															
Initial	18	18	18	17	17	17	18	17	0.22	0.66	0.68	0.57	0.79	0.43	0.34
0 to 28 d change	1.4	1.7	1.6	1.6	1.7	1.9	2.2	2.1	0.087	0.01	0.04	0.03	0.03	0.04	0.76
29 to 56 d change	2.8	2.8	3.0	3.1	2.6	2.8	2.5	2.9	0.16	0.16	0.25	0.34	0.22	0.66	0.51
0 to 56 d change	4.2	4.5	4.6	4.7	4.3	4.7	4.6	5.0	0.17	0.33	0.02	0.27	0.02	0.78	0.44

¹BW gain divided by milk replacer plus starter intake.

for calves fed 0.654 kg of MR than for calves fed 0.545 kg of MR. Serum concentrations of urea-N were greater ($P < 0.05$) for calves fed 0.545 kg of MR than for calves fed 0.654 kg of MR (Table 7). Serum concentrations of creatinine, alkaline phosphatase, albumin, total protein, amylase, and glucose were not different between MR feeding rates ($P > 0.05$). Serum concentrations of creatinine tended to be greater ($P < 0.07$) for calves fed 0.654 kg of MR than for calves fed 0.545 kg of MR.

Feed efficiency increased linearly ($P < 0.05$) as CP concentration in the MR increased at both feeding rates. This relationship tended to be quadratic ($P < 0.07$). Serum concentration of urea-N increased linearly ($P < 0.05$) as CP concentration of the MR increased. Serum concentrations of creatinine, alkaline phosphatase, albumin, total protein, amylase, and glucose were not different among CP concentrations of MR ($P > 0.05$).

During the postweaning period, ADG responded quadratically ($P < 0.05$) to concentration of CP in the MR, with ADG being lowest for calves fed the 23% CP MR. Calf ADG was maximal in calves fed 25% CP and declined with 29% CP. Other measurements did not differ among treatments during the postweaning period ($P > 0.05$).

Over the entire 56-d trial, ADG responded quadratically ($P < 0.05$) to concentration of CP in the MR, with ADG being lowest for calves fed the 23% CP MR. Calf ADG was maximized in calves fed 27% CP and declined with 29% CP. Change in hip width increased linearly ($P < 0.05$) as CP increased in the MR. Other measurements did not differ among treatments during the postweaning period ($P > 0.05$).

DISCUSSION

Prewaning ADG and feed efficiency responses in trials 1A and 1B were consistent and strongly suggest that there were limitations to ADG and feed efficiency beyond the constant concentrations of Lys, Met, and Thr when the CP concentration of the MR was 23 or 25%. The declines in ADG and feed efficiency as CP concentration of the MR declined imply that other AA or even total MP may have been limiting at the amount of energy consumed. A difference in the trials was a lower ADG in trial 1B compared with trial 1A, which is likely attributable to the heat stress conditions in trial 1B, in which the average temperature was 25°C compared with -5°C in trial 1A. Another difference in the trials was that preweaning starter intake declined as CP concentration in the MR declined in trial 1B, but not in trial 1A. This is similar to the increase in MR intake observed by Rogers and Egan (1975) when 4-wk-old lambs were fed only liquid diets and essential AA intake changed from very deficient to approximately adequate.

Donnelly and Hutton (1976), Gerrits et al. (1997), and Bartlett et al. (2006) all reported greater ADG at high versus low energy levels fed, and they reported that ADG increased as CP intake increased. The increased ADG from increased energy and CP in the calves fed starter in trial 2 are consistent with results in calves fed only MR. In trial 2, calves fed the low ME intake of 3.26 Mcal/d achieved maximal ADG with a 25% CP powder or a ratio of 51.5 g of CP/Mcal of ME. Calves fed the high ME intake of 3.71 Mcal/d achieved maximal ADG with a 27% CP MR powder or a ratio of 55.0 g of CP/Mcal of ME. These CP concentrations and ratios of CP to energy to maximize ADG at each energy intake appear different from the other values in the literature and likely relate to differences in trial design.

Selected means describing the animals, optimal diets, ADG, and trial designs from the trials in the literature and trials 1A, 1B, and 2 are assembled in Table 8. Calves in trials 1A, 1B, and 2 were 2 to 3 d old initially and the trial period was 28 d. In trials from the literature, calves were more than 14 d old when treatments began and trial periods were 35 to 49 d. Starter intake contributed a small proportion of the nutrients consumed by the calves weaned at 28 d in the current trials but could have changed the enzyme systems and utilization of nutrients relative to only MR-fed calves (NRC, 2001). Weaning later would have increased the CP-to-ME ratio of the diet because of the greater CP-to-ME ratio of starter compared with MR and would also dilute the total nutrient contribution from MR. Another difference among the trials was the AA concentration of the MR. It would appear that the MR from all of the literature trials did not contain added L-Lys and DL-Met and could have had a lower concentration of Lys and Met relative to the MR in trials 1A, 1B, and 2. Trials 1A, 1B, and 2 measured ADG, and the discussion has related to ADG reported in somewhat similar trials. Nutrients and nutrient ratios that maximize ADG may not maximize protein gain.

The different maximal ADG at the low and high energy intakes also have practical application. In production, conventional MR that are low in CP (less than 23% CP) will have limited usefulness beyond fattening the calf (Donnelly and Hutton, 1976) or reducing starter intake when fed at 0.645 kg of DM (Hill et al., 2006a,b). The increase in ADG when CP was limiting at each rate also resulted in an increase in hip width. This increase in both ADG and hip width indicates that the growth was more than just fattening when CP was limiting and is consistent with previous reports (Hill et al., 2006a,b). In addition, the high CP-to-ME ratio of 55.0 g of CP/Mcal of ME with an MR fed at the high rate and formulated for limiting Lys and Met emphasizes the importance of CP or AA to calves less

Table 6. Intake CP and energy of calves fed milk replacer powders containing 23, 25, 27, or 29% CP and fed at either 0.545 or 0.654 kg of milk replacer powder per day in trial 2

Item	0.545 kg of DM/d				0.654 kg of DM/d				SEM	<i>P</i> -value for main effects			<i>P</i> -value for CP effects		
	23% CP	25% CP	27% CP	29% CP	23% CP	25% CP	27% CP	29% CP		Rate	CP	Rate × CP	Linear	Quad	Cubic
CP intake, kg/d															
0 to 28 d	0.17	0.18	0.19	0.20	0.18	0.20	0.21	0.22	0.0094	0.01	0.01	0.48	0.01	0.36	0.82
29 to 56 d	0.37	0.37	0.38	0.39	0.36	0.38	0.38	0.37	0.014	0.38	0.34	0.73	0.29	0.57	0.78
0 to 56 d	0.27	0.27	0.29	0.29	0.27	0.29	0.29	0.29	0.019	0.27	0.22	0.62	0.12	0.60	0.95
ME intake, Mcal/d															
0 to 28 d	3.3	3.3	3.3	3.4	3.6	3.7	3.7	3.7	0.21	0.02	0.35	0.42	0.42	0.73	0.71
29 to 56 d	5.9	6.0	6.1	6.2	5.7	6.1	6.1	5.9	0.47	0.42	0.57	0.82	0.36	0.29	0.78
0 to 56 d	4.6	4.6	4.7	4.8	4.7	4.9	4.9	4.8	0.35	0.47	0.49	0.73	0.42	0.88	0.82
g of CP/Mcal of ME															
0 to 28 d	51.6	54.0	56.7	60.0	50.4	53.5	56.3	59.9	2.1	0.56	0.01	0.37	0.01	0.26	0.91
29 to 56 d	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	2.3	0.47	0.43	0.75	0.34	0.79	0.70
0 to 56 d	58.6	59.4	60.4	61.6	57.8	59.1	60.1	61.4	2.3	0.62	0.02	0.83	0.02	0.23	0.67

Table 7. Serum concentrations of selected constituents of calves fed milk replacer powders containing 23, 25, 27, or 29% CP and fed at either 0.545 or 0.654 kg of milk replacer powder per day in trial 2

Item	0.545 kg of DM/d				0.654 kg of DM/d				SEM	<i>P</i> -value for main effects			<i>P</i> -value for CP effects		
	23% CP	25% CP	27% CP	29% CP	23% CP	25% CP	27% CP	29% CP		Rate	CP	Rate × CP	Linear	Quad	Cubic
Calves, n	6	6	6	6	6	6	6	6	—	—	—	—	—	—	—
Urea-N, mmol/L	2.4	2.9	3.8	4.9	2.2	2.5	2.7	3.4	0.18	0.04	0.01	0.41	0.01	0.24	0.59
Creatinine, μmol/L	74	74	77	74	73	80	93	95	8.0	0.07	0.26	0.76	0.26	0.39	0.78
Alkaline phosphatase, units/L	224	234	245	235	226	239	257	264	47	0.17	0.29	0.37	0.29	0.43	0.57
Albumin, g/L	15	15	14	15	15	15	15	15	0.46	0.42	0.46	0.40	0.46	0.65	0.91
Total protein, g/L	56	56	56	56	57	56	57	57	1.2	0.57	0.34	0.58	0.34	0.60	0.78
Amylase, units/L	46	46	46	44	47	46	46	47	4.5	0.32	0.56	0.35	0.56	0.74	0.87
Glucose, mmol/L	5.9	5.8	5.7	5.8	6.3	6.3	6.0	6.1	0.32	0.18	0.25	0.59	0.25	0.51	0.58

Table 8. Comparisons of diet and intake characteristics of the treatments in which ADG was maximal in the current trials and selected trials from the literature in which graded concentrations of CP were fed to neonatal calves

Item	Current trial or reference ¹ /treatment Mcal ²									
	Trial 1A/ one	Trial 1B/ one	Trial 2/ low	Trial 2/ high	Bartlett/ low	Bartlett/ high ³	Bartlett/ high	Blome/ one	Donnelly/ low	Donnelly/ high
Initial age, d	2 to 3	2 to 3	2 to 3	2 to 3	>14	>14	>14	>14	>14	>14
Initial BW ⁴ , kg	42.4	42.5	43.2	42.9	46.9	44.8	46.0	44.9	38.1	37.7
Average BW ⁴ , kg	49.2	48.2	49.8	50.0	54.1	56.9	58.3	57.8	53.4	58.6
Trial length, d	28	28	28	28	35	35	35	42	49	49
ADG, kg/d	0.484	0.408	0.470	0.529	0.409	0.690	0.703	0.620	0.623	0.854
g of ADG/kg of BW daily	9.84	8.46	9.44	10.58	7.57	12.14	12.06	10.73	11.66	14.57
CP intake, kg/d	0.206	0.195	0.176	0.209	0.150	0.214	0.245	0.198	0.214	0.386
g of CP intake/kg of BW	4.19	4.05	3.54	4.18	2.78	3.76	4.20	3.42	4.01	6.58
Milk replacer CP, % of DM	27.3	27.1	25.0	26.9	22.3	22.3	24.8	25.8	21.8	31.5
Milk replacer fat, % of DM	17.7	17.9	17.7	17.9	21.4	21.4	18.9	18.6	24.2	18.3
ME intake, Mcal/d	3.76	3.49	3.26	3.71	3.08	4.40	4.52	3.82	4.94	6.31
Mcal of ME intake/kg of BW	0.0764	0.0723	0.0656	0.0743	0.0570	0.0774	0.0775	0.0661	0.0925	0.1076
Milk replacer DMI, kg/d	0.622	0.622	0.518	0.622	0.671	0.959	0.988	0.820	0.982	1.225
g of CP/Mcal of ME of milk replacer	55.6	55.2	51.5	55.0	48.7	48.6	54.2	51.7	43.3	61.2
g of CP/Mcal of ME of diet	54.9	56.0	54.0	56.3	48.7	48.6	54.2	51.7	43.3	61.2

¹Bartlett et al. (2006); Blome et al. (2003); Donnelly and Hutton (1976).²Energy levels fed in the trials: only one level or both a low and high level.³ADG was maximized at 0.703 kg of ADG/d with 0.214 kg of CP intake/d; ADG/kg of BW was maximized at 12.06 g of ADG/kg of BW with 0.245 kg of CP intake/d.⁴Depending on the reference, some initial or average BW were calculated, and then ADG, CP intake, and ME intake per average BW were calculated.

than 1 mo of age that are maintained in commercial housing and conditions.

CONCLUSIONS

From trials 1A and 1B, it was concluded that maintaining 2.44% Lys, 0.75% Met, and 1.56% Thr concentrations of the as-fed MR powder while reducing CP concentrations from 27% CP resulted in substantial linear reductions in ADG and feed efficiency. This suggests that as CP was reduced, either AA other than Lys, Met, and Thr became limiting, total MP became limiting, or both. From trial 2, it was concluded that the optimal ratio of CP to energy in an MR program adequate in AA related to energy provided by the MR fed. At the low ME intake of 3.26 Mcal/d (0.0656 Mcal/kg of BW daily), 51.5 g of CP/Mcal of ME was the optimal ratio in MR to maximize ADG. This was provided by feeding 0.545 kg of DM from an MR (25% CP, 17% fat, 2.26% Lys, and 0.68% Met, as-fed MR powder). At the high ME intake of 3.71 Mcal/d (0.0743 Mcal/kg of BW daily), 55.0 g of CP/Mcal of ME was the optimal ratio in the MR to maximize ADG. This was provided by feeding 0.645 kg of DM from an MR (27% CP, 17% fat, 2.41% Lys, and 0.75% Met, as-fed MR powder). In each trial, a 20% CP starter with 62 g of CP/Mcal of ME was fed and the calves (initially 43 kg of BW and 2 to 3 d old) were weaned at 28 d. Other trials in the literature have used calves initially more than 14 d of age and fed only MR and have determined lower optimal CP-to-energy ratios when similar amounts of energy were fed per unit of BW.

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