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Comparison of immunoglobulin G absorption in calves fed maternal colostrum, a commercial whey-based colostrum replacer, or supplemented maternal colostrum

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ABSTRACT

Successful passive transfer of antibodies in neonatal calves can be achieved by feeding an adequate quantity and quality of maternal colostrum (MC) or colostrum replacer (CR). An alternative could be feeding low-quality maternal colostrum (LMC) with added IgG from a CR. The objective of this study was to determine if a commercial whey-based CR product containing low levels of casein (Premolac PLUS Bovine IgG; Zinpro Corporation, Eden Prairie, MN) fed to replace MC or supplement LMC could lead to adequate serum IgG levels and apparent efficiency of absorption (AEA) in neonatal dairy calves. Holstein calves (n = 20 per treatment) were separated from their dam after birth and randomly assigned to be fed 3.79 L of MC (106 g/L of IgG; 401 g of IgG fed), LMC (30 g/L IgG) supplemented with CR (41 g/L IgG; 154 g of IgG total fed; LMC-CR), or 1.3 L of 1 of 2 levels of CR (110 or 150 g of IgG fed; CR-110 or CR-150) within 1.5 h of birth. Colostrum was obtained from the first (MC) or second and third milkings (LMC) of cows from Pennsylvania State University dairy and pooled by source into large batches. Blood samples were taken from calves before colostrum feeding and 24 h after birth and were analyzed for serum total protein, total IgG, hematocrit, and Brix percentage. Calves fed MC had higher 24-h IgG values (means ± SEM) than calves fed LMC-CR (27.04 ± 1.07 vs. 22.33 ± 1.08 mg/mL, respectively). Feeding 150 g of IgG from CR led to higher 24-h serum IgG values than feeding 110 g of IgG (16.90 ± 1.09 vs. 12.79 ± 1.08 mg/mL). Serum IgG levels were different between the CR-fed calves and the calves fed LMC-CR and MC, but all had average values >10 mg/mL IgG. Calves fed LMC-CR had greater AEA than calves fed MC (54.58 ± 2.39 vs. 24.38 ± 2.36%, respectively). Among calves fed CR-110 or CR-150, AEA did not differ. Serum total protein and Brix percentage had strong correlations with actual IgG values across the entire study. We found no differences in average daily gain or health variables measured, and no differences in final hip width, withers height, or body weight for calves fed MC, LMC-CR, CR-150, or CR-110. These results indicate that CR can be fed successfully as an alternative to MC or as a supplement to colostrum with low IgG.

Key words: calf, colostrum replacer, immunoglobulin G

INTRODUCTION

Early and sufficient feeding of high-quality colostrum to newborn calves is crucial for an effective calf management program. Colostrum is the first secretion a cow produces after mammary involution. Colostrum contains Ig and many other proteins, including growth factors important for development of the calf immune and digestive systems. Colostrum supplies the first nutrients for the calf at birth and contributes to intestinal protection (Davis and Drackely, 1998). At birth, calves have an immature immune system, lacking antibodies and depending on passive transfer of immunity from their dams through colostrum-acquired Ig until their own active immune system develops (Davis and Drackely, 1998).

Colostrum replacers (**CR**) have been developed as an alternative to maternal colostrum (**MC**) when the supply of high-quality, low-pathogen (either fresh or stored) MC is insufficient for newborn calves. Colostrum replacer products generally have a lower bacteria level than MC, which can reduce pathogen exposure. Colostrum replacer products have been shown to prevent failure of passive transfer (**FPT**; McGuirk and Collins, 2004; Foster et al., 2006; Lago et al., 2018). However, the efficiency of immunoglobulin absorption can differ between the CR on the market, largely due to differences in processing methods and IgG sources. The IgG in commercially produced CR can be derived from

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lacteal (milk, whey, or colostrum), blood (serum), or egg sources (Quigley, 2004) and vary in nutrient composition and absorption efficiency (Quigley et al., 2002; Foster et al., 2006; Swan et al., 2007). Supplementing low-quality maternal colostrum (**LMC**) with IgG from CR products is also an alternative. Arthington et al. (2000) demonstrated that supplementing MC with a bovine serum IgG product resulted in improved apparent efficiency of absorption (**AEA**) of IgG. Although some studies have shown that feeding CR results in FPT (Quigley et al., 1998), others have demonstrated that serum IgG concentrations can be adequate if calves are fed either MC or CR (Lago et al., 2018). The objective of this study was to compare the ability of a whey-based commercial CR to lead to similar IgG levels, growth variables, and health data as calves fed MC.

MATERIALS AND METHODS

This project was approved by the Pennsylvania State University Institutional Animal Care and Use Committee (IACUC, #47457). Holstein calves born from April 2018 to September 2018 at the Pennsylvania State University dairy (n = 80, 20 per treatment; 64 females and 16 males) were used for the experiment. Each treatment group included 16 females and 4 males. All calves were separated from their dam immediately after birth to prevent suckling and uncontrolled colostrum consumption. Calves were weighed, navel-dipped, placed in an individual pen, stratified by sex, and randomly assigned to 1 of 4 colostrum treatments. Treatments consisted of (1) high-quality MC from first milkings (106 g/L IgG; 401 g of IgG fed; positive control); (2) LMC from second and third milking (30 g/L IgG) supplemented with 40 g of IgG from a CR (**LMC-CR**; 41 g of IgG/L; 154 g of IgG fed); (3) whey-based CR containing 110 g of IgG (**CR-110**; Premolac PLUS Bovine IgG; Zinpro Corp., Eden Prairie, MN); or (4) whey-based CR containing 150 g of IgG (**CR-150**). All colostrum treatments were fed to calves within 1.5 h after birth. Calves assigned to MC and LMC-CR were fed 3.79 L. The CR powder product was derived from dried bovine colostrum and was high in IgG (40.64%) and other whey proteins, as a result of casein and fat removal during manufacturing. Calves assigned to CR-150 were fed a complete dose of the product (375 g of powder). Calves assigned to CR-110 were fed a reduced dose (270.7 g of powder) of the same CR used for calves fed CR-150. The purpose of feeding CR-110 (a low IgG dose) was to intentionally produce low levels of IgG and possibly induce FPT in some calves. Colostrum powder for CR-110 and CR-150 was mixed with 1.3 L of warm water. All calves were fed in a single feeding within 1.5 h of birth using an esophageal feeder (Handi Grip 4-Qt. Feeder, Nasco, Fort Atkinson, WI). Colostrum for the MC and LMC-CR treatments was thawed in a warm water bath (38 to 43°C). For calves fed CR, the powder was mixed into 1.3 L of warm water (42 to 47°C) and stirred with a whisk to ensure proper homogenization. Early studies have shown that pasteurizing colostrum at 60°C for 30 min denatures 12 to 30% of colostral IgG (Meylan et al., 1996). However, neither the warm bath used to thaw MC or LMC-CR nor the warm water used to mix the CR reached 60°C. As a result, we did not consider this a factor that would considerably affect colostral IgG. A volume difference existed between calves fed CR (1.3 L) and calves fed LMC-CR and MC (3.79 L); however, Stott and Fellah (1983) found that total IgG mass fed was more important than IgG concentration, which is affected by volume due to dilution.

Maternal colostrum was obtained from first, second, and third milkings from cows at the Pennsylvania State University dairy farm. First-milking colostrum was used to make the high-quality colostrum treatment (MC), and second- and third-milking colostrum was used to make the low-quality colostrum treatment (LMC). A colostrometer (Biogenics, Florence, OR) was used to initially classify colostrum on farm. All colostrum was stored in 1.89-L plastic containers and frozen immediately at −20°C until an adequate volume was available for the study. Before the study began, 2 different colostrum batches were made. After thawing, all containers of high-quality colostrum (≥75 mg/mL IgG) were mixed using a milk pasteurizer (PLV model; 2c Duecinox, Guastalla, Italy) for mixing only. Once the batch was uniformly mixed, the colostrum was stored in new individual 1.89-L plastic bottles and immediately frozen at −20°C until feeding. The same process was used to make the low-quality colostrum, using colostrum with a concentration of ≤40 g IgG/L.

Samples from the 2 colostrum batches were thawed with warm water (110°F) and analyzed for IgG levels using a radial immunodiffusion assay (#728411; Triple J Farms, Bellingham, WA). Colostrum samples were diluted 1:10 or 1:5 in 0.85% saline solution. Samples were analyzed in duplicate, and those with a coefficient of variation of 10.0% or less were accepted and averaged for the final result. High-quality MC contained 106 g of IgG/L and low-quality MC contained 30 g of IgG/L.

Before feeding the colostrum (0 h) and at 24 h, a jugular blood sample was collected into a 10-mL serum blood collection tube (Vacutainer; Becton, Dickinson and Co., Franklin Lakes, NJ) and into a 10-mL sodium heparin Vacutainer. These samples were used to measure serum total protein (**STP**), Brix percentage, IgG, AEA, and packed cell volume (hematocrit). In addition, blood samples were collected weekly through wk 7. Blood collected with sodium heparin tubes also

was used for hematocrit analysis. Serum samples were refrigerated and then centrifuged at 1,500 × *g* for 15 min at 4°C to separate the serum. The serum obtained from the clot separation was stored in 5-mL test tubes (Globe Scientific Inc., Paramus, NJ) at −20°C until further IgG analysis. The STP and Brix readings were determined using a calibrated optical refractometer (Atago Co. Ltd., Tokyo, Japan).

All frozen serum samples were thawed with warm water (43°C) and analyzed for total IgG concentration using radial immunodiffusion analysis (#728411; Triple J Farms). Serum samples that required dilution were diluted either 1:10 or 1:5 with 0.85% saline solution. We used the manufacturer's instructions (http://69.195.120.15/jjj/wp-content/uploads/2017/04/Triple-J-Bovine-IgG-728411.pdf) to determine the IgG concentration. Samples were analyzed in duplicate, and values with a coefficient of variation of 10.0% or less were accepted and averaged for final results.

A total of 80 calves were evaluated for serum IgG, birth BW, and structural growth. One calf (MC treatment) died during the trial at 3 d due to pneumonia complications and was replaced. Calves were housed in 1.2 m × 1.4 m individual pens from birth until wk 7 of age. Each pen contained bedding with straw and sawdust, and new sawdust was added daily. Calves were fed 6 L of pasteurized whole milk daily in 2 feedings at 0500 and 1500 h during wk 1 to 6 of age. Pasteurization was done using a batch pasteurizer (PLV model; 2c Duecinox) that heated the milk to 65°C (149°F) for 30 min. Milk was fed at half rate for 1 wk before weaning, and calves were weaned at 7 wk of age. From d 3 until wk 7 of age, starter grain and water were offered ad libitum. Daily health scores were taken and included scours, respiration, and general appearance using a standard scoring system (CalfTrack) defined by Lesmeister and Heinrichs (2004).

Descriptive statistics and normality were assessed for all data using the univariate procedure of SAS (version 9.4; SAS Institute Inc., Cary, NC). Serum total protein, Brix percentage, IgG, AEA, and packed cell volume (hematocrit) were analyzed using the mixed procedure. Fixed effects in the model were colostrum treatment and calf sex; birth BW was included as a covariate. Growth measurements were analyzed using repeated measures in the mixed procedure with a first-order autoregressive covariance structure. Colostrum treatment, calf sex, week, and their interactions were included as fixed effects. Calf within treatment was included as a random variable. Differences between least squares means were compared using the slice option and contrast statements. Significance was declared at $P < 0.05$, and trends at $P < 0.10$. Serum IgG, STP, and Brix data were also evaluated using receiver operator characteristic curve analysis and the logistic procedure to develop FPT cutoff points for STP and Brix. This analysis tested whether STP and Brix were good predictors of serum IgG at 24 h.

Health score data were converted to a binary format (score of 1 or 2 = healthy, score >2 = sick) and analyzed using the GLIMMIX procedure of SAS (version 9.4; SAS Institute) with the Laplace method for likelihood approximation and Morel's corrected empirical estimator for bias correction of standard errors. Newton-Raphson with Ridging was specified for nonlinear optimization. Colostrum treatment was included as a fixed effect in the model, and day was included as a repeated effect using calf within treatment as the subject term. Logit and complementary log–log link functions were evaluated, and the logit link was selected based on Akaike's information criterion and the ratio of Pearson's χ^2 to degrees of freedom.

RESULTS AND DISCUSSION

The variables at birth from all calves by colostrum treatment are reported as least squares means in Table 1. Variables including BW (kg), STP (g/dL), IgG (mg/mL), hematocrit (%), and Brix (%) did not differ among treatments ($P > 0.05$). Calves were fed within 89.13 ± 7.43 min after birth, and differences between treatments were considered minimal. All serum IgG values at birth were 0 mg/mL and similar to those reported by Gelsinger et al. (2015) and Saldana et al. (2019). Similarly, STP concentrations and hematocrit (%) at birth were similar to those reported by Saldana et al. (2019).

Findings for 24 h STP, serum IgG, AEA (Quigley et al., 1998), hematocrit, and Brix are reported in Table 2. We found that STP was lower in calves fed CR than in calves fed MC or LMC-CR ($P < 0.01$). This was expected, because only the MC and LMC-CR treatments contained casein, the predominant protein found in colostrum (Kehoe et al., 2007).

Serum TP increased as total IgG fed increased among treatments and was highest in calves fed MC (4.29, 4.45, 4.99, and 6.03 g/dL for CR-110, CR-150, LMC-CR, and MC, respectively). We found no difference in STP between calves fed CR, but calves fed MC had higher STP than calves fed CR or LMC-CR. Foster et al. (2006) and Priestley et al. (2013) reported similar STP values for calves fed MC (6.20 and 6.10 g/dL, respectively). The STP values reported by Godden et al. (2009) and Lago et al. (2018) for calves fed MC were slightly lower, but similar (5.70 and 5.84 g/dL). The STP values from calves fed CR in this study were lower than those reported from calves fed an even lower total IgG mass of 100 g (4.5 and 5.0 g/dL, respectively)

Table 1. Birth weight, age at colostrum feeding, and blood variables at birth for calves in each treatment (n = 20)[1]

Item	MC	LMC-CR	CR-150	CR-110	Contrast *P*-value: MC + LMC-CR vs. CR[2]	Contrast *P*-value: MC vs. LMC-CR	Contrast *P*-value: CR-150 vs. CR-110	SEM
BW, kg	39.15	42.39	42.42	42.19	0.17	0.04	0.89	1.12
Age at colostrum feeding, min	91.67	89.13	87.76	85.69	0.06	0.35	0.43	1.90
Total protein, g/dL	4.05	3.96	3.88	4.05	0.57	0.44	0.10	0.07
IgG, mg/mL	0	0	0	0	—	—	—	—
Hematocrit, %	35.66	36.49	34.65	35.60	0.57	0.73	0.68	1.66
Brix, %	7.05	6.92	6.87	7.05	0.76	0.28	0.13	0.08

[1]CR-110 = colostrum replacer providing 110 g of IgG; CR-150 = colostrum replacer providing 150 g of IgG; LMC-CR = supplemented low-quality MC; MC = maternal colostrum.

[2]MC and LMC-CR treatments compared with CR-150 and CR-110 treatments.

by Foster et al. (2006). As well, Godden et al. (2009) reported higher values than in the present study for calves fed 100 g of IgG (4.9 g/dL). Quigley et al. (2017) reported STP values similar to the current study, except that calves fed CR-150 had a slightly lower mean STP of 4.60 g/dL.

Previous studies have reported higher STP values for calves fed similar levels of IgG from CR products; those findings might have been influenced by the composition or manufacturing of the different CR products used. The observed variation in other studies and the consistently lower STP values observed in calves fed the commercially available CR product in this study (Premolac PLUS Bovine IgG; Zinpro Corporation) can be attributed to the distinct processing techniques used to manufacture different types of CR products (Godden et al., 2009). The STP cutoff of 5.2 g/dL to determine FPT was not suitable for this study, because although most calves had STP values below this cutoff, they had measured serum IgG values above 10 mg/mL at 24 h. These results are evidence for developing and measuring a different cutoff point to measure FPT for calves fed CR products. These overall results matched those reported by Quigley et al. (2002), in which calves with a mean STP below 5.0 g/dL still achieved blood IgG values >10 mg/mL. Quigley et al. (2002) mentioned that a cutoff value of 4.2 g/dL would be a good predictor for concentrations of 10 g of IgG/L in serum at 24 h. The cutoff value of 4.2 g/dL for STP as an indicator of successful passive transfer or FPT would be a better fit for the data in the present study, even though some calves with STP values below 4.2 g/dL still had serum IgG concentrations >10 mg/mL. Similarly, Lago et al. (2018) showed low STP values for calves fed CR from the same IgG source; consequently, the authors mentioned that success of passive transfer might also be achieved at lower refractometer readings when calves are fed CR. This contrasted with Calloway et al. (2002), who stated that STP values of 5.0 and 5.2 g/dL predicted serum IgG concentrations of 10 mg/mL with a sensitivity and specificity >0.80; however, these results were obtained from calves fed MC, and might not be accurate for calves fed a commercial CR. We analyzed the data from the present study using a receiver operator characteristic curve analysis and determined a cutoff value for STP. This analysis used STP data

Table 2. Blood variables at 24 h after birth for calves in each treatment (n = 20)[1]

Item	MC	LMC-CR	CR-150	CR-110	Contrast *P*-value: MC + LMC-CR vs. CR[2]	Contrast *P*-value: MC vs. LMC-CR	Contrast *P*-value: CR-150 vs. CR-110	SEM
Total protein, g/dL	6.03	4.99	4.45	4.29	<0.01	<0.01	0.24	0.09
IgG, mg/mL	27.04	22.33	16.90	12.79	<0.01	0.04	0.01	1.09
AEA,[3] %	24.38	54.28	40.09	41.44	0.55	<0.01	0.69	2.39
Hematocrit, %	31.53	32.26	30.58	31.94	0.68	0.74	0.53	1.56
Brix, %	9.18	8.03	7.51	7.31	<0.01	<0.01	0.17	0.10
FPT,[4] %	0	0	0	20	—	—	—	—

[1]AEA = apparent efficiency of absorption; CR-110 = colostrum replacer providing 110 g of IgG; CR-150 = colostrum replacer providing 150 g of IgG; FPT = failure of passive transfer; LMC-CR = supplemented low-quality MC; MC = maternal colostrum.

[2]MC and LMC-CR treatments compared with CR-150 and CR-110 treatments.

[3]Calculated as AEA = {[birth weight (kg) × 0.09 × serum IgG (mg/mL at 24 h)]/total IgG fed (g)} × 100.

[4]Defined by IgG values ≤10 mg/mL at 24 h.

from both the CR-150 and CR-110 groups, because they provided the data of interest and because CR-110 was the only treatment that included calves with FPT; this condition needed to be present in some calves to develop a new cutoff point. The best fit for STP was a cutoff value of 4.2 g/dL, which would predict a value of 10 mg/mL IgG in serum with a sensitivity of 1.00 and a specificity of 0.58.

Refractometry measures STP rather than IgG, but the lack of non-immunoglobulin proteins in the CR product could have affected the indirect readings and estimates (Quigley et al., 2002). Serum IgG and STP in calves fed CR-150 had a correlation of 0.64 ($P < 0.01$), which was similar to the correlations of r = 0.78 and 0.76 in CR treatments reported by Mowrey (2001) and Quigley et al. (2002), respectively. Quigley et al. (2002) also discussed the incongruence of serum IgG and STP for FPT prediction using the cutoff of greater than 10 mg/mL of IgG in serum at 24 h. They reported a weak correlation of r = 0.48 from STP and serum IgG for their MC treatment.

Serum IgG concentrations at 24 h increased as total IgG mass fed increased among the treatments (12.79, 16.90, 22.33, and 27.04 mg/mL for CR-110, CR-150, LMC-CR, and MC, respectively). These results were expected, because a positive correlation exists between total IgG mass fed and serum IgG concentration (Zaremba et al., 1993). Lago et al. (2018) reported a higher mean IgG value of 19.6 mg/mL for calves fed 150 g IgG from a colostrum-derived CR. Notably, all mean IgG concentrations in all treatments were above the FPT cutoff point of >10 mg/mL. The mean serum concentration of IgG was lower for calves fed CR-150 and CR-110 (16.9 and 12.79 mg/mL, respectively) than for calves fed MC and LMC-CR (27.04 and 22.33 mg/mL, respectively; $P < 0.001$); however, their total IgG consumption was lower than those fed MC. Calves fed CR-150 had higher 24 h IgG concentrations than calves fed CR-110 ($P < 0.01$), and calves fed MC had higher concentrations than calves fed LMC-CR. Of the calves fed CR-110 and CR-150, 20 and 0% experienced FPT. The results in this study demonstrated that calves fed CR had acceptable levels of FPT, in agreement with reports from Quigley et al. (2001), Jones et al. (2004), and Foster et al. (2006). As expected, none of the calves fed the highest-quality treatment (MC) experienced FPT.

Calves fed LMC-CR, who received colostrum with a low IgG concentration (30 g/L), did not experience FPT. This finding can be accredited to the supplementation of 40 g IgG from the CR, which elevated the concentration to 41 g/L of IgG. We found a considerable difference in colostrum IgG concentration between LMC-CR and MC (41 vs. 106 g/L of IgG, respectively). Although serum IgG concentrations between MC and LMC-CR were different ($P = 0.004$), calves fed LMC-CR had adequate mean serum IgG concentrations of 22.33 mg/mL. Hopkins and Quigley (1997) noted that calves fed MC plus a colostrum supplement containing 25 g of IgG—similar to our LMC-CR treatment—had lower serum IgG concentrations than calves fed only MC. In the present study, the addition of the CR to LMC considerably increased the mean serum IgG, even though the colostrum without supplementation had only 30 g/L IgG, and dramatically increased the AEA to 54.28%. Overall, supplementing LMC with CR in this study led to positive results, which differed from the results observed by Abel Francisco and Quigley (1993). The results of this study suggest that feeding calves CR-150 within 1.5 h after birth could lead to low levels of FPT and serum IgG concentrations similar to calves fed MC. As discussed by Godden et al. (2009), variations between studies showed that the performance of a specific CR product should not be extrapolated to other CR products.

Mean AEA values are shown in Table 2 and indicate that absorption was greatest in calves fed LMC-CR (54.28%; $P < 0.001$). The AEA values did not differ for CR-110 and CR-150 ($P = 0.69$), but did differ for MC and LMC-CR ($P < 0.01$). The mean AEA from both CR treatments compared with the mean AEA for MC and LMC-CR together was not different ($P = 0.55$). The mean AEA was considerably higher in calves fed LMC-CR than in calves that received MC (54.28 and 24.38%, respectively; $P < 0.01$). The small amount of CR supplemented in the maternal colostrum to make LMC-CR could have contributed considerably to AEA. We also assume that the second- and third-milking colostrum had a lower level of solids. This may have affected how IgG was absorbed because of reduced osmolality. Calves fed smaller doses of IgG tend to have better AEA levels; in this study, AEA decreased as the total amount of IgG fed to calves increased (41.44, 40.09, and 24.38% for 110, 150, and 401 g in CR-110, CR-150, and MC, respectively). This was also demonstrated by Hopkins and Quigley (1997), who obtained higher AEA when calves were fed MC with a lower IgG concentration. Saldana et al. (2019) noted that an upper limit of AEA may exist with the amount of IgG fed in a given time period. The AEA findings for the present study were similar to the AEA value of 38.8% for a colostrum-derived CR reported by Priestley et al. (2013) and higher than values reported by Lago et al. (2018) and Godden et al. (2009), where calves fed 150, 100, and 200 g of IgG had mean AEA of 34.4, 35.5, and 36.5%, respectively.

Brix values at birth for MC, LMC-CR, CR-150, and CR-110 were not different ($P > 0.05$). However, at 24

h, MC was greater than LMC-CR ($P < 0.01$), and CR-150 and CR-110 were not different ($P = 0.17$). Brix values from CR were lower than the average of the MC and LMC-CR treatments ($P < 0.01$). We also conducted a receiver operator characteristic curve analysis for Brix data to obtain a cutoff value for estimating a concentration of 10 mg/mL of IgG at 24 h. This curve analysis included data from both the CR-150 and CR-110 groups, because they were the data of interest and because CR-110 was the only treatment that included calves with FPT; FPT needed to be present in some calves to develop a new cutoff point. The Brix cutoff value determined was 7.4%, with a sensitivity of 1 and specificity of 0.39. This cutoff value was slightly lower than the 7.8% reported by Morrill et al. (2013). As mentioned before, feeding calves a CR product without casein and other proteins may affect readings of STP and serum solids. Brix percentage and STP were found to be equivalent for predicting serum IgG concentration ($P = 0.59$).

Mean hematocrit values did not differ between treatments at birth or at 24 h but were lower at 24 h than at birth. At 24 h, calves fed MC had a hematocrit value of 35.66%, similar to values reported by Saldana et al. (2019).

The least squares means for BW gain and structural measurements (including hip width and withers height) are reported in Table 3. Calves were offered ad libitum grain starter and water from birth. The ADG from wk 1 to 7 for MC, LMC-CR, CR-150, and CR-110 were similar (590.42, 515.57, 523.89, and 535.75 g, respectively; $P = 0.41$).

Least squares means for weekly IgG concentrations by treatment are shown in Figure 1. Weekly IgG concentrations differed among colostrum quality treatments ($P < 0.001$) and by the fixed effect of time point ($P < 0.001$). Calves fed MC and LMC-CR had their lowest IgG concentration point at wk 6 and wk 4, respectively (Figure 1). Calves fed CR-150 and CR-110 had their lowest IgG concentration point at wk 3. On all treatments, IgG concentration gradually increased after the lowest point. These findings matched with the half-life of 19.1 d from IgG derived from colostrum-derived CR reported by Murphy et al. (2014). Burton et al. (1989) also reported the lowest IgG concentrations at wk 4 of age. The difference with these past studies was that the data were obtained from calves fed MC. Devery et al. (1979) stated that calves start to produce their own antibodies at 3 wk of age. Husband and Lascelles (1975) stated that colostrum-deprived calves or calves fed a lower total IgG mass start to produce IgG earlier than colostrum-fed calves. The results from calves fed CR-150 differed from the findings reported by Quigley et al. (2017), in which calves fed 150 g of IgG from a lacteal-based CR had little IgG change from wk 0 to wk 4. Quigley et al. (2017) reported a similar weekly IgG behavior graph for calves fed 450 g of IgG, in which the lowest concentration was also in wk 3 and had a gradual increase afterward. At the end of the present study, calves fed MC, LMC-CR, CR-150, and CR-110 had slight differences in IgG concentration values regardless of the initial IgG peak at 24 h (14.08, 13.79, 13.35, and 12.14 mg/mL, respectively). Calves fed CR-110, who had the lowest total IgG ingestion, were able to return to their highest IgG concentration point (24 h) at wk 7 of age. Overall, the average weekly IgG concentrations from all calves had a peak concentration at 24 h and a gradual increase after the lowest concentration time point. In general, these IgG concentration changes were similar to those reported by Klinkon et al. (2008) and

Table 3. Least squares means for calf growth variables from wk 1 to 7 (n = 80, 20 per treatment)[1]

Item	MC	LMC-CR	CR-150	CR-110	*P*-value	SEM
BW, kg						
Initial, wk 1	45.60	46.57	46.97	47.27	0.89	1.57
Weaning, wk 6	62.15	63.01	62.87	63.73	0.92	1.57
Final, wk 7	68.08	67.54	68.13	68.53	0.98	1.57
Difference[2]	22.48	20.97	21.16	21.26	0.91	1.61
ADG wk 1–7, g/d	590.42	515.77	523.89	535.75	0.41	34.21
Hip width, cm						
Initial, wk 1	16.86	17.33	17.26	17.36	0.33	0.22
Final, wk 7	19.95	20.15	20.09	20.21	0.86	0.22
Difference[2]	3.09	2.82	2.83	2.85	0.59	0.17
Withers height, cm						
Initial, wk 1	76.68	77.32	77.29	78.60	0.29	0.72
Final, wk 7	86.04	85.50	86.35	87.23	0.38	0.72
Difference[2]	9.36	8.18	9.06	8.63	0.34	0.48

[1]CR-110 = colostrum replacer providing 110 g of IgG; CR-150 = colostrum replacer providing 150 g of IgG; LMC-CR = supplemented low-quality MC; MC = maternal colostrum.

[2]Calculated as wk 7 – wk 1.

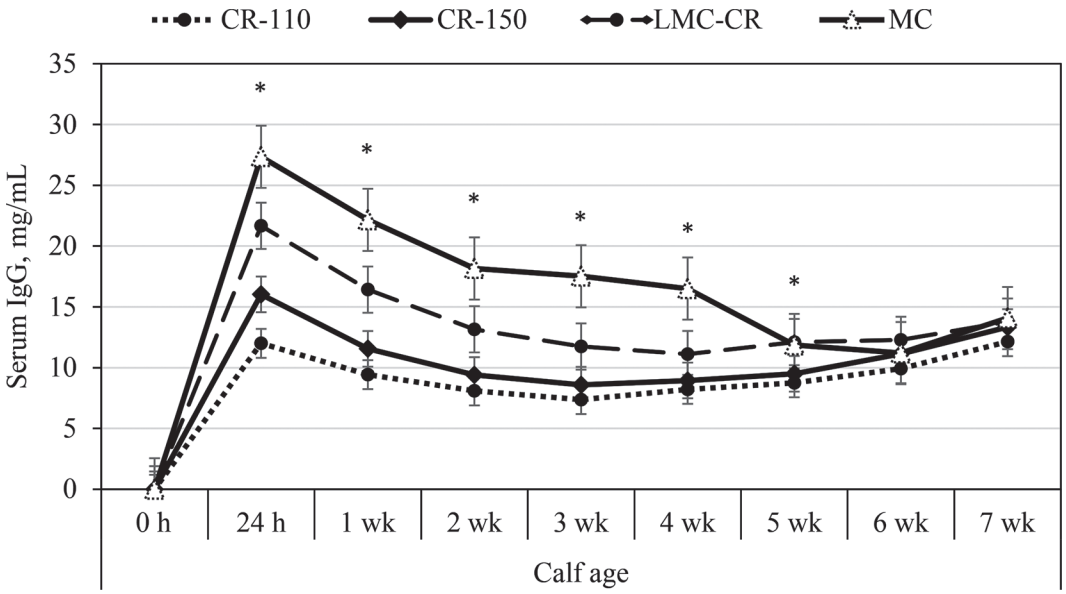

Figure 1. Serum IgG concentrations at different time points for calves fed maternal colostrum (MC), supplemented low-quality colostrum (LMC-CR), or colostrum replacer providing 150 g or 110 g of IgG (CR-150 and CR-110, respectively). SEM = 0.54. Time point ($P < 0.001$) and colostrum treatment ($P < 0.001$) effects were detected. *Indicates treatment differences within a time point.

Quigley et al. (2017). Calves were healthy overall, and calves fed the 4 colostrum sources had similar scour scores ($P = 0.82$).

CONCLUSIONS

Calves fed CR-150 attained serum IgG concentrations >10 mg/mL at 24 h, similar to calves fed 3.79 L of high-quality MC. Overall, AEA was high, specifically for calves fed the CR. A partial dose of CR supplemented with low-quality MC (LMC-CR) resulted in acceptable serum IgG concentrations, and none of the calves had FPT. This finding indicates that CR can be effectively fed with a low-quality MC to reduce FPT levels on farm. Calves fed CR had greater AEA than calves fed MC, but calves fed LMC-CR had a higher AEA than calves fed CR. None of the calves fed MC experienced FPT. Calves fed CR achieved mean serum IgG concentrations >10 mg/mL, but their mean STP levels were below the FPT cutoff point of 5.2 g/dL. Our data suggest that an STP cutoff point of 4.2 g/dL would be a better predictor of 10 mg/mL IgG in serum at 24 h. Consequently, cutoff points to determine FPT using STP by refractometry should be further investigated, or measuring direct IgG concentrations should be considered instead of indirect methods when calves are fed CR products. For calves fed CR, serum IgG levels at 24 h were a successful indicator for determining FPT, but STP at 24 h led to inadequate FPT estimates. These results indicate that this CR product is an effective alternative to MC or a supplement to LMC.

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