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Comparison of the effects of high and low milk-replacer feeding regimens on health and growth of crossbred dairy heifers

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Abstract

Context. Pre-weaning growth in dairy heifers is highly dependent on the amount of milk fed. Both milk replacer (MR) and associated labour are costly, encouraging restricted milk rations and once-a-day feeding.

Aims. This study compared performance relating to the growth and health of calves receiving one of two commercial feeding regimens: High or Low.

Methods. All heifers born during the Spring (January–March) calving block on a commercial UK farm with mixed-breed genetics were recruited at birth, randomly assigned to the High ($n = 104$, receiving MR-A) or Low ($n = 88$, receiving MR-B) feed group and reared indoors on straw bedding, with free access to concentrate. Both groups initially received MR twice daily. The High group continued to receive MR twice daily throughout the experiment, whereas the Low group calves were reduced to a single MR feed daily during Weeks 4–8. Blood samples were taken in Weeks 1 and 6 to assess passive transfer and measure circulating insulin-like growth factor 1 (IGF1). The Wisconsin calf-scoring system was used to assess health of calves in Weeks 1, 2, 4, 6 and 8 and at 6 months and size was also measured at these times. Data were analysed by univariate and multivariate models.

Key results. Passive transfer was good in both groups (serum total protein (mean ± s.d.) 60.9 ± 9.1 mg/mL) with no differences in pre-weaning disease incidence; diarrhoea occurred in 64.5% and bovine respiratory disease in 26.3% of calves. High group calves were significantly heavier, taller and longer at all pre-weaning examinations except recruitment owing to more growth in the first month, and remained significantly larger at 6 months: weight 157 ± 8 vs 149 ± 7 kg, height 103 ± 5 vs 100 ± 5 cm, length 90 ± 4 vs 88 ± 5 cm. Plasma IGF1 concentrations at around Week 6 were doubled in the High group (101 ± 38.6 vs 55 ± 34.1 ng/mL). Bovine respiratory disease was associated with reduced weight gain. Heifers with diarrhoea were leaner at weaning. High feed group, weight at recruitment and good passive transfer were positively associated with weight at 6 months.

Conclusions. Higher feeding levels pre-weaning increased growth rates and IGF1, although the disease incidence was unaffected.

Implications. Previous studies have shown that more growth and higher IGF1 pre-weaning are associated with a lower age at first calving and an increased chance of reaching the end of first lactation. These in turn improve long-term performance.

Additional keywords: colostrum, ponderal index, skeletal development.

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Introduction

Recent changes in the UK dairy industry have led to the expansion of New Zealand-style grazing-based management systems. These systems aim for lower inputs and outputs by using mixed-breed cows and maximising the use of forage in the diet. Calving down heifers at 23–26 months of age increases longevity and maximises economic returns (Bach 2011; Wathes *et al*. 2014; Boulton *et al*. 2017). The early rearing period is key to achieving this target, because suboptimal nutrition delays the onset of puberty and adversely affects skeletal growth, increasing the risk of dystocia at first calving (Ettema and Santos 2004). Poor growth is also a main reason for culling heifers before calving (Esslemont and Kossaibati 1997). Targets are therefore needed to maintain economically efficient growth so that breeding and first calving occur at the ideal weight and age (Brickell *et al*. 2009a). The recommended age at first calving for Holstein Friesian cows is 24 months, at ~85–90% of their mature bodyweight (Margerison and Downey 2005).

Management of dairy heifer calves in many countries (e.g. UK, Ireland, USA, Canada, Israel, Australia) conventionally involves separation from the dam on the first day of life and then feeding whole milk at a rate of 4–6 L/day, or 400–600 g milk replacer (MR)/day, until weaning at 42–56 days of age (reviewed by Morrison *et al*. 2009). This is much lower than *ad libitum* intake, which is ~12 L/day of whole milk (Jasper and Weary 2002; Curtis *et al*. 2018). Weaning at 8 weeks is recommended, owing to the risk of calves developing insulin resistance when they are maintained on a diet primarily of milk for more than two months (Bach *et al*. 2013; MacPherson *et al*. 2016), coupled with data demonstrating good calf performance when they are weaned at this age (Eckert *et al*. 2015). Total nutrient intake, source of energy, and protein content of the diet have additive effects on how calves partition nutrients into tissue (Van Amburgh and Drackley 2005). Calves benefit when MRs contain more protein and less fat, achieving higher levels of skeletal growth (Hill *et al*. 2010). Provision of greater quantities of MR therefore improves both growth and feed efficiency (Bartlett *et al*. 2006). Increased nutrient intake is also associated with increased plasma insulin-like growth factor 1 (IGF1) (Smith *et al*. 2002; Bartlett *et al*. 2006), which in part regulates the subsequent growth rate (Hammon *et al*. 2002; Brickell *et al*. 2009*a*). Factors such as age, environmental temperature, disease and other stressors all affect the maintenance requirement of the neonatal calf, meaning that calves fed restricted amounts of milk may be unable to meet their daily energy requirements (Khan *et al*. 2007; Nielson *et al*. 2008).

Development of the ruminal papillae is necessary during the pre-weaning period to enable absorption and utilisation of volatile fatty acids, and this is promoted by ingestion of dry feeds (Khan *et al*. 2011). Calves start to ingest solid food at ~14 days of age (Khan *et al*. 2008). Limiting the supply of milk during the pre-weaning period can increase concentrate intake; however, this still resulted in lower growth rates (Flower and Weary 2001). Conversely, increasing the amount of milk fed to calves resulted in higher weight gains (Jasper and Weary 2002). Despite evidence for improved performance and welfare of calves fed more milk, the typical practice in the UK remains to restrict the milk ration (Brickell *et al*. 2009*a*; Johnson *et al*. 2017*a*). Milk or MRs are more expensive than concentrate and forage, and feeding milk to calves is also labour-intensive (Boulton *et al*. 2015). Glucose and fatty acids are the main sources of energy in calves, and low blood glucose triggers the onset of hunger. Curd formation attained by skim-milk-based MRs may play an important role in controlling milk intake because of abomasal mechano-receptors (Quigley *et al*. 2006; Khan *et al*. 2011). Calves display behaviours consistent with hunger when fed restricted levels of milk or MR (Jensen 2003; De Paula Vieira *et al*. 2008; Nielsen *et al*. 2008; Herskin *et al*. 2010). When calves were given unrestricted access to milk via a teat feeder, they took most of their daily intake in two main meals, but averaged 10.8 ± 1.5 meals per day (Appleby *et al*. 2001). Another study showed increased vocalisations in response to hunger in calves fed milk twice a day compared with every 4 h (Thomas *et al*. 2001). Some studies have shown that once-daily milk feeding reduces the total labour input per calf without adversely affecting calf performance (Gleeson *et al*. 2008) or glucose metabolism (Stanley *et al*. 2002). Other evidence suggests that once-a-day feeding is a stressor compared with twice-a-day feeding, producing transient neutrophilia and suppressed functional capacities of neutrophils (Hulbert *et al*. 2011). However, calves fed 4 L of MR twice daily had decreased insulin sensitivity compared with those fed 3 L twice daily (Bach *et al*. 2013). This could be avoided with multiple smaller feeds, suggesting that higher rates of >6 L/day would require three or more feeds, necessitating either an increase in labour or spending on equipment such as computerised feeding systems. UK legislation does not allow once-daily milk feeding to begin before 4 weeks of age, by which time calves are considered able to obtain sufficient additional nutrients from solid feed (Van der Burgt and Hepple 2013).

Calves are highly susceptible to disease during the milk-feeding period, in particular diarrhoea and bovine respiratory disease (BRD) (Svensson *et al*. 2003, McGuirk 2008). Achieving higher colostral immunoglobulins in the calf serum improves both health and growth in the first few weeks of life (DeNise *et al*. 1989). Morbidity and intensity of disease is lower in calves with higher serum immunoglobulins, and these heifers achieve service bodyweight more quickly, allowing earlier breeding (Virtala *et al*. 1999; Furman-Fratczak *et al*. 2011). Nutritional deficiency can suppress immune function and increase susceptibility to disease (Nonnecke *et al*. 2003).

Low growth rates and behavioural signs of hunger have been used to indicate compromised animal welfare in calves fed at 10.0–12.5% of bodyweight (von Keyserlingk *et al*. 2004; Lorenz *et al*. 2011). The current economic climate therefore presents a challenge to dairy producers: to rear good-quality heifers with high welfare outcomes while minimising the input costs of the enterprise. As outlined above, the standard feeding practise in the UK is to feed calves twice daily, typically providing them with up to 750 g/day of milk powder. For farms targeting high growth rates, calves are fed more milk powder (≥900 g/day) in the form of MR with a higher protein content (26%) and lower fat content (16%) to promote lean-tissue growth and limit body fat. A typical cost-effective system, targeting lower growth rates, would provide calves with less milk powder (600 g/day) and a change from twice-a-day to once-a-day feeding through to weaning once they are eating a sufficient amount of solid feed (usually ~4 weeks of age). Such systems typically use a lower protein MR (20% crude protein).

The present study was performed on a commercial dairy farm in the South West of England that uses mixed-breed genetics in a grazing-based system. The objectives were to compare weight and skeletal growth rates and calf health parameters between two commercially available but contrasting MR feeding systems, which were based on either high input (High group, fed MR-A twice daily) or low input (Low group, fed MR-B initially twice daily then once daily from 4 weeks).

Materials and methods

Heifer management

Animals were from a single commercial UK dairy farm with a herd size of 574 cows, operating a grass-based low-input–low-output system. The predominant breed was New Zealand-type Friesian, with some Friesian crossed with Jersey, Montbéliarde or Hereford. All heifers born during Spring-block calving between 27 January and 31 March 2013 were recruited ($n = 192$). All heifers were born outdoors. Pastures were inspected at least once every 3 h and dams requiring calving assistance were noted. Newborn calf navels were treated with 10% iodine solution. Newborn calves were separated from their dams once per day and taken to the calf barn. The barn had been arranged previously into four rows of 10 pens divided by hurdles, with five calves allocated per pen. Pens were assigned to one of two treatment groups (Low and High) in blocks throughout the barn and marked with coloured tape. In this way, the farm staff could identify the correct feeding regimen per pen, whereas the veterinarians collecting data remained blind to the treatment. The pen arrangement accounted for potential environmental factors within the barn itself, such as proximity to other cattle, wind, temperature differences and ventilation. After 4 weeks, two adjacent pens of the same colour were opened up to create pens of 10 calves, and the calves were disbudded at this time.

Each calf was eartagged on arrival at the barn on day 1, assigned randomly to treatment group by a coin toss (regardless of breed) and placed in an appropriate pen. All calves were given 2 L of pooled first-milking colostrum when first observed in the paddock, after the next milking, and on arrival in the barn, ensuring three colostrum feeds within the first 24 h. The subsequent feeding schedule was managed by use of a white board in the barn showing each pen number with the age of the calves (in weeks). As soon as a calf was placed in a pen, it was fed according to the instructions for Week 1 (see Table 1). The pen moved to the feeding treatment for Week 2 on the Friday at least 1 week after it contained five calves. Calves were therefore fed colostrum for the first 24 h, then whole milk from the dairy for 1–14 days (mean 7.2 days). Thereafter, each Friday all pens were moved up one week on the white board and fed at the required level of MR for that week.

Calves were fed MR for 8 weeks via Wydale teat feeders (Wydale Plastics, Crewkerne, UK) following the protocol detailed in Table 1. These feeders allow group feeding of calves while maintaining an individual approach, with each calf drinking a fixed volume of MR from a teated compartment. The morning and afternoon feeds were at 0600 and 1600 hours. MR was fed at a temperature ranging from 35°C to 40°C in both groups. Both MRs were fed according to the instructions on the bag. In brief, the High group had the same feeding schedule for 6 weeks with 900 g/day of MR-A fed twice daily throughout. This product contained 26% crude protein, 16% crude oils and fats, nil crude fibre and 7% crude ash and was composed of whey protein, vegetable oil (palm and coconut), hydrolysed wheat gluten, calcium carbonate, magnesium oxide, and Gardion® (Spectra Animal Health, Marietta, GA, USA) together with vitamin and trace elements. The Low group were fed 600 g/day of MR-B twice daily for 3 weeks and then once daily for 3 weeks. This product contained 20% crude protein, 15% crude fat, 0.02% crude fibres, 7.5% ash and was composed of skim milk powder, whey powder, palm oil, buttermilk, coco oil, wheat gluten, colza oil, soja oil and inactive yeast extract together with vitamin and trace elements. Starting in Week 8, both groups were weaned over 2 weeks with the amount of MR fed reduced by one-third each week. All heifers were also provided with *ad libitum* 18% protein, molassed coarse calf mix (containing micronised barley, peas, beans, maize and crushed oats) and water throughout the MR-feeding period. The amount of solid feed consumed per pen was recorded by counting the bags of feed used on an individual-pen basis. Calves were bedded on wheat straw on a deep litter system, which was topped up daily; *ad libitum* straw was also available in feeders.

Data collection

Two blood samples were collected from each calf according to the UK Animals (Scientific Procedures) Act 1986, under a project licence that was approved by the Royal Veterinary College's ethical review process. A serum sample in Week 1 was used to assess passive transfer by measuring serum total proteins with a hand-held refractometer (RHC-200; Huake Instrument Co. Ltd, Shenzhen, China) (Elsohaby *et al*. 2017).

Table 1. Feeding schedule for the two milk-replacer (MR) treatment groups

All feeding rates are expressed as volume of feed (L) and type of milk: whole milk (WM); milk replacer MR-A or MR-B, followed by mixing rate with water (% dry matter). All calves received 6 L colostrum in the first 24 h. ME. Metabolisable energy calculated from milk-powder constituents and NRC data (NRC 2001)

Week	High group				Low group			
	Morning	Afternoon	MR/day (g)	ME from MR (MJ/day)	Morning	Afternoon	MR/day (g)	ME from MR (MJ/day)
1	3 L WM	3 L WM			2 L WM	2 L WM		
2	3 L MR-A 15%	3 L MR-A 15%	900	17.2	2 L MR-B 20%	1 L MR-B 20%	600	10.8
3	3 L MR-A 15%	3 L MR-A 15%	900	17.2	2 L MR-B 20%	1 L MR-B 20%	600	10.8
4	3 L MR-A 15%	3 L MR-A 15%	900	17.2	2 L MR-B 20%	1 L MR-B 20%	600	10.8
5	3 L MR-A 15%	3 L MR-A 15%	900	17.2	3 L MR-B 20%	None	600	10.8
6	3 L MR-A 15%	3 L MR-A 15%	900	17.2	3 L MR-B 20%	None	600	10.8
7	3 L MR-A 15%	3 L MR-A 15%	900	17.2	3 L MR-B 20%	None	600	10.8
8	3 L MR-A 15%	1 L MR-A 15%	600	11.5	2 L MR-B 20%	None	400	7.2
9	2 L MR-A 15%	None	300	5.7	1 L MR-B 20%	None	200	3.6
10	None	None	0	0	None	None	0	0
Total MR fed (kg)			44.1				29.4	

Failure of passive transfer was defined as having a total protein reading <55 mg/mL (Buczinski *et al*. 2018). A heparinised plasma sample was taken between Weeks 5 and 7 and stored frozen at –20°C for subsequent IGF1 assay with a commercial ELISA kit (IDS, Bolden, UK) (Brickell *et al*. 2009a). All enrolled heifers also had five clinical examinations before weaning, in the first, second, fourth, sixth and eighth weeks of life. All visits were performed on the same day of each week, so intervals between sampling were consistent for all calves. Calves were assessed for diarrhoea and BRD by means of the Wisconsin calf scoring system (McGuirk 2008), with minor modification for the UK (Johnson *et al*. 2017*b*). For BRD, both ocular and nasal discharges and presence of induced or spontaneous cough were recorded on scales of 0–3, and temperature cut-offs were taken at 38.5°C, 39.0°C and 39.5°C. For diarrhoea, faecal consistency was scored as 0–3 (normal, pasty, loose and watery). The navel was also checked each time. A single follow-up check was performed in September 2013 when calves were 5–7 months old. At each pre-weaning examination and the follow-up examination, calf height at the withers, girth behind the forelimb and diagonal trunk length (measuring from the dorsal point of the scapula spine on one side to the tuber ischii on the opposite side) were measured.

Calves with clinical signs were recorded in the diary, and farm staff then treated them according to protocols developed with their veterinary surgeon. Calves with signs of respiratory disease were given florfenicol and flunixin meglumine (Resflor; MSD Animal Health, Walton, UK), and calves with signs of diarrhoea were treated with electrolytes given in addition to their milk ration.

Growth rates and size parameters

For pre-weaning calves, girth was used to calculate weight. This was based on a previous study in which dairy heifers of varying breeds between birth and 9 weeks old were weighed and measured on the same occasion (Johnson *et al*. 2017*a*). The relationship between girth and weight was as follows: weight (kg) = girth (cm) × 1.96 – 113 ($r^2 = 0.89$, $P < 0.001$). To confirm this relationship, weight was calculated from girth by using this linear association, and then a Bland–Altman plot was used to check for agreement. This showed that the mean value of the difference between the calculated and actual weight was 0.06 kg (95% confidence interval –10.3 to +10.4 kg). Calibrated weighing scales were used at 6 months. Growth rates were calculated for height, length and weight for each calf individually, based on their actual age in days at each examination, to give average daily weight gains (ADG, kg/day) and skeletal growth rates (cm/day). To account for the difference in age at the final check, each heifer's individual post-weaning ADG was used to calculate an estimated weight at 182 days (6 months) via regression analysis. The ponderal index (PI) was used to compare leanness across the different sizes and breeds, calculated using the formula PI (kg/m^3) = weight (kg)/(height (m) + length (m))^3 (Swali and Wathes 2007).

Statistical analyses

Diarrhoea and BRD disease scores were both analysed through two approaches. First, a binary system was used to classify whether calves did or did not have the disease. Second, all weekly scores were summed over the pre-weaning period to give a single total score over the threshold for diagnosis for each calf. For BRD, calf temperature, cough, and ocular or nasal discharges were all scored on a scale of 0–3, with weekly scores ≥5 classed as respiratory disease. In any week where the score was ≤4, it was counted as zero towards the total score. If the score was ≥5, then the actual score minus 4 was added to the total for that calf (e.g. actual score of 6 – 4 = 2). This method could not distinguish between symptom severity and disease duration but was used to avoid overlap between calves with no diagnosed disease (all individual weekly scores below the threshold) and those with alternating low and higher scores in weeks when they were categorised as healthy or diseased. In the same way, diarrhoea over the threshold score (i.e. scores >1) were totalled to give an overall score over the diagnosis threshold for the period.

All statistics were completed in R (https://www.r-project.org/about.html) and graphics used the 'lattice' package (Sarker 2017). Descriptive statistics comparing the two treatment groups were calculated to look for initial differences between groups, with *t*-tests used to compare group means and chi-squared tests to compare count data between groups. All candidate variables were initially tested in univariate analysis for subsequent inclusion in multivariate models, using regression analysis for continuous variables and ANOVA for categorical data (see Table S1, available as Supplementary Material to this paper). Candidate variables were included if $P < 0.2$ in the univariate analysis. The variables were also tested for collinearity. In several cases there was high correlation between variables, particularly different parameters for size and growth rate. In these cases, the variable that most improved the model was included by using the Akaike information criterion (Maindonald 2009) and likelihood-ratio tests. A backwards-stepwise approach was then used to exclude any variable that did not improve the fit of the model. For the pre-weaning data, repeated-measures mixed-effects models were fitted with calf as a random factor. To control for differing sizes at recruitment, all of the measurements once a calf was on the feeding-group treatment were used as outcomes, but the initial size at recruitment was included as a potential explanatory variable. The exact age (in days) at recruitment was also tested as a candidate variable for inclusion in the model and checked for interactions with size at recruitment. Other interactions were tested for and included if they both improved the fit of the model significantly and were biologically plausible (e.g. between age and treatment group and age and disease).

Results

Animals and feed

Of the 192 dairy heifers recruited over a 9-week calving block, 100 were New Zealand Friesian type and the remainder were Friesian crossbred (80 crossed with Jersey, 11 with Montbéliarde and one with Hereford). There were no significant differences of any time-point or variable between the pure Friesian and the Montbéliarde or Hereford crossbred calves, so these were combined into a single Friesian-type group and compared with the Jersey crossbred group in the multivariable analyses.

Table 2. Summary data of passive transfer, recruitment weight and disease scoring in pre-weaning dairy heifer calves fed High or Low milk-replacement regimens

BRD, bovine respiratory disease; CI, confidence interval. Clinical assessments were based on weekly checks using the Wisconsin scoring system. **, $P < 0.01$

Variable	All calves (n = 192)		High group (n = 104)		Low group (n = 88)		P-value
	Mean	95% CI	Mean	95% CI	Mean	95% CI	
Serum total protein (mg/mL)	60.9	42.3 to 79.6	61.3	42.0 to 80.7	60.4	42.6 to 78.1	0.49
Recruitment weight (kg)	37.7	29.1 to 46.3	38.2	22.5 to 54.0	36.7	17.4 to 56.5	0.45
Total BRD score	7.8	0.6 to 15.0	7.6	0 to 15.6	8.1	1.5 to 14.6	0.37
BRD incidence (%)	26.3	20.2 to 33.2	25.2	17.4 to 34.9	27.7	18.5 to 38.4	0.83
Total faecal score	3.0	0 to 6.1	2.8	0 to 5.8	3.4	0.3 to 6.4	0.01**
Diarrhoea incidence (%)	64.5	57.4 to 71.4	61.2	51 to 70.4	68.7	57.9 to 78.4	0.3

The total amount of MR fed per calf was 29.4 kg in the Low group and 44.1 kg in the High group (Table 1). The amount of solid feed mix consumed during the trial was not significantly different, with the High group consuming 0.57 kg/calf.day and the Low group 0.56 kg/calf.day. Based on costs at the time of the trial of £1700/t for MR-A and £1600/t for MR-B, the costs of total MR fed per calf were £74.97 and £47.04. This equates to a difference of £2793 per 100 calves.

Health

Summary data on health status are given in Table 2. Passive transfer was good in both groups with mean serum total protein values of 61.3 (High) and 60.4 (Low) mg/mL in the first week of life. Failure of passive transfer occurred in 21% (n = 39) of the calves, defined as having a total protein reading <55 mg/mL; of these, only 7.5% (n = 14) had a total protein reading <50 mg/mL. Pre-weaning disease was nevertheless common, with 64.5% of heifers affected by diarrhoea and 26.3% with BRD. Calves in the Low group had a higher total faecal score (3.4 vs 2.8, $P < 0.01$) but they did not show a significant difference in the proportion diagnosed with diarrhoea. There was also no significant difference in either the total BRD score or the incidence of BRD between groups. Eleven calves died between birth and 8 weeks (11/192 = 5.7% mortality rate; 7 High, 4 Low), with two more dying between 8 weeks and 6 months (2/181 = 1.1% mortality rate; both Low). Cause of death was not investigated.

Univariate analysis of size and growth

The mean recruitment weight was 37.7 ± 8.6 kg (mean ± s.d.) with no significant difference between treatment groups (Table 2). However, at all subsequent pre-weaning examinations, calves in the High group were significantly heavier, taller and longer (Fig. 1). This was because calves in the High group had higher weight and skeletal growth in the first month of life (Fig. 2). Growth rates in terms of weight and height were similar in both groups during Weeks 4–8; however, the High group continued to have increased ($P < 0.01$) length growth compared with the Low group (0.24 ± 0.14 vs 0.17 ± 0.14 cm/day). Over the whole pre-weaning period, both groups had moderate ADG (High 0.58 ± 0.15 kg/day, 5th–95th percentiles 0.32–0.82 kg/day; Low 0.5 ± 0.15 kg/day, 5th–95th percentiles 0.24–0.68, $P < 0.01$). Calves in the High group gained 28.3 ± 8.1 kg, compared with 24.3 ± 8.1 kg in the

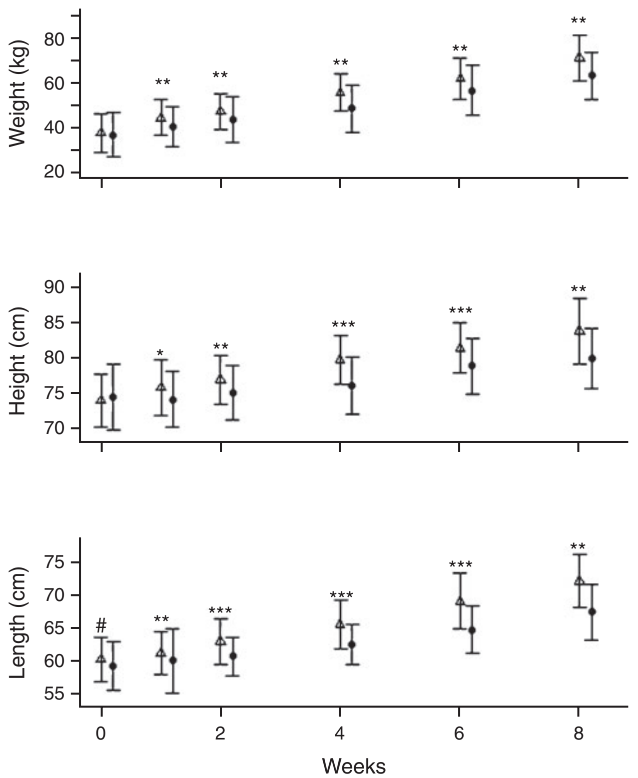

Fig. 1. Heifer (a) weight, (b) height and (c) trunk length measured at clinical examinations during 0, 1, 2, 4, 6 and 8 weeks of age. Δ, High feed group, n = 104; •, Low feed group, n = 88 (offset by 0.2 weeks to avoid symbols overlapping, with error bars showing 95% confidence intervals). Differences in group means were tested by using t-tests: #, $P < 0.1$; *, $P < 0.5$; **, $P < 0.01$; ***, $P < 0.001$. Weights were estimated from girth measurements using the formula: weight (kg) = girth (cm) × 1.96 – 113.

Low group (P = 0.002). Length increased by 11.4 ± 4.6 cm (High) vs 8.23 ± 4.2 cm (Low) ($P < 0.001$) and height by 8.3 ± 3.7 cm (High) vs 5.7 ± 3.2 cm (Low) ($P < 0.001$). There were also differences in PI at weaning, with the High group significantly leaner than the Low group (Fig. 3), following their higher skeletal growth rates.

Between weaning and 6 months of age, calves in the Low group showed some catch-up skeletal growth (Low vs High: 0.17 ± 0.04 vs 0.14 ± 0.04 cm/day for height and 0.16 ± 0.04 vs 0.14

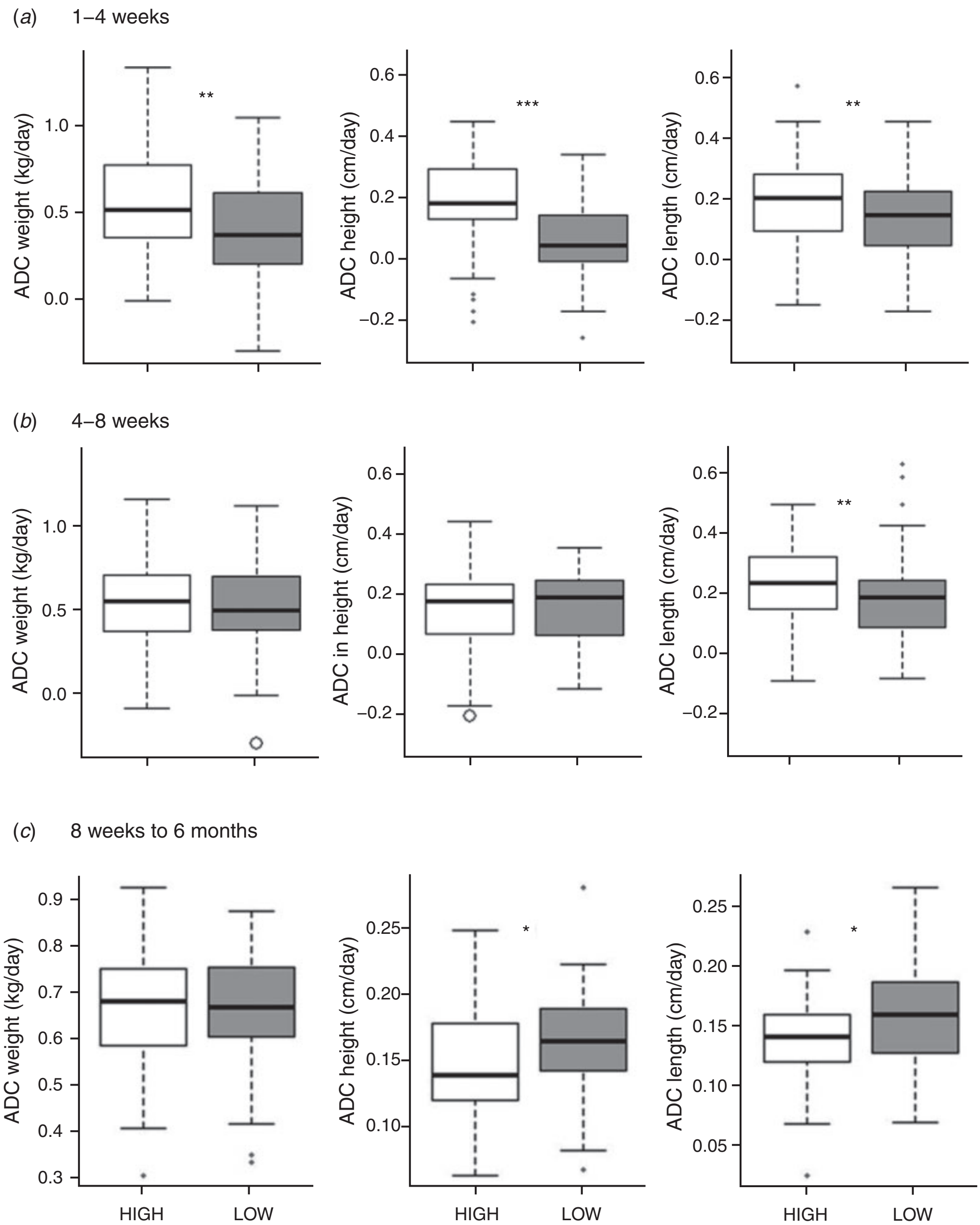

Fig. 2. Growth rates of withers height, trunk length and weight in dairy heifer calves. These are split into age intervals of: (*a*) 1–4 weeks, (*b*) 4–8 weeks, and (*c*) 8 weeks–6 months. ADC, Average daily change; *t*-tests were used to test for differences between group means: *, $P < 0.5$; **, $P < 0.01$; ***, $P < 0.001$. High feed group, $n = 104$; Low feed group, $n = 88$. The boxplots represent the minimum, maximum, median, first quartile, third quartile and outliers in the data set.

$\pm$ 0.04 cm/day for length; $P < 0.05$) (Fig. 2). However, there was, no significant difference in ADG, with both groups growing at 0.67 kg/day. The High calves remained significantly larger at 6 months of age in all three measurements: weight 157 $\pm$ 18 vs 149 $\pm$ 17 kg ($P < 0.01$), height 103 $\pm$ 5 vs 100 $\pm$ 5 cm ($P < 0.05$) and length 90 $\pm$ 4 vs 88 $\pm$ 5 cm ($P < 0.05$). With the relative differences in post-weaning growth, the differences in PI seen at weaning were no longer present at 6 months (Fig. 3).

Multivariate analysis

The candidate variables tested for inclusion are described in Table S1. These included age, calving week, breed, passive transfer, dam dystocia, calf size and age at recruitment, and disease (yes/no and total scores for BRD and diarrhoea). Weight, height and length measurements were all normally distributed continuous variables, and for these, repeated-measures linear mixed-effects models were fitted with calf as a random factor.

The initial size in Week 1 was included as an explanatory variable to control for the size at recruitment. Age at recruitment was included as a candidate variable but it did not significantly improve the fit of the models. Pre-weaning size measurements were associated with several variables (Table 3). Calves on the Low feeding regimen were 3.7 ± 1.1 kg lighter with a trunk length 2.7 ± 0.95 cm shorter by Week 8 (pre-weaning). For height, there was a significant treatment × age interaction, so Low

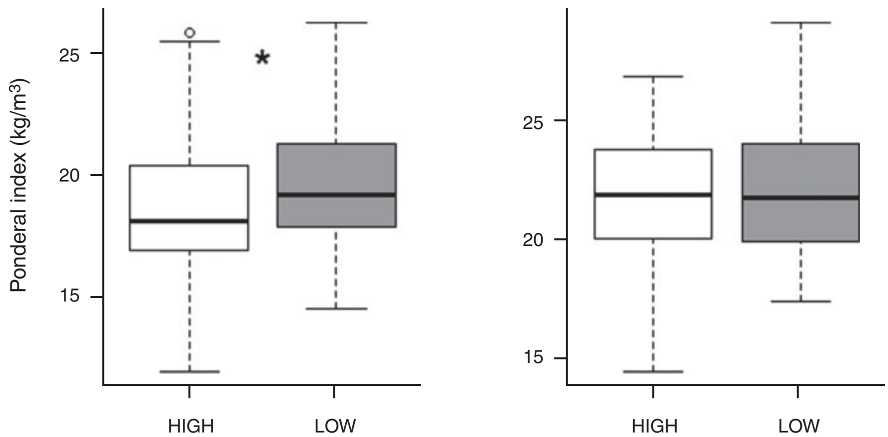

Fig. 3. Ponderal index in dairy heifer calves measured at (*a*) 8 weeks and (b) 6 months of age. Ponderal index was defined as weight (kg) over sum of withers height and trunk length (m) cubed. *$P < 0.05$. High feed group $n = 104$; Low feed group, $n = 88$. The boxplots represent the minimum, maximum, median, first quartile, third quartile and outliers in the data set.

Table 3. Variables associated with weight (kg), length (cm) and height (cm) in pre-weaning calves in linear mixed-effects models with measurements nested within calf

CI, confidence interval; (ref), reference group. Bovine respiratory disease (BRD) severity score was calculated by including every score over the threshold for disease treatment based on weekly scoring on the Wisconsin scoring system. †, $P < 0.1$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$

Variable	Estimate	95% CI	*P*-value	
Repeated-measures linear mixed-effects model for weight pre-weaning				
(Intercept)	8.78	1.81 to 15.75	0.014	*
Feeding group, High	(ref)			
Feeding group, Low	–3.75	–4.87 to –2.64	<0.001	***
Age (days)	0.52	0.49 to 0.56	<0.001	***
Weight at recruitment (kg)	0.69	0.6 to 0.78	<0.001	***
Calving week	–0.35	–0.64 to –0.06	0.019	*
Breed, Friesian type	(ref)			
Breed, Jersey cross	–2.47	–3.9 to –1.05	<0.001	***
Total BRD score	–0.45	–0.86 to –0.04	0.032	*
Repeated-measures mixed-effects model for length pre-weaning				
(Intercept)	33.99	28.35 to 39.64	<0.001	***
Feeding group, High	(ref)			
Feeding group, Low	–2.73	–3.29 to –2.16	<0.001	***
Age (days)	0.2	0.19 to 0.21	<0.001	***
Length at recruitment (cm)	0.47	0.38 to 0.56	<0.001	***
Breed, Friesian type	(ref)			
Breed, Jersey cross	–1.12	–1.78 to –0.45	0.001	**
Calving week	–0.35	–0.48 to –0.22	<0.001	***
Repeated-measures mixed-effects model for height pre-weaning				
(Intercept)	30.96	24.3 to 37.62	<0.001	***
Feeding group, High	(ref)			
Feeding group, Low	–1.28	–2.21 to –0.34	0.008	**
Age (days)	0.16	0.15 to 0.18	<0.001	***
Serum total protein (mg/mL)	0.03	0 to 0.06	0.0995	†
Breed, Friesian type	(ref)			
Breed, Jersey cross	–1.46	–2.12 to –0.8	<0.001	***
Height at recruitment (cm)	0.57	0.49 to 0.65	<0.001	***
Treatment (Low) × age (days) interaction	–0.03	–0.05 to –0.01	0.013	*

group calves were predicted to be 1.7 ± 0.78 cm shorter at 14 days and 3.0 ± 0.95 cm shorter at 56 days. Size at recruitment was also significant, with larger animals remaining larger for both weight and skeletal measurements. There was a significant breed effect, with Jersey-cross animals smaller in all measures than Friesian-type heifers. Calving week had a significant impact on both length and weight, with heifers born later in the calving block being smaller. This occurred despite controlling for size at recruitment, suggesting that these later born animals grew less well during the pre-weaning period. BRD score was associated with reduced weight gain pre-weaning but not with the skeletal measures of height or length. Serum total protein remained in the model for height, although it failed to achieve significance ($P = 0.099$).

Factors affecting PI were tested at 8 weeks (pre-weaning) and at 6 months. At 8 weeks there was a trend ($P = 0.07$) for increased serum total protein at recruitment to be associated with increased PI, with an estimated increase of 1.01 kg/m^3 from the 10th to 90th percentile of passive transfer (Table 4). The other factors identified were all associated with a decrease in PI, to give a leaner animal. The High treatment was associated with a decrease of 0.89 kg/m^3 in PI. Diarrhoea had the largest effect size found, with a reduction of 1.3 kg/m^3 compared with healthy calves. Height at recruitment was also influential, with taller born calves remaining leaner. At 6 months no recorded variables were associated with PI, so no model could be fitted.

A general linear model was also fitted to explain the estimated weight at 6 months of age (Table 5). Weight at recruitment and good passive transfer were both positively associated with weight at 6 months, whereas it was reduced in heifers in the Low feed group, in Jersey crossbred heifers compared with Friesian types, and in those with a more severe BRD score pre-weaning (Table 5).

Table 4. Variables associated with ponderal index (weight in kg/(height + length in m)^3) in calves at 8 weeks of age

CI, confidence interval; (ref), reference group. †, $P < 0.1$; *, $P < 0.05$; **, $P < 0.01$

Variable	Estimate	95% CI	*P*-value	
Feeding group, Low	(ref)			
Feeding group, High	–0.888	–1.693 to –0.082	0.031	*
Serum total protein (mg/mL)	0.042	–0.004 to 0.087	0.070	†
Diarrhoea: none				
Diarrhoea: yes	–1.331	–2.172 to –0.489	0.002	**
Height at recruitment (cm)	–0.150	–0.251 to –0.049	0.004	**

Table 5. Variables associated with adjusted calf weight at 182 days (6 months)

CI, confidence interval; (ref), reference group. Bovine respiratory disease (BRD) severity score was calculated by including every score over the threshold for disease treatment based on weekly scoring on the Wisconsin scoring system. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$

Variable	Estimate	95% CI	*P*-value	
(Intercept)	105.62	80 to 135.51	<0.001	***
Feeding group, High	(ref)			
Feeding group, Low	–5.75	–10.93 to –0.57	0.03	*
Breed, Friesian type	(ref)			
Breed, Jersey cross	–8.71	–14.92 to –2.5	0.006	**
BRD score	–2.16	–4.35 to 0.02	0.053	
Weight at recruitment (kg)	0.81	0.4 to 1.21	<0.001	***
Serum total protein (mg/mL)	0.32	0.03 to 0.62	0.033	*

Plasma IGF1

There were large differences in IGF1 between the two feeding groups at 5–7 weeks of age (High vs Low (mean ± s.d.): 101 ± 38.6 vs 55 ± 34.1 ng/mL, $P < 0.001$). This time-point was chosen after calves in the Low group had moved to once-a-day MR feeding but before either group began weaning. In multivariate analysis, feeding group was estimated to have a large effect size and was associated with an increase of 42.2 ng/mL in IGF1 in the High group (Table 6). Passive transfer also had a large effect size with an estimated increase of 22.6 ng/mL in IGF1 from the 10th to 90th percentile of serum total protein. Finally, growth rate in weight in the period preceding the sampling was correlated with increased IGF1. A higher diarrhoea score was associated with lower IGF1. BRD score remained in the model but was not significant.

Discussion

This study was designed to replicate a real choice for farmers in calf-feeding strategy on a commercial mixed-breed dairy farm. We compared two commercial brands of MR, one of which was based on skim milk powder fed once a day, the other utilising whey-based milk powder with twice-a-day feeding. The Welfare of Farmed Animals (England) Regulations (2007) state that 'Animals must be fed a wholesome diet which is appropriate to their age and species and which is fed to them in sufficient quantity to maintain them in good health, to satisfy their nutritional needs and to promote a positive state of well-being'. To comply with UK legislation, the once-a-day regimen was not implemented until the calves reached 4 weeks of age, by which time they are considered able to obtain sufficient additional nutrients from solid feed (Khan *et al*. 2008; Van der Burgt and Hepple 2013). The mixing rates and amounts fed followed each of the manufacturer's recommendations, as written on the bags. This resulted in calves in the High group receiving 14.7 kg more MR over the

Table 6. Variables associated with circulating IGF1 in pre-weaning calves measured at 5–7 weeks of age

CI, confidence interval; (ref), reference group. Bovine respiratory disease (BRD) and diarrhoea severity scores were calculated by including every score over the threshold for disease treatment based on weekly scoring on the Wisconsin scoring system. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$

Variable	Estimate	95% CI	*P*-value	
(Intercept)	44.82	9.66 to 79.99	0.013	*
Feeding group, Low	(ref)			
Feeding group, High	–42.19	–52.4 to –31.98	<0.001	***
Serum total protein (mg/mL)	0.74	0.19 to 1.29	0.009	**
Total BRD score	–2.7	–7.17 to 1.77	0.2353	
Total diarrhoea score	–6.04	–12.07 to –0.02	0.0494	*
Average daily growth Weeks 1–4 (kg/day)	32.15	14.52 to 49.77	<0.001	***

8-week feeding period, meaning an additional cost of MR alone of £27.93 per calf, a value that excludes the reductions in labour associated with providing one vs two daily milk feeds over a 4-week period. Despite the growth improvements found here in both pre- and post-weaning performance, most UK farmers feed lower rates than the High group in this trial (Brickell *et al*. 2009*a*; Boulton *et al*. 2015; Johnson *et al*. 2017*a*). The weight increases in this study for the pre-weaning calves were estimated from measurements of girth, which, as we have shown previously, provide a reliable method and have the advantage for the calf of not requiring the stressful procedure of repeated removal from the pen (Johnson *et al*. 2017*a*).

Pre-weaning growth rates were, not unexpectedly, increased by higher rates of MR feeding. This was most noticeable with respect to skeletal growth, which resulted in calves in the High group being physically larger and having a lower PI, indicating that they were also leaner. Calves are known to have high feed-conversion efficiency and lean growth in early life, and this result agrees with these earlier studies (Diaz *et al*. 2001; Jasper and Weary 2002; Quigley *et al*. 2006; Khan *et al*. 2007; Morrison *et al*. 2009). However, both groups achieved relatively modest ADGs of 0.58 kg (High group) and 0.50 kg (Low group). The study was based on mixed-breed Friesian-type calves and took place during a period of particularly cold Spring weather, with a UK average temperature over the trial period of 2.2°C (Met Office 2014). Calves were housed on deep straw, in small groups, in an unheated barn with spaced boarding; therefore, interior temperatures would have been significantly lower than thermoneutral conditions (NRC 2001). When the environmental temperature drops below 15°C, which is the lower critical temperature for young calves, the calf must expend energy to maintain its body temperature, thereby increasing the maintenance energy requirement (NRC 2001). If energy was limiting, the calves might also have been unable to utilise all of the protein offered in the diet (NRC 2001; Van Amburgh and Drackley 2005).

There were significant differences in growth rates in the first month of life between treatment groups, when calves are unable to eat and digest adequate amounts of solid feed to contribute to weight gain (Lorenz *et al*. 2011; van der Burgt and Hepple 2013). Although all calves were fed twice daily over this period, the High feed contained more nutrients. In the second month, only growth rates of length differed significantly, suggesting that solid feed was able to bridge the gap in MR feeding rates despite the Low group having by then been put onto the once-a-day feeding regimen. An inverse relationship has been shown between milk and solid-feed intake (Raeth-Knight *et al*. 2009). However, in this study, the amount of solid-feed mix consumed during the trial was not significantly different between the two groups, although this was recorded only per-pen rather than on an individual-calf basis. In healthy animals, catch-up growth is expected after a period of feed restriction (Hornick *et al*. 2000). In this study, the Low group showed a small increase in skeletal but not weight increases post-weaning, even though the diet fed at this stage was the same. Calves in the High group were 9.7 kg heavier at 6 months, underlining the importance of early feeding for heifer performance. For heifers to reach breeding weight for first insemination at 13–14 months, they need to gain weight at an adequate rate of ~0.7–0.8 kg/day in early life. Later breeding and delayed age at first calving are associated with increased rearing costs (Boulton *et al*. 2017) and with reduced fertility and reduced lifetime yields (Wathes *et al*. 2014). This is a particular problem with seasonal-calving herds such as the one in this study.

Colostrum management was good on this farm, with all calves receiving three feeds of 2 L each within the first 24 h. Definitions of adequate passive transfer based on total protein vary between studies, but generally, cut-off values of either 52 or 55 mg/mL have been used (reviewed by Buczinski *et al*. 2018). Use of a value >55 mg/mL resulted in 79% of calves classified as adequate, with only 7% falling below 50 mg/mL. Although absorption of IgG almost ceases after the first 12 h (Patel *et al*. 2014), high IgA content in colostrum is thought to act locally to promote gut health (Korhonen *et al*. 2000). Higher levels of passive transfer were associated with increased PI at 8 weeks ($P = 0.07$) and with a significant increase in the model for estimated weight at 6 months, reinforcing the benefit of receiving a good supply of colostrum.

Nevertheless, overall disease incidences were quite high, with 64.5% of heifers affected by diarrhoea and 26.3% with BRD. This diarrhoea incidence was similar to the 64% reported on farms deliberately recruited with a known diarrhoea problem attributed to *Cryptosporidium parvum* (Trotz-Williams *et al*. 2007) but higher than that reported in most other cohorts on commercial farms in other countries (USA, Canada, Holland, Sweden), which ranged from 10% to 35% (Johnson *et al*. 2011). The diagnostic criteria used were similar to those used in several previous studies. In a study of 11 UK farms, an overall diarrhoea incidence of 48.2% was recorded, ranging from 24.1% to 74.4% between farms (Johnson *et al*. 2017*b*). This suggests that the UK incidence may be higher than elsewhere, although the reasons for this are uncertain. BRD was in the same range as reported for other cohorts, with incidences of 1–39% (Johnson *et al*. 2011). There were no significant differences in disease incidence between the two groups. There have been concerns that increased milk feeding may be associated with faeces that are more liquid (Diaz *et al*. 2001; Quigley *et al*. 2006), but the present results contribute to the consensus view that this is not the case (Jasper and Weary 2002; Khan *et al*. 2007, 2011). Providing the calf with enough milk will also minimise cross-sucking, which can be an issue for group housing when calves are hungry. Although the present trial was not designed to assess this aspect, navels were checked weekly, and no evidence of cross-sucking was found. This is in accordance with a previous study over 14 weeks, in which cross-sucking was observed only five times (of a total of 651 scans) in four different pairs of calves (Whalin *et al*. 2018). Despite the lack of feed-group differences, disease was significant in the multivariable models for growth. BRD was associated with reduced weight gain, but not height or length increases, in the pre-weaning period and also with estimated weight at 6 months. Diarrhoea had the largest effect size with respect to PI, with a reduction of 1.3 kg/m^3 in sick compared with healthy calves.

Insulin-like growth factor 1 is a metabolic hormone whose circulating concentration mainly reflects production in the liver in response to stimulation of growth hormone (Grochowska *et al*. 2001). It also has a variable half-life, based on the circulating levels of six different IGF-binding proteins, whose expression is also affected by disease and energy balance (Fenwick *et al*. 2008; Wathes 2012). The circulating concentration of IGF1 in calf blood is relatively stable throughout the day, making it a more reliable marker of metabolic state than other commonly used measures such as β-hydroxybutyrate or non-esterified fatty acids (Swali *et al*. 2008). In previous studies on dairy heifers, IGF1 at 1 month was inversely correlated with the risk of future mortality (Brickell *et al*. 2009b) and chance of completing first lactation (Swali *et al*. 2008; Wathes *et al*. 2014). The very large differences in IGF1 found between the feeding groups (almost 2-fold) therefore suggest that the MR feeding rate in young calves may influence long-term survival. The differences in IGF1 between feeding groups were twice as large as those associated with the range of passive transfer measured and had approximately eight times the effect of a single week of diarrhoea or respiratory disease. This is supported by the study of Bartlett *et al*. (2006), which reported progressively increasing IGF1 levels by 5 weeks of age in bull calves fed at 14% vs 10% bodyweight, and with MRs containing 14–26% crude protein.

Pre-weaning performance in dairy heifers has generally been associated with performance in first lactation (Khan *et al*. 2011; Soberon *et al*. 2012). However, some studies reported that pre-weaning differences associated with different feeding regimens were no longer statistically significant as calves aged (Morrison *et al*. 2009; Quigley *et al*. 2006). This may, in part, be explained by compensatory growth, but another likely explanation for this variation in findings might be related to study size. Calf growth rates, even on a single unit with a consistent feeding policy, are still highly variable (Brickell *et al*. 2009*a*; Johnson *et al*. 2017*a*). With a mean pre-weaning growth rate of 0.5 kg/day and a standard deviation of 0.16 kg/day (based on the present study), 83 calves would be required to detect a 10% difference in groups with a significance level of P = 0.05 and a power of 0.8 (Champely 2009). This study had 88 and 104 calves in the two treatment groups and found significant differences in size for pre-weaning performance, which in this case persisted until 6 months. Studies that include multiple farms would be expected to have even higher standard deviation and require higher sample sizes to find significant size differences over long time-scales.

Conclusions

The pre-weaning growth rates for calves on both MR regimens were ~0.5–0.6 kg/day, below the recommended rate of 0.7–0.8 kg/day (Wathes *et al*. 2014). This rate was lower than expected and indicates that calves born in Spring-block calving systems in a cold environmental climate require more energy to keep warm and therefore have less energy available for growth, particularly with respect to skeletal development. It is recommended that calves be provided with a heat source or calf coat during cold weather, and/or be provided with more milk powder than is generally offered by current commercial feeding programs, enabling the calf to have enough energy available to achieve optimum growth rates. Nevertheless, a higher plane of nutrition derived from more MR with a higher protein content fed in the High group was associated with increased growth during the pre-weaning period. The Low group showed some catch-up in skeletal growth after weaning but remained smaller in all size parameters than the High group at 6 months of age. Higher rates of feeding also had a marked impact on circulating IGF1. This has previously been associated with a reduced risk of death (Brickell *et al*. 2009*b*) and increased chances of reaching the end of first lactation (Swali *et al*. 2008), highlighting the importance of early nutrition in long-term performance. Both groups achieved high levels of passive transfer before the dietary treatments were initiated, and subsequently, there was no significant difference in disease incidence between groups. However, BRD was associated with reduced weight gain and diarrhoea had a large effect on PI, resulting in leaner calves at weaning.

Conflicts of interest

The authors declare no conflicts of interest.

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