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Analysis of pre-weaning feeding policies and other risk factors influencing growth rates in calves on 11 commercial dairy farms

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Growth rates in pre-weaned calves influence their health, age at first calving and lifetime productivity. Many farms restrict milk rations to encourage solid feed intake and facilitate early weaning, but this can compromise growth. This study determined the milk feeding policies and associated growth rates on 11 commercial dairy farms in South East England, each following their normal management regime. Between 26 and 54 heifers were recruited per farm, providing a final cohort of 492, of which 71% were pure Holstein. Information on calf rearing practices (feeding, weaning, housing) and health was collected via questionnaires and weekly observations. Estimates of actual milk fed (kg solids) between 1 and 63 days were calculated for individual calves. Morphometric data (weight, height, length) were taken at weeks 1, 5 and 9 and at a median age of 7.5 months and growth rates were calculated. Most calves were fed milk replacer via automated feeders (four farms), teat feeder (one) or buckets (four) whereas two farms provided drums of acidified waste milk. Farms fed between 4 and 6 l/day of milk at mixing rates of 10% to 15%, providing 400 to 900 g/day of milk solids. Both skeletal growth rates and average daily weight gain (ADG) increased in the second month of life compared with the first: height growth from 0.17 ± 0.14 to 0.25 ± 0.16 cm/day and ADG from 0.48 ± 0.25 to 0.71 ± 0.28 kg/day. Post-weaning heifers up to 7.5 months had height increases of 0.16 ± 0.035 cm/day and ADG of 0.83 ± 0.16 kg/day. From 1 to 63 days 70% of calves had growth rates <0.7 kg/day and of these 19.6% gained <0.5 kg/day. Mean ADG before 9 weeks varied between farms from 0.52 ± 0.30 to 0.75 ± 0.20 kg/day. This was related to the amount of milk fed at both a farm and individual calf level. Increasing the total milk solids fed between 1 and 63 days from 20.4 to 46.3 kg (the 10th to 90th percentile observed) was associated with an increase of 0.11 kg/day ADG. All farms had a wide variation in growth rates despite single feeding policies. Higher circulating immunoglobulin G and IGF1 concentrations were associated with better growth, whereas low temperatures in month of birth, high scores for diarrhoea, respiratory and umbilical disease and large birth size reduced growth. Many commercially grown dairy heifers therefore experienced growth restriction in the pre-weaned period, potentially reducing their health, welfare and productivity.

Keywords: dairy cow, milk feeding, growth rate, welfare, risk factors

Implications

Growth rates of dairy heifers influence their health and lifetime productivity. Many farms restrict milk rations for dairy calves, encouraging solid feed intake and early weaning, but this risks reducing growth. We found that 70% of pre-weaned calves on 11 commercial farms had growth rates below the recommended 0.7 kg/day and of these 20% grew <0.5 kg/day. Milk offered correlated positively with growth. Early growth restriction can affect the long-term performance of the adult cow. Farmers should be encouraged to feed more physiologically normal levels of milk to replacement heifers and to monitor growth rates, to improve health and welfare.

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Introduction

Maintaining a first-calving age of 23 to 25 months is important to minimise rearing costs (Boulton *et al.*, 2017), improve longevity and increase lifetime productivity (Wathes *et al.* 2014). However, dairy heifers in the UK do not have their first live calf birth registered until a median age of 31.9 months (Gates, 2013). Dairy cows generally have a productive life of about three lactations (Wathes *et al.*, 2014), so one-third of a milking herd needs replacing annually to maintain herd size. Accordingly, under-performance in the heifers can have a large impact on farm productivity and finances.

Only 28% of 101 representative UK dairy farms routinely recorded heifer growth rates, with only a quarter using objective weight measurements rather than subjective visual assessments (Boulton *et al.*, 2015). Yet growth rate is a key determinant of whether a heifer is ready to breed at 13 to 15 months (Brickell *et al.*, 2009a). Both BW and age influence the timing of puberty (Wathes *et al.*, 2014). To reach puberty in good time for breeding, a Holstein heifer requires an average growth rate of 0.7 to 0.8 kg/day (Brickell *et al.*, 2009a; Soberon *et al.*, 2012). Low growth rates in early life delay age at first calving (Correa *et al.*, 1988; Wathes *et al.*, 2014) and are often associated with reduced productivity in the milking herd (Bach and Ahedo, 2008; Soberon *et al.*, 2012; Cooke *et al.*, 2013).

The milk feeding phase of calf development is a critical period, with the highest rates of mortality and contagious disease (Bach, 2011; Khan *et al.*, 2011) and the highest costs (Boulton *et al.*, 2017). Typically dairy heifers are separated from the dam within 24 h of birth and then fed either saleable milk, waste milk or milk replacer for 6 to 8 weeks (Lorenz *et al.*, 2011; Boulton *et al.*, 2015). The industry standard has been to provide milk at 10% of calf BW/day in two feed portions (Quigley *et al.*, 2006; Terré *et al.*, 2009). Jasper and Weary (2002) reported negligible solid feed intake in the first 2 weeks: calves on conventional ×2 daily bucket feeding then consumed 6.1 kg starter pellets and 0.98 kg hay by 35 days. Early growth is therefore heavily dependent on the milk ration. A recent UK study demonstrated that calves grew very little in their first few weeks, with a median growth rate of only 0.12 kg/day between 8 and 30 days old (Bazeley *et al.*, 2015). Growth rates of pre-weaned calves generally increase from about week 3 onwards (Bazeley KJ and Wathes DC, unpublished observations) and can exceed 1 kg/day in calves kept with their dam or on *ad libitum* milk (Appleby *et al.*, 2001; Khan *et al.*, 2011; Bach *et al.*, 2013). There is little evidence on the acceptable minimum growth rates for calves, but substantially reduced growth rates clearly compromise welfare (Scientific Veterinary Committee, 1995). This report suggested that calves in which the average growth rate was reduced by 50% were likely to have compromised welfare due to feed restriction. To prevent this occurring, Lorenz *et al.* (2011) therefore proposed feeding calves at least 15% of BW in daily milk ration in the early period when calves eat little concentrate.

In a thermoneutral environment, a 40 kg calf consuming 4 l/day whole milk should grow at 0.35 kg/day (National Research Council (NRC) 2001) but the environmental temperature affects feed conversion efficiency. The lower critical temperature is 20°C for calves up to 3 weeks old (NRC, 2001) but the mean UK temperature in 2014 was only 9.9°C (Met Office, 2014). Even though the internal calf house temperature is generally somewhat higher, energy expenditure is also required for thermoregulation as well as growth. Clinical disease, in particular diarrhoea and bovine respiratory disease (BRD) are both common in young calves (McGuirk, 2008), and are also known to reduce early growth rates and compromise long-term performance (Bach, 2011). The predominant dairy breed is the Holstein, but other purebred (e.g. Jersey) and crossbred cows are becoming increasingly popular, and these have differing nutrient requirements and growth rates (Ware *et al.*, 2015).

Monitoring heifer growth rate is therefore a valuable tool for farmers, but they need targets against which to benchmark performance. Most reported values are from data collected on Holstein heifers on research farms. Information is therefore lacking as to current practice on commercial farms. This study was designed to determine the feeding strategies and other potentially relevant management factors for pre-weaned heifers on commercial dairy farms in England, and to monitor and compare the associated calf growth rates with targets. Our hypotheses were (a) that sub-optimal growth rates for some animals were due to an insufficient milk supply and (b) that growth variations between calves on the same farm were influenced by differing amounts of milk fed and disease.

Material and methods

Cohort design and recruitment, herd profiles and management

A convenience sample of 11 dairy herds (designated A to K) in South East England were recruited between October 2011 and November 2012. Farmers needed to expect to have 30 to 50 heifers born during a 4-month recruitment period. Herd size ranged from 200 to 550 adult cows. Each farm was first visited to complete a consent form. All newly born heifer calves were recruited at subsequent weekly visits. The final cohort size was 492 heifers. Information on calf rearing practices was collected at an initial interview with the herdsmen using a standardised data capture template (Brickell *et al.* 2009b). These farm records were updated with additional information on individual calves obtained during the weekly data collection visits. Protocols for calf housing were recorded, including group sizes and any transfers between pens, the age at which this occurred and whether or not it involved mixing calves from different groups.

Collection of morphometric data

It was not possible to obtain birth weights due to limited staff time availability on commercial farms. Calves were first measured at recruitment (week 1, 4.1 ± 2.2 days), in week 5 (37 ± 6.0 days) and week 9 (60 ± 4.0 days) and at a single follow-up visit to each farm at ~7.5 months (227 ± 37.7 days). Dimensions were measured in centimetres using a standard measuring tape: girth behind the forelimb, height at withers and trunk length (diagonal distance from shoulder to the tuber ischium). All heifers were weighed at 6 to 9 months and the first 300 calves recruited were also weighed at recruitment and in week 9 using a crush placed on two calibrated weigh bars (EziWeigh5; Tru-Test Ltd, Auckland, New Zealand). As girth and weight in pre-weaned heifers were found to be highly correlated ($r^2 = 0.89$, $P < 0.001$), the weights of the remaining 192 calves were estimated from girth measurements at weeks 1, 5 and 9 after analysis by linear regression. This showed a relationship of Weight = (Girth × 1.96) − 113. The agreement between girth and weight was confirmed using a Bland–Altman plot, which showed a mean difference between the calculated and actual weight of 0.06 kg. For consistency, subsequent analyses of data for pre-weaned calves used estimated weights, whereas actual weights were used at 7.5 months. The ponderal index was also calculated as follows: ponderal index (kg/m^3) = weight (kg)/(height (m) + length (m))^3. This determines the relationship between mass and skeletal size, providing a measure of leanness (Swali and Wathes, 2007).

Actual growth rates for each calf were calculated by subtracting the starting from the end dimension and dividing by the exact number of days between the two measurements. Growth rates were calculated over four periods: 1 to 5 weeks, 5 to 9 weeks, the overall rate from 1 to 9 weeks and 9 weeks to 7.5 months. Adjusted sizes were also calculated for each animal using their individual growth rate to give an estimated size at each of 35, 63 and 229 days. This allowed for compatible comparisons between all calves, regardless of the exact age at each measurement. No adjustments were made for recruitment size because many calves either maintain a steady weight or even lose weight in their 1st week (Bazeley *et al.*, 2015), meaning that a linear growth rate could not be assumed.

Calf nutrition

Details of the milk feeding and weaning strategy on each farm were recorded. Milk feeding was classified as bucket, teat or automated and frequency was recorded as once, twice or thrice daily or continuously available. The type of milk was either waste milk from the herd or milk replacer (Table 1). For milk replacer, the brand details and mixing rate were noted (Supplementary Table S1). All farms fed warm milk in the approximate range 35°C to 40°C. To ensure that the actual feeding process agreed with stated farm policy, feeding was observed twice on each farm at unannounced visits to check milk replacer weights, mixing rates and calibration of automated feeders. One farm (H) had a calibration problem, so a mixing rate of 9% was used rather than the intended rate of 12.5% until the machine was serviced. This affected 30 calves for 4 weeks. Information was also obtained on concentrate feeding (which was always *ad libitum*) and availability of roughage (hay, silage, straw in feeder or straw as bedding). Age at weaning was recorded on an individual calf basis. All farms used a step-down process. The criteria used to define weaning were classified as being based on a fixed plan, or on calf age and/or condition.

All farms offered a commercial concentrate feed *ad libitum* during the weaning period. The same feed was subsequently fed at a fixed rate in older heifers. After weaning, all heifers continued to receive fibrous feed (straw, hay or silage) depending on farm and season. All post-weaned calves were initially housed on deep straw. All farms subsequently reared at least some heifers outside depending on age and season. Most calves (on 6/11 farms) were at pasture at the follow-up check but some calves on one of these six farms and all on the remainder were considered too young for turnout and were housed throughout the study period.

Calculation of milk solids fed

Determination of an average daily feed rate was precluded as the amount of milk fed to calves always changed at least once pre-weaning (Table 1). Consequently, the most reliable comparison of total milk allocation in each time period was based on milk solids rather than volume. Several brands of milk powder were used across the 11 farms as well as transitional and antibiotic waste milk. Details of their respective nutritional contents are provided in the Supplementary Table S1. The initial feed of colostrum was assumed to be taken from the dam for 319 calves. The remaining 173 calves were initially fed colostrum by bottle or oesophageal tube. After separation from the dam all farms fed transitional waste milk when available, with all farms allocating each calf 2 l twice daily. Calves were then transferred to pens where feeding rates varied depending on the farm (Table 1). Estimates of actual milk consumed in the first 5 weeks (1 to 35 days) and subsequently (35 to 63 days) for each individual calf were calculated based on the number of days the calf was fed colostrum/transitional milk, calf feeding volume on farm, the mixing rate used, any changes in calf feeding on an individual basis (e.g. age moved to automated feeder or day changed to once daily feeding) and the actual weaning age. For calves fed from drums the milk consumption was averaged across the group.

Calf health monitoring

Each individual calf underwent a weekly clinical examination by the same veterinarian from 1 to 9 weeks of age. The scoring system for calf health was developed by the University of Wisconsin-Madison and used a systematic approach to assess signs of BRD and faecal consistency according to McGuirk (2008) with minor modifications. Temperature scoring used cut-off values of 38.5°C, 39.0°C and 39.5°C to generate scores between 0 and 3. Ocular and nasal discharges and the presence of induced or spontaneous cough were also scored on a scale from 0 to 3. Animals with a total respiratory score $\geqslant 5$ (combined scores for temperature, cough, ocular and nasal discharges) were classified as having BRD. Faecal consistency was given a score of 0, normal; 1, pasty, 2, loose and 3, watery and calves with a faecal score $\geqslant 2$ were classified as having diarrhoea. Notes were also taken at each visit to record any other health problems, most commonly umbilical infection. Head tilt, a sign of inner ear infection, was excluded because it was not seen in any calf.

Measurement of passive transfer and circulating IGF1

Three jugular vein blood samples per calf were collected under the UK Animals (Scientific Procedures) Act 1986 under a project licence approved by the RVC Ethical Review Process. A week 1 recruitment sample was taken into a plain vacutainer (BD, Oxford, UK), centrifuged after clotting and the serum stored at −18°C for later analysis. A refractometer (RHC-200; Huake Instrument Co. Ltd., Shenzhen, China) was calibrated with distilled water then used to assess serum total protein (TP). Immunoglobulin G (IgG) was

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Table 1 *Summary of pre-weaned feeding practices for dairy heifer calves for the 11 farms included in the study*

Management practices[1]	Farm										
	A	B	C	D	E	F	G	H	I	J	K
Calves recruited (*n*)	54	36	48	51	48	39	35	54	56	26	45
Breed(s)[2]	Mixed	H	H/VRX	F/VRX	H/VRX	H	H/A	H/VRX	H	H	H
Group size (P1)	10 to 20	1	3	1	3	5	1	10 to 20	5	1	5
Feeds/day (P1)	2	2	2	2	2	2	2	2	2	2	2
Transition milk (l/day) (1)	4	4	4	4	4	4	4	4	4	4	4
Age at transfer	3 to 5 d	1 to 2 days	1 week	1 week	1 week	3 weeks	2 to 3 weeks	3 to 5 days	1 week	NA	1 to 2 weeks
Group size (2)	30	1	4 to 6	12	4 to 6	20	3	30	30 to 45	NA	15
Feeding method	Auto	Bucket	Drum	Bucket	Drum	Auto	Bucket	Auto	Auto	Bucket	TF
Feeds/day (2)	3	2	NA	2/1	NA	3	2/1	3	3	2	2
Milk (l/day) (2)	6	6	4 to 7	4	4 to 6	6	3	6	6	4	6
Mixing rate (2) (%)[3]	10	15	NA	10	NA	10	15	10	10	10	10
Forage feed	Hay	Straw[4]	Silage	Straw	Silage	Straw	Straw	Hay	Straw	Straw[4]	Straw[4]
Weaning period	1 week	1 week	2 weeks	1 week	2 weeks	1 week	1 week	1 week	1 week	1 week	2 weeks
Decision to wean criteria[5]	Plan	Age/cond	Age/cond	Age/cond	Age/cond	Plan	Age/cond	Plan	Plan	Age/cond	Age/cond

NA = not applicable; H = Holstein; F = Friesian; SRX = Viking Red cross; A = Ayrshire; TF, teat feeder.
[1]Feeding policies are summarised over an initial period (1) when all calves were fed 4 l/day transition milk and subsequently (2) when the amounts and types of feed provided are as described.
[2]Mixed, included Jersey and Jersey crosses alongside Friesian cross heifers.
[3]All herds were fed milk replacer except C and E which provided acidified waste milk in a drum. Mixing rate defined as proportional weight of milk powder in final volume of reconstituted milk replacer.
[4]Straw only provided as bedding, rather than in a feeder.
[5]Age/cond: weaned on a combination of calf age and condition; plan, programmed by automatic feeder.

also measured using a radial immuno-diffusion assay kit (VMRD, Pullman, WA, USA) according to the manufacturer's instructions. Heparinised samples were collected at weeks 1, 5 and 9, centrifuged to collect plasma and IGF1 was measured using a commercial ELISA kit (IDS, Tyne and Wear, UK) as described previously (Brickell *et al.*, 2009b).

Data analysis and univariate statistics

Data were stored in Excel and arranged into a relational database using Access to allow for further analysis (Microsoft Office; Microsoft, Redmond, WA, USA). All analysis was completed in R using the lattice package for graphics (http://www.r-project.org). For each variable, normality was assessed by plotting a *q*/*q* plot and using the Shapiro–Wilk test. The morphometric measurements and growth rates were normally distributed and are presented as mean ± SD. Differences between farm and breed groups were assessed by ANOVA, using the 'aov' function. *Post hoc* testing was completed using the Tukey honest significant difference method in the R package 'agricolae' to correct for multiple testing. Linear regression was used to assess the relationships between continuous variables using the 'lm' function in R.

Multivariable statistics

The four growth-related outcomes examined were weight and height at 63 and 229 days and weight and height increases between 1 and 63 and 63 and 229 days. Candidate variables which might influence these outcomes are described in the Supplementary Table S2. Each variable was initially tested for normality and transformed if necessary. Variables were then plotted against the outcome in turn and tested in univariate analysis. For binary outcomes, generalised linear models were used with the formula: binary outcome = constant + β(variable of interest). For continuous outcomes, linear models were fitted with the formula: Continuous outcome = constant + β(variable of interest). The results were recorded with the effect estimate and SD, the *z* (binary) or *t* (continuous) values for each intercept and variable and the *P* values.

All multivariable models included farm as a random factor, using a hierarchical model with calf nested within farm. An identity covariance structure was used, as farms were assumed to be independent from each other. Models were fitted using the lmer function in the package lme4 with the lmerTest package used to calculate *P* values for each variable (https://cran.r-project.org/web/packages/lmerTest/index.html). Variables were initially considered for inclusion in the multivariate linear mixed effects models if $P < 0.2$. To remove covariance between fixed effects recording related information (e.g. serum TP and serum IgG), only the variable with the highest model r^2 was included. All remaining candidate variables were tested in a multivariate model with a backwards stepwise approach using the 'anova(model1, model2)' function in R. This uses likelihood ratio tests to assess differences between two nested models and displays the Akaike Information Criterion (AIC) and the Baysian Information Criterion (BIC), providing measures of relative model quality. The significantly best model was taken forward. Where there was no significant difference, the model with the lower AIC and BIC was selected. All variables that did not improve the model were excluded to give a final model. The effect estimate, the 95% confidence intervals (using the Wald procedure) and the *P*-value were calculated.

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Results

Farms, calf recruitment and breeds

Three farms used autumn block calving, with the remaining eight having an all-year-round calving pattern. On the 11 farms the breeds of calves kept were as follows (Table 1): pure Holstein ($n = 5$), Holstein with some Viking Red crosses ($n = 3$), and one farm each with both Holsteins and Ayrshires, New Zealand type Friesians with some Viking Red cross Friesian, and mixed breed cattle with many Jersey and Jersey crosses alongside Friesian cross heifers. From these farms 492 calves were recruited, with a range of 26 to 56 sequentially born dairy heifer calves per farm. In total, 351/492 (71%) of the calves were Holsteins followed by black and white cross Viking Red (43/492, 8.7%) and Friesians (37/492, 7.5%).

Pre-weaning feeding and housing management

Table 1 provides a summary of farm management information relevant to calf feeding. One farm (F) removed calves from dams shortly after birth. On the remaining farms, calves usually stayed with their dams for 12 to 24 h, although on two farms (G, J) calves were left with dams for several days. Four farms subsequently fed groups of 18 to 30 calves using automated feeders. On three of these four farms calves were moved from the farm of origin to a nearby rearing unit as soon as their passports were issued (typically 1 week old). On the fourth farm, calves were bucket-fed twice daily on the farm of origin for ~3 weeks until a batch was moved to the rearing unit. Four farms fed milk twice daily, two using buckets and keeping calves in single pens and two using feeders with teats and keeping calves in groups of 12. A further two farms fed milk to calves twice daily for ~2 weeks and then switched to once daily feeding. Finally, two farms kept calves in small groups where there was a single teat per pen of four to six calves supplied by a mixed drum of acidified waste milk. No calves received milk *ad libitum*. No farms weighed milk replacer powder: consequently, feeding rates were approximate. Farms fed between 4 and 6 l milk/day and aimed for a mixing rate of between 10% and 15% milk powder/l, providing 400 to 900 g/day milk solids (Table 1). The milk powders had a DM protein content between 20.6% and 27.1% and a DM fat content between 16.7% and 18.8% (Supplementary Table S1). The protein content of whole milk is similar to that in milk powder. Whole milk DM fat in Holstein milk is higher than in powder at about 28% but contains less lactose (41% *v.* about 52%).

All farms provided concentrate feed *ad libitum* once calves were in the main housing, typically at <1 week old. Only two farms gave access to concentrate later than 1 week: calves in farm G were housed with the dam for up to 10 days and calves at farm F were not moved to the rearing unit until they were ~3 weeks old. Forage was provided on all farms as hay, silage, straw in feeder or straw as bedding (Table 1). All farms used gradual step-down weaning, typically over 1 week, either by limiting milk availability on computerised feeders, cutting bucket feeds to once per day, or providing watered down waste milk only in the mornings. The age at which weaning began was variable: most farms based their decisions on a combination of calf age, calf or group appearance and farm convenience. On the farms that used automated feeders, calves were always programmed to receive milk for a certain number of days, so their age at arrival at the rearing unit determined their weaning age. Amounts of milk fed from 1 to 35 days were fairly consistent within farm, but large differences in weaning age meant that the milk solids fed from 35 to 63 days were highly variable, even within farm (Table 2).

Calf size and growth rates

Plots of individual calf size data against age in days are illustrated in Figure 1. Summary data (mean ± SD) of size measurements at each age and their range between farms are

Table 2 *Ranges of estimated colostrum and milk solids fed and weaning age for calves on each farm*[1]

Farms	Period 1 (1 to 35 days) (kg milk fed)	Period 2 (35 to 63 days)[2] (kg milk fed)	Total kg milk fed (1 to 63 days)	Weaning age (days)	
				Mean ± SD	Range
D	12.6	4.2 to 8.4	16.8 to 21.0	59.1 ± 5.5	49 to 67
J	14.0	7.6 to 11.2	21.6 to 25.2	61.7 ± 4.4	54 to 70
G	14.9	0.9 to 12.6	15.8 to 27.5	58.9 ± 9.5	37 to 81
H	16.8 to 16.9[3]	14.0 to 15.1	30.9 to 32.0	66.6 ± 2.9	61 to 77
F	14.0 to 20.6[3]	16.8[4]	30.8 to 37.4	80.8 ± 5	72 to 91
I	14.0 to 20.8[3]	12.6 to 16.8	26.6 to 37.4	71.6 ± 8.4	56 to 97
E	21.9	6.3 to 17.5	21.2 to 39.4	49.9 ± 7.8	34 to 67
K	23.0	8.4 to 6.8	31.4 to 39.8	62.2 ± 5.4	49 to 79
C	25.0	13.5 to 21.0	38.5 to 46.0	62.8 ± 4.1	53 to 68
A	25.3	16.5 to 21.0	41.7 to 46.2	67.3 ± 2.8	57 to 72
B	30.7	16.2 to 25.2	46.9 to 55.9	63.2 ± 3.9	53 to 74

[1]All calves experienced changes in feeding policy at variable ages, so total figures per period (rather than per unit time) are provided. Data were calculated on an individual calf level.
[2]Some calves (e.g. on Farm G) were weaned early so received very little milk during Period 2.
[3]These farms moved calves onto automatic feeders at variable ages.
[4]No variation because all calves were weaned at >63 days.

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presented in the Supplementary Figure S1. At recruitment in week 1 calf weights were 39.6 ± 8.8 kg (n = 492), increasing to 74.6 ± 10.9 kg at 9 weeks. At the final follow-up visit at 227 ± 37.7 days, the median weight was 213 kg. Both skeletal growth rates and average daily weight gain (ADG) were higher between 35 and 63 days than between 1 and 35 days of age (Figure 2): height growth increased from 0.17 ± 0.14 to 0.25 ± 0.16 cm/day, length growth increased from 0.16 ± 0.1 to 0.22 ± 0.1 cm/day and ADG increased from 0.48 ± 0.25 to 0.71 ± 0.28 kg/day. Post-weaning, heifers had slower skeletal height and length growth rates of 0.16 ± 0.04 cm/day and 0.2 ± 0.04 cm/day, respectively, whereas ADG increased further to 0.83 ± 0.16 kg/day. Calf weight and height by breed are shown in the Supplementary Table S3. Jersey calves were lighter than the other pure bred calves at recruitment, with intermediate weights in the crossbred calves. No weight differences remained significant at 229 days, due to the large variability within breeds. Jersey calves were 6.5 cm shorter that Holsteins at recruitment and this height difference remained similar at 7.4 cm at 229 days.

The mean ADG up to 63 days varied from 0.52 ± 0.3 to 0.75 ± 0.2 kg/day between farms, compared with a range from 0.66 ± 0.1 to 0.94 ± 0.1 kg/day between 63 and 229 days (Figure 2). There was a wide range of growth rates even on the best performing farms, despite a single farm feeding policy (Figure 2). Neither individual animal nor farm mean growth rates were correlated between the two time periods of 1 to 63 and 63 to 229 days. For example, the three farms with the lowest initial ADG (D, E, G) all had higher rankings subsequently, whereas Farm A had the second highest ADG before 63 days but the lowest subsequently. Across all farms, the mean growth rate per farm over the first 9 weeks was positively correlated with the total amount of milk solids fed (R^2 = 0.687, P = 0.02, Figure 3).

Calves were also classified according to the distribution of growth rates in different ADG ranges (Figure 4). Overall 19.6% of calves grew <0.5 kg/day between 1 and 63 days. Subsequently, calves gained weight more quickly, with 81.9% of calves growing at or above the target rate of 0.7 to 0.8 kg/day and only 2.7% falling below the threshold of 0.5 kg/day. On all farms except B the majority of calves gained <0.7 kg/day during the period before 63 days, with 69.6% below this figure. On farms D, E and G, >80% of calves were below this figure (Figure 2).

Predictors of growth from 1 to 63 days of age

The same variables were retained in the final models for both estimated weight at 63 days and ADG between 1 and 63 days, so only the latter model is described in Table 3 . Increasing milk solids fed during this period from 20.4 to 46.3 kg (the 10th to 90th percentile observed) was associated with an increase of 0.11 kg/day ADG. Calf weight at recruitment was inversely correlated with subsequent weight gain. Increasing weight in week 1 from 28.7 to 48.4 kg (10th to 90th percentile) predicted a 0.093 kg/day fall in ADG. There was a predicted increase of 0.044 kg/day ADG when serum IgG at recruitment increased from 2.9 to 31.5 mg/ml

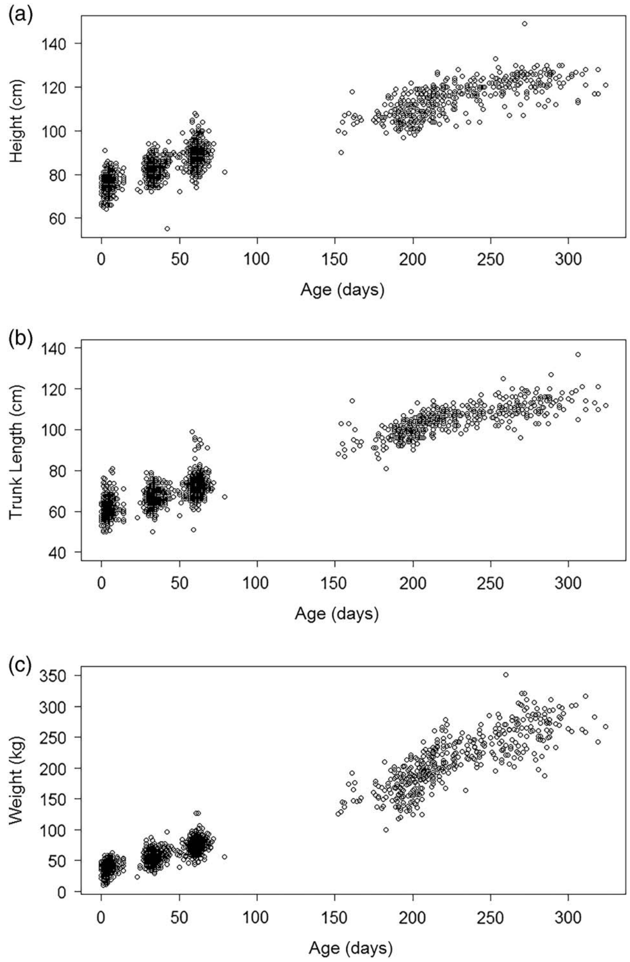

Figure 1 Plots of the size measurements (a, height; b, trunk length; c, weight) for 492 individual calves at each of the four time points, recruitment in weeks 1, 5, 9 and the follow-up visit at a mean age of 227 ± 37.7 days.

(10th to 90th percentile), indicative of better passive transfer. Higher circulating IGF1 at 35 days was associated with a higher ADG: an increase in IGF1 from 16.3 to 107.6 ng/ml (10th to 90th percentile) was associated with a 0.059 kg/day increase. Pre-weaning disease was associated with a reduced ADG: 10% of calves had at least 2 weeks of diarrhoea, which was associated with a reduction in ADG of 0.067 kg/day. The 10% of calves most severely affected with BRD, which experienced over 4 weeks of disease, had a 0.039 kg/day reduction in ADG. Finally, calves that moved to a rearing unit in this period were predicted to be 4.82 kg larger at 63 days than those staying on the same holding.

The model determining effects on the height increase between 1 and 63 days is described in Table 4. There was a small breed influence, with breeds other than Holstein growing at 0.002 cm/day less. Mean environmental temperature in the month a calf was born was also associated with a lower growth rate. Decreasing temperature from 16.6°C to 5.5°C (90th to 10th percentile) was associated with a decrease of 0.04 cm/day in height growth. Increasing height at recruitment from 71 to 81 cm (10th to 90th percentile) was associated with a 0.08 cm/day decrease in

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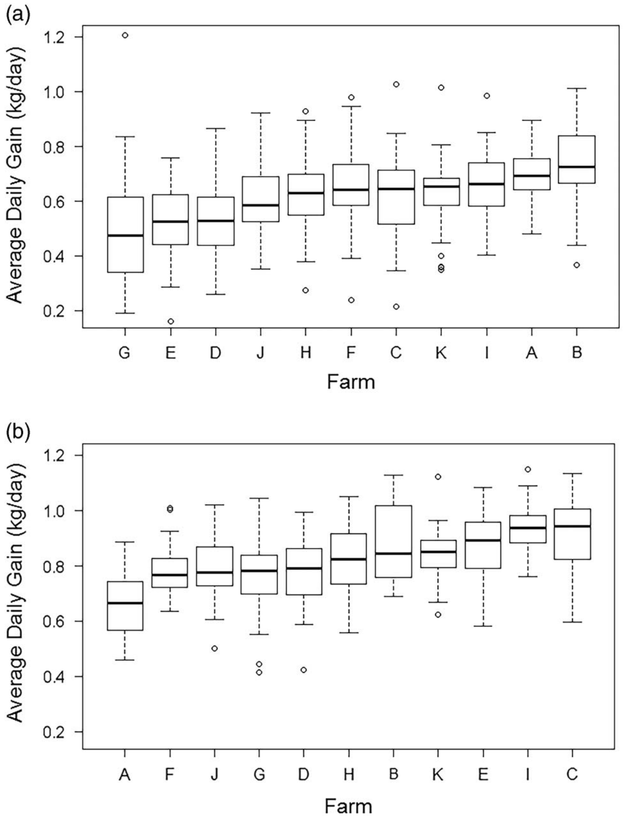

Figure 2 Box and whisker plots showing the average daily weight gain for calves on each of the 11 farms in the study, ranked according to the median value. Two time periods are shown (a) from 1 to 63 days, and (b) from 63 to 229 days. There were between 26 and 56 calves recruited per farm (see Table 1 for details).

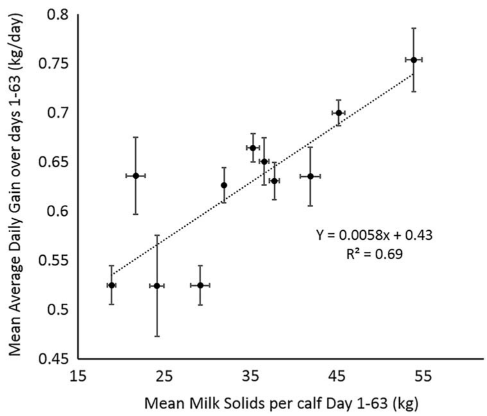

Figure 3 Mean total milk solids ± SEM fed on each of the 11 farms plotted against actual average daily weight gain from 1 to 63 days. There was a significant correlation, $P = 0.02$.

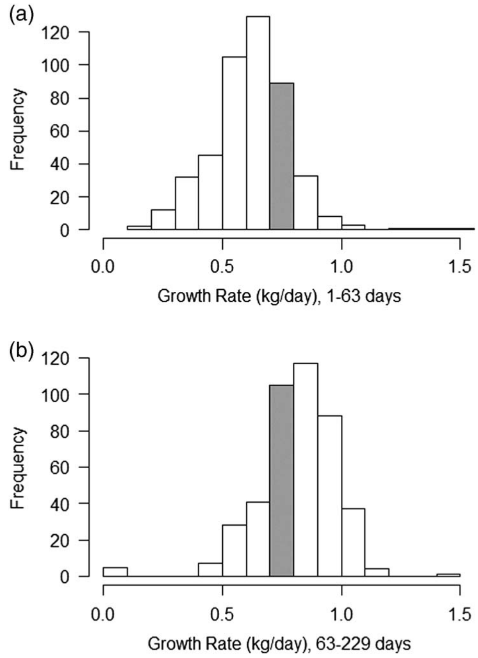

Figure 4 Histograms showing the proportions of calves according to differing average daily weight gain (ADG) (a) from 1 to 63 days and (b) from 63 to 229 days (7.5 months). Data in (a) are for 463 calves (22 had died, seven missing values). Data in (b) are for 447 calves (27 had died, 18 missing values). The target ADG of 0.7 to 0.8 kg/day as suggested by Cooke *et al.* (2013) is shaded.

height growth. Bovine respiratory disease and umbilical infections were also associated with decreased height growth. In both cases calves on the 90th percentile for disease score grew at 0.02 cm/day less throughout this period. Increasing total milk solids fed during this period from 20.4 kg to 46.2 kg (10th to 90th percentile) was associated with a 0.05 cm/day increase in height growth. Similar variables were retained in the final model for estimated height at 63 days, with the following exceptions (data not shown). Breed was not significant and this was the only model generated that was significantly improved by the addition of exact calf age at recruitment. Increasing ponderal index at recruitment and IGF1 at day 35 from the 10th to the 90th percentile increased the height at 63 days by 5.6 and 0.97 cm, respectively.

Predictors of growth from 63 to 229 days of age

Variables associated with both weight at 229 days and the ADG from 63 to 229 days are given in Table 5. The response to milk solids fed was greater after than before 63 days: calves were predicted to be 13.4 kg heavier if fed 46.3 rather than 20.4 kg milk pre-weaning (90th and 10th percentiles). Both weight at recruitment and ADG from 1 to 63 days were positively correlated with weight at 229 days. Finally, IGF1 at 63 days was positively associated with greater weight at 229 days, Calves at the 90th centile for IGF1 were expected to be 7.5 kg heavier than those of the 10th centile.

The ADG from 63 to 229 days was also associated with milk solids fed to younger calves and with IGF1. A calf fed 46.3 kg of milk solids was predicted to grow 0.075 kg/day faster than one fed 20.4 kg. Length, height and weight at recruitment were all associated with higher weight gain in this period: length provided the largest improvement, so was retained in the final model. Increasing length at recruitment from 56 to 67.3 cm (10th to 90th percentile) was associated with a 0.042 kg/day increase in ADG. An increase from the 10th to the 90th percentile in IGF1 at 63 days was associated with an increase of 0.041 kg/day compared with calves on the 10th percentile. Finally, temperature in the month of birth

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Table 3 *Variables associated with calf average daily weight gain (ADG) (kg/day) between 1 and 63 days of age for 492 dairy heifer calves on 11 commercial farms*

Variables	Estimate	95% CI[1]	*P*-value
(Intercept)	0.525	0.393 to 0.657	<0.001***
Total milk solids fed 1 to 63 days (kg)	0.004	0.002 to 0.006	<0.001***
WT at recruitment (kg)	−0.005	−0.007 to −0.003	<0.001***
IGF1 at 5 weeks[2] (ng/ml)	0.032	0.016 to 0.049	<0.001***
Weeks with diarrhoea pre-weaning	−0.034	−0.052 to −0.015	<0.001***
Weeks with BRD pre-weaning	−0.019	−0.032 to −0.007	0.003**
IgG at recruitment (mg/ml)	0.002	0 to 0.003	0.042*
Moved pre-weaning – FALSE	(ref)		
Moved pre-weaning – TRUE	0.078	0.012 to 0.143	0.032*

CI = confidence intervals; WT = weight; BRD = bovine respiratory disease.
[1]CI for parameter estimate: * $P<0.05$, ** $P<0.01$, *** $P<0.001$.
[2]Data were log transformed.

Table 4 *Variables associated with calf height increase between 1 and 63 days of age for 492 dairy heifer calves on 11 commercial farms*

Variables	Estimate	95% CI[1]	*P*-value
(Intercept)	0.978	0.828 to 1.121	<0.001***
Breed – Holstein	(ref)		
Breed – other	−0.002	−0.064 to −0.033	<0.001***
Mean temp in month of birth[2](°C)	−0.041	−0.061 to −0.02	<0.001***
Total milk solids fed 1 to 63 days (kg)	0.002	0.001 to 0.003	<0.001***
HT at recruitment (cm)	−0.009	−0.01 to −0.007	<0.001***
Total BRD score	−0.004	−0.007 to −0.001	0.007**
Total umbilical disease score	−0.007	−0.011 to −0.003	0.002**

CI = confidence intervals; HT = height at withers; BRD = bovine respiratory disease.
[1]CI for parameter estimate: ** $P<0.01$, *** $P<0.001$.
[2]Data were log transformed.

was influential. The 10% of calves born in the warmest months grew 0.047 kg/day faster than those born in the coldest months. As February was the coldest month, calves born at this time therefore grew more slowly between the ages of 63 and 229 days despite the warmer weather experienced post weaning.

The linear mixed effects model for estimated calf height at 229 days is presented in Table 5. Increasing recruitment height from 71 to 81 cm and pre-weaning height growth from 0.125 to 0.317 cm/day (10th to 90th percentile) was associated with taller calves at 229 days, by 6.2 and 3.6 cm, respectively. The only pre-weaning variable that significantly improved the multivariate model was again total milk solids fed. An increase from 20.4 to 46.3 kg (10th to 90th percentile) was associated with a 3.1 cm increase in height. Milk solids fed was also significant in the model for height growth from 63 to 229 days. However, the taller calves that were at the 90th height percentile at 63 days (96 cm) subsequently grew 0.04 cm/day more slowly than those at the 10th percentile (83.7 cm).

Discussion

Most previous studies into calf nutrition and growth rates have followed prescribed protocols on research farms. This study measured the amounts of milk supplied to calves and their resulting growth rates on commercial farms applying their normal management practices. Both the milk rations offered and growth rates were below optimal for many pre-weaned calves, with 20% growing at <0.5 kg/day. Given that an ADG of 1 kg/day is achievable on an *ad libitum* milk supply (Khan *et al*., 2011) this could be considered as a level of growth restriction that would be expected to reduce calf welfare (Scientific Veterinary Committee, 1995; Lorenz *et al*., 2011). Furthermore, 70% grew at <0.7 kg/day. This is the rate required to reach growth targets for first calving at 24 months, which is associated with increased productivity and longevity (Cooke *et al*., 2013). The management practices observed here on the 11 farms studied were similar to those recorded in a stratified sample of 101 commercial dairy herds (Boulton *et al*., 2017). It is possible that the results were influenced by farm selection, but we believe that the herds in the study were representative of typical UK farms.

Advice to farmers for over 80 years has been to restrict the milk ration for young calves, to encourage early intakes of calf starter feed and so facilitate weaning from about 6 weeks of age (Khan *et al*., 2011). In their 1st month calves are, however, unable to eat sufficient solid feed to meet their energy requirements and are therefore dependent on the milk ration (Khan *et al*., 2011). Calf rearing systems have

Table 5 *Variables associated with size at 229 days and average growth rates from 63 to 229 days of age for 492 dairy heifer calves on 11 commercial farms*

Variables	Estimate	95% CI[1]	*P*-value
WT at 229 days (kg)			
(Intercept)	89.4	66.7 to 112.1	<0.001***
WT at recruitment (kg)	1.41	1.13 to 1.69	<0.001***
ADG days 1 to 63 (kg/day)	55.4	40.4 to 70.3	<0.001***
Total milk solids fed 1 to 63 days (kg)	0.517	0.17 to 0.863	0.004**
IGF1 at 63 days[2] (ng/ml)	3.8	1.23 to 6.36	0.004**
ADG 63 to 229 days (kg/day)			
(Intercept)	0.314	0.068 to 0.559	0.013*
Total milk solids fed 1 to 63 days (kg)	0.003	0.001 to 0.005	0.007**
IGF1 at 63 days[2] (ng/ml)	0.021	0.006 to 0.036	0.007**
Length at recruitment (cm)	0.004	0 to 0.007	0.028*
Mean temp in month of birth[2] (°C)	0.042	0.001 to 0.084	0.048*
HT at 229 days (cm)			
(Intercept)	58.6	48 to 69.2	<0.001***
HT at recruitment (cm)	0.626	0.5 to 0.75	<0.001***
HT growth 1 to 63 days (cm/day)	18.5	12.4 to 24.6	<0.001***
Total milk solids fed 1 to 63 days (kg)	0.12	0.05 to 0.19	0.001**
HT gain 63 to 229 days (cm/day)			
(Intercept)	0.376	0.3223 to 0.4297	<0.001***
Estimated HT at 63 days (cm)	− 0.0027	− 0.0033 to −0.0022	<0.001***
Total milk solids fed 1 to 63 days (kg)	0.0006	0.0002 to 0.0011	0.005**

CI = confidence intervals; WT = weight; HT = height at withers; BRD = bovine respiratory disease.
[1]CI for parameter estimate: * $P<0.05$, ** $P<0.01$, *** $P<0.001$.
[2]Data were log transformed.

typically fed liquid milk at 10% of BW, supplying 400 to 500 g milk solids/day to achieve growth rates of around 0.4 to 0.6 kg/day under thermoneutral conditions (Quigley *et al.*, 2006; Morrison *et al.*, 2009). All 11 farms in this study limited milk availability. Two farms used waste milk with added acidifiers. This reduces palatability (Hepola, 2003) and the amount fed was also limited by daily availability. Overall ADG in the first 5 weeks was 0.48 kg/day. This exceeded the 0.12 kg/day previously recorded by Bazeley *et al.* (2015) on UK farms but was similar to growth rates of 0.35 to 0.56 kg/day reported in a review of 19 research studies (Morrison *et al.*, 2009). These restrictions in milk supply occurred even though numerous studies have shown that calves fed more milk at a young age have higher feed conversion efficiencies and better growth rates (e.g. Raeth-Knight *et al.*, 2009; Khan *et al.*, 2011; Soberon *et al.*, 2012).

Little information is currently provided to farmers and veterinary surgeons as to what constitutes a physiologically normal milk intake as most educational materials reflect industry standards. Calves provided with higher volumes of milk in early life can consume 20% of their BW daily and gain weight by up to 1 kg/day (Khan *et al.*, 2011). Calves will choose to drink about 8 l/day whole milk in the 1st month of life (Appleby *et al.*, 2001; Jasper and Weary, 2002; Moallem *et al.*, 2010). This is equivalent to the metabolisable energy (ME) from about 1.1 kg/day of a typical milk replacer (22% protein, 18% fat, 7% ash, therefore ME = 19.7 megajoules/kg dry matter (DM)). For a 50 kg calf in a thermoneutral environment this would result in a growth rate of 0.95 kg/day (NRC, 2001).

Growth rates in older calves in this study (from 9 weeks to 7.5 months) were higher than in early life. As a consequence, mean growth rates over the whole study period were often within the target range of 0.7 to 0.8 kg/day. However, this disguised the extremely high variation observed between individual calves. Even on the best performing farm a third of their pre-weaned calves grew at <0.7 kg/day, and the bottom 5% grew at <0.16 kg/day. Such variability has consistently been reported in previous studies (Virtala *et al.*, 1996; Brickell *et al.*, 2009b; Bach *et al.*, 2013). It suggests uneven rates of milk intake even though all animals on the same farm were, in theory, on the same feeding regime. This variability may in part be due to competition for feed between group housed calves (O'Driscoll *et al.*, 2006). There was, however, also high variability on the two farms that housed calves individually, suggesting that additional factors were involved.

The total amount of milk solids fed was the main variable consistently associated with a greater weight and height at both 63 and 229 days and the ADG and height increases from 1 to 63 and 63 to 229 days. The beneficial effect of a good milk supply on growth therefore continued long after weaning. There was a positive influence of IGF1 on both weight and ADG, confirming results of an earlier study (Brickell *et al.*, 2009b). IGF1 production is in part controlled by nutrient intake and IGF1 is a known regulator of muscle development (Bass *et al.*, 1999; Smith *et al.*, 2002). IgG at recruitment also had a small positive effect on growth, implying that calves benefited from a high initial intake of

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colostrum. Colostrum is itself highly nutritious. It is also associated with improved gut maturity (Blum, 2006) and improved health (McGuirk, 2008). Calves moved to a separate rearing unit also had a higher ADG from 1 to 63 days. These animals were all kept in larger groups and fed three times daily from automatic feeders. Calves left with their dams suckle between 6 and 12 kg milk/day, spread between several meals each lasting about 10 min (Khan *et al*., 2011), so more frequent feeding is closer to the natural situation. Compared with individual penning, calves housed with an older companion were found to ingest more starter pre-weaning and experience a lesser growth check post weaning (De Paula Vieira *et al.,* 2012).

Not surprisingly, there was a negative influence of disease. Diarrhoea, BRD and umbilical disease were recorded in 48.2%, 45.9% and 28.7% of the pre-weaned calves in this study, respectively. Calves with more weeks of either diarrhoea or BRD had a lower ADG from 1 to 63 days whereas the total scores for both BRD and umbilical disease were associated with a reduced height increase. A good immune response requires adequate nutrition (Galyean *et al*., 1999). Sick animals have a reduced feed intake (Johnson, 2002) and differences in immune function of calves on a low plane of nutrition may predispose them to clinical disease (Ballou, 2012).

Calves which were heavier or taller at recruitment had a lower ADG or height increase from 1 to 63 days but were again heavier and taller at 229 days. It may be that smaller birth size was associated with *in utero* growth restriction followed by post natal catch-up growth, as suggested by Swali and Wathes (2007). A more likely explanation is that larger calves experienced some growth restriction pre-weaning. Growth rate depends on the ME available after maintenance and temperature regulation, which in turn depend on BW (NRC, 2001). Thus, a higher growth rate would be expected for a smaller than for a larger calf if both received the same restricted amount of milk. For example, a 30 kg calf offered 0.36 kg milk powder per day, in environmental temperatures of 15°C, should grow at 0.21 kg/day, whereas a 50 kg calf under similar conditions would have no ME available for growth. This may in part explain why breed was not significant in any of the weight-associated models, as the Jersey calves were lighter at birth, but were fed similar amounts of milk to the larger breeds. Breed was, however, a significant factor in height increase from 1 to 63 days, which was greater for Holsteins than other breeds. Holsteins have been selected for stature, which has positive genetic correlations with milk yield and feed efficiency (Lin *et al*., 1987; Manafiazar *et al*., 2016).

One strategy to help maximise the amount of energy available for growth is to avoid exposing calves to low environmental temperatures. Thermoneutral conditions for calves below 3 weeks of age are above 20°C but this temperature is increased with higher air speeds or wet bedding (NRC, 2001). Experiencing a low environmental temperature in the month of birth was associated with a reduced height increase from 1 to 63 days and was also significant in the model for ADG from 63 to 229 days. Housing calves in groups on dry, deep straw with shelter allows calves to huddle and provides a warmer local environment, reducing their need to use energy to stay warm and so improving feed conversion efficiency (Relic and Bojkovski, 2010; Lorenz *et al*., 2011). The mean UK monthly temperatures during the study period ranged from 4.4°C to 16.6°C with a median of 9.5°C (Met Office, 2014). The temperature within a calf house is generally higher than externally; nevertheless many calves within the UK are kept below their thermoneutral environment, so achieving adequate growth rates may require additional feed, a strategy often used in colder regions (Quigley *et al*., 2006). Moving pens away from external barn walls (Lundborg *et al*., 2005) and providing calf jackets (Rawson *et al*., 1989) also reduces heat loss.

There is mounting evidence that early growth restriction affects the long-term performance of that animal in the adult milking herd (Khan *et al*., 2011; Soberon *et al*., 2012). Conversely, increasing the ADG to >0.8 kg/day for the first 6 weeks (Bar-Peled *et al*., 1997) or 6 months of life (Brickell *et al*., 2009a) can reduce the age at conception and calving by at least 1 month. This produces an economic saving to set against the higher early costs (Boulton *et al*., 2017). Farmers should therefore be encouraged to feed more physiologically normal amounts of milk. Consistent with our hypotheses, growth rates of calves within the same farm were affected by quantity of milk fed, air temperature and disease and sub-optimal growth rates were strongly associated with an insufficient milk supply.

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Supplementary material

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References

Appleby MC, Weary DM and Chua B 2001. Performance and feeding behaviour of calves on *ad libitum* milk from artificial teats. Applied Animal Behaviour Science 74, 191–201.

Bach A 2011. Associations between several aspects of heifer development and dairy cow survivability to second lactation. Journal of Dairy Science 94, 1052–1057.

Bach A and Ahedo J 2008. Record keeping and economics of dairy heifers. Veterinary Clinics of North America: Food Animal Practice 24, 117–138.

Bach A, Terré M and Pinto A 2013. Performance and health responses of dairy calves offered different milk replacer allowances. Journal of Dairy Science 96, 7790–7797.

Ballou MA 2012. Immune responses of Holstein and Jersey calves during the pre-weaning and immediate post-weaned periods when fed varying planes of milk replacer. Journal of Dairy Science 95, 7319–7330.

Bar-Peled U, Robinzon B, Maltz E, Tagari H, Folman Y, Bruckental I, Voet H, Gacitua H and Lehrer AR 1997. Increased weight gain and effects on production parameters of Holstein heifer calves that were allowed to suckle from birth to six weeks of age. Journal of Dairy Science 80, 2523–2528.

Bass J, Oldham J, Sharma M and Kambadur R 1999. Growth factors controlling muscle development. Domestic Animal Endocrinology 17, 191–197.

Bazeley KJ, Barrett DC, Williams PD and Reyher KK 2015. Measuring the growth rate of UK dairy heifers to improve future productivity. The Veterinary Journal 212, 9–14.

Blum JW 2006. Nutritional physiology of neonatal calves. Journal of Animal Physiology and Animal Nutrition 90, 1–11.

Boulton AC, Rushton J and Wathes DC 2015. The management and associated costs of rearing heifers on UK dairy farms from weaning to conception. Open Journal of Animal Sciences 5, 294–308.

Boulton AC, Rushton J and Wathes DC 2017. An empirical analysis of the cost of rearing dairy heifers from birth to first calving and the time taken to repay these costs. Animal 11, 1372–1380.

Brickell JS, Bourne N, McGowan MM and Wathes DC 2009a. Effect of growth and development during the rearing period on the subsequent fertility of nulliparous Holstein-Friesian heifers. Theriogenology 72, 408–416.

Brickell JS, McGowan MM and Wathes DC 2009b. Effect of management factors and blood metabolites during the rearing period on growth in dairy heifers on UK farms. Domestic Animal Endocrinology 36, 67–81.

Cooke JS, Cheng Z, Bourne NE and Wathes DC 2013. Association between growth rates, age at first calving and subsequent fertility, milk production and survival in Holstein-Friesian heifers. Open Journal of Animal Sciences 3, 1–12.

Correa MT, Curtis CR, Erb HN and White ME 1988. Effect of calfhood morbidity on age at first calving in New York Holstein herds. Preventive Veterinary Medicine 6, 253–262.

De Paula Vieira A, von Keyserlingk MA and Weary DM 2012. Presence of an older weaned companion influences feeding behavior and improves performance of dairy calves before and after weaning from milk. Journal of Dairy Science 95, 3218–3224.

Galyean ML, Perino LJ and Duff GC 1999. Interaction of cattle health/immunity and nutrition. Journal of Animal Science 77, 1120–1134.

Gates MC 2013. Evaluating the reproductive performance of British beef and dairy herds using national cattle movement records. Veterinary Record 173, 499.

Hepola H 2003. Milk feeding systems for dairy calves in groups: effects on feed intake, growth and health. Applied Animal Behaviour Science 80, 233–243.

Jasper J and Weary DM 2002. Effects of *ad libitum* milk intake on dairy calves. Journal of Dairy Science 85, 3054–3058.

Johnson RW 2002. The concept of sickness behavior: a brief chronological account of four key discoveries. Veterinary Immunology and Immunopathology 87, 443–450.

Khan MA, Weary DM and von Keyserlingk MAG 2011. Invited review: effects of milk ration on solid feed intake, weaning, and performance in dairy heifers. Journal of Dairy Science 94, 1071–1081.

Lin CY, Lee AJ, McAllister AJ, Batra TR, Roy GL, Vesely JA, Wauthy JM and Winter KA 1987. Intercorrelations among milk production traits and body and udder measurements in Holstein heifers. Journal of Dairy Science 70, 2385–2393.

Lorenz I, Mee JF, Earley B and More SJ 2011. Calf health from birth to weaning. I. General aspects of disease prevention. Irish Veterinary Journal 64, 10.

Lundborg GK, Svensson EC and Oltenacu PA 2005. Herd-level risk factors for infectious diseases in Swedish dairy calves aged 0-90 days. Preventive Veterinary Medicine 68, 123–143.

Manafiazar G, Goonewardene L, Miglior F, Crews DH Jr, Basarab JA, Okine E and Wang Z 2016. Genetic and phenotypic correlations among feed efficiency, production and selected conformation traits in dairy cows. Animal 10, 381–389.

McGuirk SM 2008. Disease management of dairy calves and heifers. Veterinary Clinics of North America. Food Animal Practice 24, 139–153.

Met Office 2014. UK Climate Data. Retrieved on 17 October 2015 from http://www.metoffice.gov.uk/climate/uk/summaries/2014/annual.

Moallem U, Werner D, Lehrer H, Zachut M, Livshitz L, Yakoby S and Shamay A 2010. Long-term effects of *ad libitum* whole milk prior to weaning and prepubertal protein supplementation on skeletal growth rate and first-lactation milk production. Journal of Dairy Science 93, 2639–2650.

Morrison SJ, Wicks HCF, Fallon RJ, Twigge J, Dawson LER, Wylie ARG and Carson AF 2009. Effects of feeding level and protein content of milk replacer on the performance of dairy herd replacements. Animal 3, 1570–1579.

National Research Council 2001. Nutrient requirements of dairy cattle, 7th revised edition. National Academy Press, Washington, DC, USA.

O'Driscoll K, von Keyserlingk MAG and Weary DM 2006. Effects of mixing on drinking and competitive behavior of dairy calves. Journal of Dairy Science 89, 229–233.

Quigley JD, Wolfe TA and Elsasser TH 2006. Effects of additional milk replacer feeding on calf health, growth, and selected blood metabolites in calves. Journal of Dairy Science 89, 207–216.

Raeth-Knight M, Chester-Jones H, Hayes S, Linn J, Larson R, Ziegler D and Broadwater N 2009. Impact of conventional or intensive milk replacer programs on Holstein heifer performance through six months of age and during first lactation. Journal of Dairy Science 92, 799–809.

Rawson RE, Dziuk HE, Good AL, Anderson JF, Bates DW and Ruth GR 1989. Thermal insulation of young calves exposed to cold. Canadian Journal of Veterinary Research 53, 275–278.

Relic R and Bojkovski J 2010. Housing conditions in calves welfare risk assessment. Journal of Agricultural Sciences, Belgrade 55, 283–292.

Smith JM, Van Amburgh ME, Díaz MC, Lucy MC and Bauman DE 2002. Effect of nutrient intake on the development of the somatotropic axis and its responsiveness to GH in Holstein bull calves. Journal of Animal Science 80, 1528–1537.

Soberon F, Raffrenato E, Everett RW and van Amburgh ME 2012. Preweaning milk replacer intake and effects on long-term productivity of dairy calves. Journal of Dairy Science 95, 783–793.

Scientific Veterinary Committee 1995. Report on the welfare of calves. Scientific Veterinary Committee, Animal Welfare Section, Directorate General for Agriculture, VI/BII.2, 9 November, p. 120. Brussels.

Swali A and Wathes DC 2007. Influence of primiparity on size at birth, growth, the somatotrophic axis and fertility in dairy heifers. Animal Reproduction Science 102, 122–136.

Terré M, Tejero C and Bach A 2009. Long-term effects on heifer performance of an enhanced-growth feeding programme applied during the preweaning period. Journal of Dairy Research 76, 331–339.

Virtala AM, Mechor GD, Gröhn YT and Erb HN 1996. The effect of calfhood diseases on growth of female dairy calves during the first 3 months of life in New York State. Journal of Dairy Science 79, 1040–1049.

Ware JV, Franklin ST, Jackson J, McAllister AJ and Cassell BG 2015. Genetic and environmental effects on early growth and performance in purebred Holstein, Jersey, and reciprocal crossbred calves. Journal of Dairy Science 98, 1255–1260.

Wathes DC, Pollott GE, Johnson KF, Richardson H and Cooke JS 2014. Heifer fertility and carry over consequences for lifetime production in dairy and beef cattle. Animal 8, 91–104.

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