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Association of body weight at first calving with growth, health, and reproductive performance during rearing and with subsequent milk production, health, and culling risk in dairy cows in the first and second lactation from a single commercial dairy farm

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ABSTRACT

The objective of this retrospective cohort study was to evaluate the association between body weight (**BW**) at first calving and growth, health, and reproductive performance during the rearing period, as well as subsequent milk production, calving related events, transition cow health, and culling risk in the first and second lactation in dairy cows from a single commercial dairy herd in northern Germany. The final data set consisted of 3,891 primiparous cows that calved between 2017 and 2021 and 1,894 of which were followed until their second lactation. Data were extracted from a commercial dairy herd management software system including information from 1) the heifer rearing phase: growth, calfhood morbidity and reproductive performance as nulliparous heifers and from 2) first lactation and second lactation: including age at first calving, calving related events, transition cow health, milk yield, culling risk, and growth from lactation 1 until 2. The animals were categorized into 4 quartiles based on their BW at first calving Body weight quartile 1–4 (**BW_Q1**): 394 – 564 kg (n = 1,019), **BW_Q2**: 566 – 588 kg (n = 996), **BW_Q3**: 589 – 612 kg (n = 923), **BW_Q4**: 614 – 768 kg (n = 953). Mixed effect models were used for continuous outcomes, multiple logistic regression for binary risk outcomes and Cox-proportional hazard models were used for time to event outcomes. Cows in BW_Q1 were already lighter at birth by 1.5 kg compared with cows from BW_Q4 and experienced higher pre-weaning morbidity (BW_Q1: 40.5% vs. BW_Q3: 34.3%) without showing a difference in failed transfer of passive immunity. Although lighter heifers in BW_Q1 had reduced pre-weaning growth, and therefore lower BW at weaning and at d 360 they showed better reproductive performance as nulliparous heifers, resulting in an 18-d reduction in age at conception and a 19-d reduction in age at first calving compared with heavier heifers in BW_Q4. In the first and second lactation, lighter cows had an approximately 2 kg/d lower milk production during the first 8 weeks of each lactation than heavier cows. Average daily gain in lactation 1 was significantly higher in BW_Q1 (0.359 ± 0.006 kg/d) compared with BW_Q4 (0.253 ± 0.006 kg/d) suggesting some compensatory growth. Further, in lactation 1, lighter cows from BW_Q1 had an approximately 43% greater risk for culling within 300d in milk, compared with the heavier cows from all other quartiles. Overall, body weight at first calving was associated with subsequent performance, with lighter cows producing less milk but exhibiting greater post-calving growth, while reproductive performance differed during rearing but not after calving.
Key words: Heifer rearing, Body weight, Milk yield, Reproduction, Culling

INTRODUCTION

The rearing phase of heifers is a crucial period for dairy farms, as it significantly impacts future productivity of the cow and economic outcome of the farm. The average rearing cost of replacement heifers is approximately $2,500 (Karszes and Hill, 2020). Specifically, days on feed and ultimately age at first calving (**AFC**) have a significant impact on overall heifer rearing costs.

Decreasing AFC from 25 to 21 mo resulted in decreased rearing costs by 18%, under the assumption of adequate growth relative to mature body size (**MBS**) (Tozer and Heinrichs, 2001). However, reducing AFC without tak-

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The list of standard abbreviations for JDS is available at adsa.org/jds-abbreviations-26. Nonstandard abbreviations are available in the Notes.

ing into consideration the physiological maturity of heifers will compromise milk production. Undersized heifers have a significant growth requirement during lactation, leading to nutrient partitioning to growth rather than lactation (van Amburgh et al., 1998). To ensure that reductions in AFC do not adversely affect future milk yield and animal health, the "Target Growth Concept" has become an important framework in heifer management (NASEM, 2021). This concept focuses on achieving specific developmental milestones throughout the rearing phase, to ensure that heifers are physiologically mature at the time of first calving. Body weight (**BW**) at defined ages during the rearing phase and at first calving serve as key benchmarks for optimizing heifer rearing, as they reflect physiological maturity and adequate skeletal and mammary development.

Several studies have reported positive associations between BW at defined ages and subsequent milk yield, with heifers of greater BW at first calving being associated with increased first-lactation milk yield (Fisher et al., 1983; Han et al., 2021; Lauber and Fricke, 2023), and may therefore be better prepared to meet the metabolic demands of early lactation. However, heavier heifers at first calving exhibited greater BW loss in early lactation and encountered a greater risk of culling (Han et al., 2021). Overall, BW at first calving and maturity rate were associated with first-lactation milk yield, but accounted for less than 3% of the variation in milk production (Han et al., 2021). However, these findings may have been affected by the relatively low BW at first calving (<80% of mature BW) and by the inclusion of multiple herds with differing management, nutritional, and environmental conditions.

Despite some evidence for greater milk yield, there are certain risk factors associated with an intensive rearing program and greater BW at calving. Rapid growth during heifer rearing can lead to overconditioning, which, like underconditioning, has been shown to increase the risk of dystocia among heifers (Meijering, 1983; Mee, 2004). However, research on BW at first calving and the relationship between BW and calving difficulty has yielded mixed results. One study reported that heavier calves combined with lower dam BW increased the likelihood of calving difficulty (Sieber et al., 1989). Conversely, another study observed no significant relationship between pre-calving body condition score or BW and dystocia (Berry et al., 2007). These findings underscore the complex relationship between BW, calving difficulty, and subsequent animal health outcomes in dairy cattle. There is limited evidence for an association of BW at first calving and health related disorders in lactation 1 and 2.

The objective of this retrospective cohort study was to evaluate the association between BW at first calving and growth, health, and reproductive performance during the rearing period, as well as subsequent milk production, calving related events, transition cow health, and culling risk in the first and second lactation in dairy cows from a single commercial dairy herd. Although excessively intensive growth programs may increase the risk for overconditioning and dystocia or other health disorders, greater BW at first calving does not necessarily indicate inappropriate growth management. Instead, greater BW at first calving may reflect improved physiological maturity at calving and therefore support subsequent productive performance. We hypothesized that higher body weight at first calving is associated with improved growth and reproductive performance during rearing and with increased milk production without negative effects on health or culling risk in subsequent lactations.

MATERIALS AND METHODS

An exemption from protocol review of the Institutional Animal Care and Use Committee of the Freie Universität Berlin was granted because only electronic records of the farm were used.

Dairy Farm and Animal Enrollment

This retrospective observational cohort study included data from a commercial dairy farm in Mecklenburg-Vorpommern, Germany. The final data set consisted of 3,891 primiparous cows that calved between 2017 and 2021 and 1,894 of which were followed until their second lactation. The farm holds approximately 2,500 Holstein cows with an average annual milk yield of 11,500 kg/cow.

Immediately after birth, calves were separated from their dams. The pre-weaning and weaning management were performed as previously described by Sutter et al. (2023) with all calves receiving 4L of high-quality colostrum within the first 4h after birth. During the pre-weaning period the calves had access to water from d1 of life and a calf starter from d7 (21% CP; 11.6 MJ ME / kg DM). The further feeding protocol consisted of milk feeding twice daily with whole milk and added milk replacer (Pro Elite 60, Dairytop, Beilen, the Netherlands; 24% CP, 18.5% crude fat, and 60% skim milk powder). The quantity fed was 4 L twice daily in the first week of life, 2 × 4.5 L from d 8 to d 14, 2 × 5 L from d 15 to d 21, and 2x 6 L from d 22 until 49 d of age. Afterward, the milk volume was reduced stepwise by 0.5 L in a 4 d rhythm until d 89 of life. On d 90 and 91 calves received 0.5 L of milk until weaning finally ended at 92 d of age.

Female calves aged 2 to 7 d were assessed for passive immunity by determination of TS in serum by the farm personnel. Calves with clinical signs of dehydration, such as skin tenting, sunken eyes, and delayed skin graft, were excluded from the blood testing. Blood withdrawal was performed by jugular vein puncture once a week. Blood samples were centrifuged at 4.500 × g for 6 min at approximately 20°C on the farm 1 to 2 h after collection and were directly assessed via a digital Brix refractometer (Misco PA201, Misco, Solon, OH). Calibration of the Brix refractometer was performed once a week with distilled water by the farm personnel. Transfer of passive immunity (**TPI**) was categorized according to Lombard et al. (2020) with excellent (≥9.4% Brix), good (8.9–9.3% Brix), fair (8.1–8.8% Brix), or poor TPI (<8.1% Brix).

Calves were considered clinically healthy when visible signs of disease were not observed. Appearance of disease was monitored once daily by the farm personnel using the calf health scoring chart created by the University of Wisconsin. The chart applies validated methods for fecal scoring (McGuirk, 2008), respiratory screening (McGuirk and Peek, 2014), and detection of omphalitis. Farm personnel were trained to assess clinical signs and apply treatments according to veterinarian's instructions. Neonatal diarrhea was defined as visibly loose feces of decreased consistency (Renaud et al., 2020). Pneumonia was defined as visibly detectable tachypnea with nasal discharge (serous, mucous, or purulent) and presence of cough (McGuirk, 2005). Omphalitis was present when a combination of several signs was observed: clinical signs (redness, swelling, purulent discharge, painful response to palpation) in addition to fever (>39.5°C) or lack of appetence (Fordyce et al., 2018). Only cases of disease associated with treatment were included in the statistical analysis. Cases of diarrhea were treated once daily for 3 d with 1.25 mg/ kg i.m. danofloxacin (Advocid, Zoetis GmbH, Berlin, Germany). Cases of pneumonia were treated with a single administration of 2.5 mg/kg i.m. tulathromycin (Draxxin, Zoetis GmbH, Berlin, Germany), and cases of omphalitis were treated once daily for 3 d with 15–20 mg i.m. procaine benzylpenicillin (Procain Penicillin G, AniMedica International GmbH, Frankfurt, Germany).

In the third week of life, female calves were reallocated into 35 m^2 group housing pens (10 calves/pen) until weaning (d 92). Each group was fed via a calf group feeder equipped with 10 teats (Milk Bar 10, Milk Bar, Oldenburg, Germany). During group housing the calves had access to dry total mixed ration (**TMR**) consisting of a mixture of concentrate, chopped straw, soy meal, molasses and chalk. Weighing was performed directly after birth and at d 60 with an electronic scale (WA200 mobile platform scale, Meier-Brakenberg GmbH & Co. KG, Extertal, Germany). After weaning, all heifers were managed together in free stall pens, grouped according to age and reproductive status. Heifers were fed a TMR based on corn and grass silage following the nutrient requirements of dairy cattle (NASEM, 2021) guidelines.

Heifers were weighed on a monthly basis, starting at 10 mo of age using a walk over scale (Tru-Test EziWeigh, Datamars) and artificially inseminated by trained farm staff once they reached 12 mo of age and weighed more than 400 kg. Further measures, such as BCS or body height were not recorded.

Estrus detection was facilitated by the use of tail chalking. Heifers were observed daily for signs of estrus based on removal of the tail chalk. In cases of no estrus detection for 3 weeks via tail chalk method, the heifers' cycle was ultrasonographically evaluated. Heifers with at least one corpus luteum (**CL**) ≥ 15 mm received a $PGF_{2\alpha}$ (Cloprostenol; PGF Veyx® forte, 0.250 mg/mL; Veyx-Pharma GmbH; Schwarzenborn, Germany) treatment. Heifers that did not meet the criteria to be included in the CL group received a modified 5-d Cosynch protocol (i.e., 2 $PGF_{2\alpha}$ treatments) with progesterone (P4) supplementation through an intravaginal P4-releasing device (CIDR; 1.38 g of progesterone, Eazi-Breed CIDR, Zoetis, Florham Park, NJ) from d 0 until d5. Pregnancy was confirmed via rectal ultrasonography 32 ± 3 d after insemination by the farm personal. A second pregnancy diagnosis was performed 60 ± 3 d after AI. Sex sorted Holstein semen was used for first and second insemination. In cases of no confirmed pregnancy after 2 AIs the third and fourth insemination was performed with conventional Holstein semen. Heifers that failed to conceive after the fourth insemination were considered "do not breed."

Pregnant heifers were moved once weekly to the close-up pen at d 255.7 ± 4.5 (SD) of gestation. Nulliparous and parous cows were kept separately in sand-bedded freestall pens during the close-up period. Prepartum heifers were monitored every hour to detect signs of imminent parturition (i.e., restlessness, vaginal discharge with bloody traces, lying lateral with abdominal contractions, a visible or broken amniotic sac, or feet of the emerging calf outside the vulva). Animals were moved into an individual maternity pen (3.5 × 3.5 m) bedded with fresh straw when the amniotic sac was visible or broken outside the vulva, or appearance of feet of the emerging calf were detected outside the vulva. If the cow had not delivered the calf within 1 h calving assistance was provided (Schuenemann et al., 2011). Intensity of calving assistance was recorded on a 4-point scale (1 = no assistance; 2 = assistance by 1 person; 3 = assistance by at least 2 persons; 4 = cesarean section). A detailed description of the calving management and the first milking after calving has been described previously (Sutter et al., 2019).

After parturition cows were weighed using a scale mounted under the chute (Tru-Test EziWeigh, Datamars), and colostrum was collected for each cow separately. The first 20 d after parturition cows were milked thrice daily in a separate side-by-side milking parlor before milking was performed in 2 24 places side-by-side milking parlors. Postpartum cows were examined daily by the farm personnel until 10 d in milk (**DIM**) following standard operating procedures, described in detail previously (Venjakob et al., 2021). Vulvovaginal lacerations (**VL**) were assessed using the scoring system developed by Vieira-Neto et al. (2016) at d 2: VLS0 = no laceration; VLS1 = laceration less than 2 cm at dorsal commissure of the vulva or at the lateral walls of the vulva/vagina, or both; VLS2 = laceration greater than 2 cm at dorsal commissure of the vulva or at the lateral walls of the vulva/vagina, or both. Early postpartum diseases were defined as retained fetal membranes (**RFM**) when fetal membranes were not expelled by 24 h after calving, and puerperal metritis (**PM**) as signs of systemic illness (e.g., decreased milk production, dullness, or other signs of toxemia) in combination with an abnormally enlarged uterus, fetid watery red-brown uterine discharge and fever > 39.5°C (Sheldon et al., 2006). Between 11 and 30 DIM cows were screened for health disorders based on visual observations performed by the farm personnel every morning at 8 a.m. and on deviations in their daily milk production. If cows left the study due to culling, reasons for culling were classified according to the coding system described by Fetrow et al. (2006).

Reproductive Management

Lactating cows were enrolled in a Double-Ovsynch protocol at 45 ± 3 DIM with timed artificial insemination (**TAI**) at 72 ± 3 DIM. The protocol consisted of GnRH (Gonadorelin acetate; Gonavet Veyx ®0.05 mg/mL; Veyx-Pharma GmbH, Schwarzenborn, Germany), followed 7 d later by $PGF_{2\alpha}$, 3 d later by GnRH, 7 d later by GnRH, 7 d later by $PGF_{2\alpha}$, 24 h later by $PGF_{2\alpha}$, 32 h later by GnRH, and TAI 16 to 18 h later at 72 ± 3 DIM (Souza et al., 2008). A combination of sex sorted Holstein semen and Angus semen was used for first TAI. In subsequent inseminations only Angus semen were used. At 25 d after AI, all cows received a GnRH treatment. Seven days later at 32 d after AI, cows underwent pregnancy diagnosis through transrectal ultrasound examination (Easi-Scan:GO, IMV Imaging, Bellshill, Scotland). Open cows with at least one corpus luteum (**CL**) ≥ 15 mm received a $PGF_{2\alpha}$ treatment, a second $PGF_{2\alpha}$ 24 h later, GnRH 32 h after the second $PGF_{2\alpha}$, and TAI 16 to 18 h later. Cows that did not meet the criteria to be included in the CL group received a modified Ovsynch protocol (i.e., 2 $PGF_{2\alpha}$ treatments) with progesterone (P4) supplementation through an intravaginal P4-releasing device (CIDR; 1.38 g of progesterone, Eazi-Breed CIDR, Zoetis, Florham Park, NJ) from the time of the first GnRH to the first $PGF_{2\alpha}$ treatment of the protocol (GnRH and CIDR inserted, 7 d later CIDR removal and $PGF_{2\alpha}$, 24 h later $PGF_{2\alpha}$, 32 h later GnRH, and 16 to 18 h later TAI; Pérez et al., 2020). All pregnancy diagnoses were conducted by trained farm personnel. A second pregnancy diagnosis was performed 60 d after AI.

Statistical Analyses

Individual cow data from primiparous and secundiparous cows that calved between January 2017 and December 2021 were transferred from Dairy Comp 305 (Valley Ag Software, Tulare, CA) to Microsoft Excel (Office 2013, Microsoft Deutschland Ltd., Munich, Germany). Statistical analyses were performed using SPSS for Windows (version 25.0, SPSS Inc., Chicago, IL).

According to their BW at first calving, 3,891 primiparous cows were categorized into 4 quartiles, body weight quartile 1–4 (**BW_Q1**): 394 – 564 kg (n = 1,019), **BW_Q2**: 566 – 588 kg (n = 996), **BW_Q3**: 589 – 612 kg (n = 923), **BW_Q4**: 614 – 768 kg (n = 953). We had complete data from 1,894 cows in second lactation. In total, 1,206 cows were culled in the first lactation and 791 cows had missing BW data at second calving. A flowchart regarding follow-up losses is depicted in Figure 1.

Normality of continuous outcome variables was evaluated by visual inspection of histograms and quantile–quantile (Q–Q) plots, in combination with the Shapiro–Wilk test. Variables that deviated strongly from normality were log-transformed or analyzed using non-parametric methods as appropriate. Differences in continuous data among quartiles were analyzed using ANOVA (GENLINMIXED procedure of SPSS) with a model that included the fixed effect of BW quartile. Cow was the experimental unit. Data are presented as the least squares means ± standard error of the mean (**SEM**). To account for multiple comparisons, the *P*-value was adjusted using a Bonferroni correction. Variables were declared significant when $P < 0.050$.

Categorical outcomes, including binary variables (e.g., stillbirth, dystocia) and multi-category variables (e.g., FTPI), were compared between groups using Pearson's chi-squared test.

Repeated measures ANOVA with first-order autoregressive covariance (GENLINMIXED procedure of SPSS) was performed to analyze the association of BW at first calving and weekly milk production during the first 8 wk of lactation. Cow was considered the experimental unit. Early lactation was selected a priori as the primary period of interest because differences in nutrient partitioning between growth and milk production are expected to be most pronounced during this biologically demanding phase, particularly in lighter, primiparous cows. In addition, evaluation of early lactation milk yield minimized potential bias associated with culling,

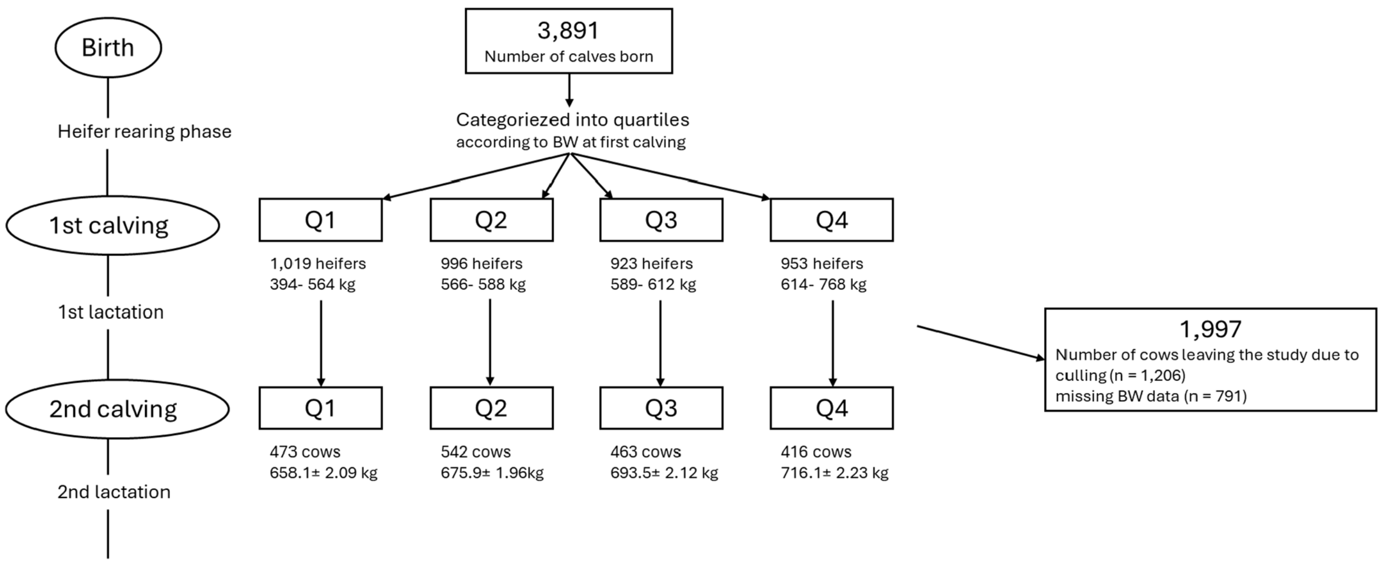

Figure 1. Flow diagram of the number of cows included in this study.

pregnancy status, dry-off timing, and incomplete lactation records later in lactation.

As described by Dohoo et al. (2009) each variable considered for the mixed model was analyzed in a univariate model, including the variable as a fixed factor (i.e., categorical variable) or covariate (i.e., continuous variable). Two separate models were calculated for lactation 1 and 2. The final mixed model included all variables resulting in univariate models with $P \leq 0.100$. Selection of the model that best fit the data was performed by using a backward stepwise elimination procedure that removed all variables with $P > 0.10$ from the model.

We included age at first calving, year of calving (2017 to 2021), season of calving (winter from 1st of December to 28th of February, spring from 1st of March to 31st of May, summer from 1st of June to 31st of August, and autumn from 1st of September to 30th of November), wk after calving (wk 2, 4, 6, 8), and BW at first calving (Quartile 1 - 4) as explanatory variables, as well as the interaction of wk after calving and BW at first calving.

To provide additional descriptive information regarding milk production patterns across the entire lactation, weekly milk yield from wk 5 to 50 of first lactation was additionally analyzed using a repeated-measures model as described above.

Using the SURVIVAL procedure of SPSS, 2 different Cox proportional hazards were calculated to model the time from calving to culling (i.e., culling or death during the first 300 DIM) for cows in lactation 1 and 2. The variables year of calving, season of calving, BW at first calving were tested as risk factors. Adjusted survival curves were generated from the Cox proportional hazards regression model, based on the covariates included in the final model. The proportional hazard assumption was checked using Schoenfeld residuals.

RESULTS

Heifer rearing

The following section describes the health and performance data from birth to first calving. Therefore, the terms “calves” and “heifers” are used to describe the results. However, the classification into different BW quartiles (**BW_Q1 - 4**) was based on BW at first calving.

Pre- weaning period. The records of 3,891 female dairy calves were analyzed for this study. Descriptive data, including analyzed statistics from the heifer rearing phase are summarized in Table 2. There was an association of the dam’s birth weight with their BW at first calving (P = 0.001). Cows in BW_Q1 had lower birth weights as calves compared with all other quartiles, while cows in BW_Q4 had the greatest birth weight (P = 0.001). BW at first calving was associated with preweaning ADG (P = 0.001) and BW at d 60 (P = 0.001). Calves in BW_Q1 and BW_Q2 had reduced pre-weaning ADG compared with calves in BW_Q3 and BW_Q4. Calves in BW_Q4 had the greatest BW at weaning compared with all other groups (P = 0.001). There was no association of BW at first calving and the proportion of calves within the different TPI categories (P = 0.699). Calves from BW_Q1 and BW_Q2 showed a greater incidence of pre-weaning diarrhea (P = 0.007) than calves from BW_Q4. Calves from BW_Q2 showed a greater incidence of pre-weaning pneumonia (P = 0.007), than calves from BW_Q3.

There was no significant association between BW at first calving and the incidence of omphalitis ($P = 0.860$).

Pre- breeding and breeding period. Body weight at first calving was associated with pre-breeding BW ($P = 0.001$; Table 2). Nulliparous heifers from BW_Q4 had the highest pre-breeding BW. Body weight in all quartiles differed from each other before the first AI ($P = 0.001$). Age at first insemination in nulliparous heifers was associated with the BW quartile ($P = 0.022$). The heifers were first inseminated at an average age of 368 d. Nulliparous heifers from BW_Q1 were approximately 4 d older at first insemination than nulliparous heifers from BW_Q3. Pregnancy per AI (**P/AI**) at first service was associated with the BW quartile ($P = 0.001$). Nulliparous heifers in BW_Q1 had greater P/AI compared with the other BW quartiles ($P = 0.001$). Pregnancy loss at first service was associated with the BW quartile ($P = 0.001$). Nulliparous heifers in BW_Q1, BW_Q2 and BW_Q3 had reduced pregnancy losses than nulliparous heifers from BW_Q4 ($P = 0.001$). Consequently, a large difference among BW quartiles was observed in age at conception. Nulliparous heifers from BW_Q1, BW_Q2 and BW_Q3 were significantly younger at conception than heifers from BW_Q4 ($P = 0.001$). The number of nulliparous heifers from BW_Q4 which needed more than 3 inseminations before conceiving was 35%. In comparison only 8.3% of heifers from BW_Q1 needed more than 3 inseminations. Nulliparous heifers from BW_Q1, BW_Q2 and BW_Q3 had a lower AFC with approximately 652–655 d, compared with heifers from BW_Q4 which calved at 671 ± 1.18 d of age ($P = 0.001$). Descriptive statistics for BW at first calving across AFC categories are provided in Table 1.

Lactation 1

Descriptive data including statistical analyzes from the first lactation phase for calving related events are summarized in Table 3.

Calves. There was an association between the dam's BW at first calving and the sex of the calf ($P = 0.001$; Table 3). The lighter primiparous cows from BW_Q1, BW_Q2, and BW_Q3 had a greater proportion of female calves, compared with heavier cows from BW_Q4. The proportion of twin births was highest among the lightest primiparous cows from BW_Q1 and lowest in cows from BW_Q4 ($P = 0.001$). After accounting for the sex of the calf, there was an association between the dams' BW at first calving and the BW of the calf at birth for singletons. Lighter dams in BW_Q1 delivered smaller female and male calves compared with all other quartiles ($P = 0.001$). Male calves that were born from cows in BW_Q4 were heavier compared with all other quartiles ($P < 0.05$). There was an association between the ratio of the calves' birth weight and the dams' BW at first calving ($P = 0.001$). Lighter primiparous cows from BW_Q1 had calves that were heavier relative to their BW (7.2%) compared with heavier cows from BW_Q4. The heavier cows from BW_Q4 had lighter calves relative to their BW (6.3%).

Gestation and birth. There was an association of the dam's BW at first calving and gestation length (Table 3). The gestation length of the lightest primiparous cows in BW_Q1 was shorter than the gestation length of the heavier cows in BW_Q3 and BW_Q4 ($P = 0.001$). There was no association between the BW at first calving and the occurrence of calving related events, including stillbirth ($P = 0.104$; Table 3), dystocia ($P = 0.849$; Table 3), or VLS ($P = 0.292$; Table 3). However, there was an association between BW quartile and the incidence of retained fetal membranes ($P = 0.006$) and metritis ($P = 0.002$). The incidence of retained fetal membranes after calving, was highest in BW_Q1 and lowest in BW_Q3. The incidence of metritis was greater in BW_Q1 compared with BW_Q3 and BW_Q4.

Milk production. Milk production within the first 8 weeks of lactation 1 was associated with the BW quartile ($P = 0.001$), time ($P = 0.001$), and showed an interaction between quartile x time ($P = 0.001$; Figure 2). Overall, primiparous cows in BW_Q1 (30.8 ± 0.16 kg/d) produced less milk compared with all other quartiles ($P < 0.001$; BW_Q2 32.0 ± 0.15 kg/d; BQ_Q3 32.3 ± 0.16 kg/d; BW_Q4 33.3 ± 0.16 kg/d). Milk production increased ($P = 0.001$) from wk 2 (26.3 ± 0.08 kg/d), 4 (32.1 ± 0.09 kg/d), 6 (34.5 ± 0.10 kg/d), and 8 (35.5 ± 0.10 kg/d) of lactation.

To complete the early-lactation analyses, weekly milk yield across wk 5–50 of first lactation was evaluated by BW quartile at first calving (Figure 5). Milk yield was associated with week of lactation ($P < 0.001$) and BW quartile ($P < 0.001$), whereas the association between week of lactation and BW quartile only tended to be significant ($P = 0.08$).

Across the entire lactation, cows in the heaviest body weight quartile (Q4) produced more milk than cows in the lightest quartile (BW_Q4 36.1 ± 0.35 vs. BW_Q1 34.1 ± 0.37 kg/d; $P < 0.001$). Estimated marginal means

Table 1. Descriptive statistics of body weight (BW) at first calving according to age at first calving (AFC) category

AFC Category, month	n	BW, kg	Min	Max
<20	248	578	394	672
20	1,022	583	415	720
21	1,308	585	451	720
22	787	592	440	756
23	357	600	472	699
>24	169	611	470	768

Table 2. Descriptive data from birth to first calving

Item[1]	Body weight at first calving Q1	Q2	Q3	Q4
Number of cows	1,019	996	923	953
Birth weight, kg	38.0 ± 0.14[a]	38.7 ± 0.14[b]	38.7 ± 0.14[b]	39.5 ± 0.14[c]
Gestation length, d	275 ± 0.17	275 ± 0.17	275 ± 0.17	275 ± 0.17
FTPI, %				
Excellent	52.7	52.2	53.2	54.3
Good	22.9	22.5	22.5	22.6
Fair	19.6	19.7	19.8	18.0
Poor	4.8	5.7	4.4	5.0
BW at d 60, kg	100.4 ± 0.5[a]	101.6 ± 0.5[ab]	102.0 ± 0.5[b]	103.6 ± 0.5[c]
ADG pre-weaning, kg/d	1.00 ± 0.01[a]	1.01 ± 0.01[a]	1.03 ± 0.01[b]	1.05 ± 0.01[b]
Morbidity pre-weaning, %	40.5[a]	41.8[a]	33.9[b]	34.3[b]
Diarrhea, %	7.0[a]	7.5[a]	5.5[a, b]	4.1[b]
Pneumonia, %	35.7[a, b]	36.8[b]	30.6[a]	31.6[a, b]
Omphalitis, %	0.9	1.2	1.1	1.3
BW at d 360, kg	390.0 ± 0.6[a]	393.4 ± 0.6[b]	395.7 ± 0.6[c]	399.3 ± 0.6[d]
Age at 1st AI, d	370 ± 0.90[a]	369 ± 0.91[a, b]	366 ± 0.94[b]	367 ± 0.93[a, b]
P/AI 1st AI 32d, %	76.8[a]	70.2[b]	62.2[c]	39.1[d]
P/AI 1st AI 60d, %	76.3[a]	69.6[b]	61.4[c]	37.1[d]
Pregnancy loss, %	0.8[a]	0.9[a]	1.4[a]	5.1[b]
Semen type at conception, %				
Gender sorted Holstein	70.2	72.4	71.7	67.1
Conventional Holstein	29.8	27.6	28.3	32.9
Age at conception, d	377 ± 1.14[a]	379 ± 1.15[a]	380 ± 1.20[a]	395 ± 1.18[b]
Number of AI, %				
1	75.0[a]	69.1[b]	59.5[c]	36.7[d]
2	16.7[a]	19.5[a]	24.9[b]	28.3[b]
≥3	8.3[a]	11.4[a]	15.6[b]	35.0[c]
Age at 1st calving, d	652 ± 1.14[a]	654 ± 1.15[a]	655 ± 1.20[a]	671 ± 1.18[b]
Body weight at calving, kg	542 ± 0.50[a]	577 ± 0.51[b]	600 ± 0.53[c]	637 ± 0.52[d]

Data are presented as the least squares means ± standard error of the mean (**SEM**).

[1]Values with different letters (a–d) differed significantly.

FTPI: Failed transfer of passive immunity (excellent: ≥ 9.4% Brix; good: 8.9–9.3% Brix; fair: 8.1–8.8% Brix; poor: < 8.1% Brix; Lombard et al., 2020).

ADG: Average daily gain.

AI: artificial insemination.

P/AI 1st AI 32d: Pregnancy check 32d after first insemination per AI.

P/AI 1st AI 60d: Pregnancy check 60d after first insemination per AI.

Number of AI: Number of AI needed before pregnant.

for BW_Q2 and BW_Q3 were 34.9 ± 0.36 and 35.5 ± 0.39 kg/d, respectively. There tended to be a difference between BW_Q1 vs. BW_Q3 (P = 0.072), BW_Q2 vs. BW_Q4 (P = 0.082). All remaining comparisons were not significant (P > 0.1). All BW quartiles followed a similar lactation curve, with peak milk yield occurring around wk 10, followed by a gradual decline toward wk 50 (Figure 5). Differences between BW quartiles were most pronounced during early and mid-lactation (wk 10–30), when cows in BW_Q4 produced approximately 2.0 to 2.5 kg/d more milk than cows in BW_Q1. Toward the end of lactation, milk yield differences between BW quartiles decreased.

Milk yield in lactation 1 at d 305 of lactation was associated with the body weight quartile (P < 0.001). Cows from BW_Q1 (9,458 ± 55 kg) had a significantly lower 305 d milk yield than cows in BW_Q2–4. Cows in BW_Q2 (9,805 ± 51 kg) and BW_Q3 (9,793 ± 53 kg) did not differ from each other in their 305 d milk yield, while BW_Q4 (10,068 ± 59 kg) cows had the greatest milk production in lactation 1.

Breeding in the 1st lactation. There was no association between P/AI at first service and the BW quartile at d 32 (P = 0.432) or d 60 (P = 0.176; Table 3) post AI. However, there was an association between pregnancy loss at first service and the BW quartile (P = 0.050; Table 3). The proportion of pregnancy losses was greater among cows in BW_Q1 compared with cows from BW_Q2. The proportion of semen type that resulted in a pregnancy did not differ (P > 0.100) among body quartiles (BW_Q1: conventional Holstein semen 4.2%; sex sorted Holstein semen 46.1%; Angus semen 49.7%; BW_Q2: 2.8%; 53.7%; 43.5%; BW_Q3: 4.1%; 52.7%; 43.2%; BW_Q4: 3.1%; 56.3%; 40.6%).

Table 3. Descriptive data for calving related events in lactation 1

Item[1]	Body weight at first calving Q1	Q2	Q3	Q4
Number of cows	1,019	996	923	953
Number and sex of the calves, %				
Singleton Female	85.4^{a}	88.5^{a}	88.1^{a}	80.5^{b}
Singleton Male	13.1^{a}	11.0^{a}	11.5^{a}	19.4^{b}
Twins	1.5^{a}	0.5$^{a, b}$	0.4$^{a, b}$	0.1^{b}
Weight of the calf, kg				
Singleton Female	39.2 ± 0.16^{a}	39.8 ± 0.16^{b}	39.8 ± 0.17^{b}	39.9 ± 0.17^{b}
Singleton Male	40.2 ± 0.42^{a}	40.8 ± 0.47$^{a, b}$	40.8 ± 0.47$^{a, b}$	42.0 ± 0.36^{b}
Ratio of calf weight over cow weight, %	7.2 ± 0.03^{a}	6.9 ± 0.03^{b}	6.6 ± 0.03^{c}	6.3 ± 0.03^{d}
Gestation length, d	274.5 ± 0.14^{a}	275.0 ± 0.14$^{a, b}$	275.3 ± 0.14^{b}	275.5 ± 0.14^{b}
Stillbirth, %	3.9	3.6	2.7	2.2
Dystocia, %	22.0	21.0	21.7	20.5
VLS, %				
Score 0	10.1	9.3	11.4	13.4
Score 1	24.1	26.6	25.3	23.6
Score 2	65.8	64.1	63.3	63.3
Retained fetal membranes, %	3.7^{a}	2.3$^{a, b}$	1.3^{b}	2.3$^{a, b}$
Metritis, %	10.5^{a}	8.1$^{a, b}$	6.8^{b}	6.2^{b}
305 d milk yield, kg	9,458 ± 54.9^{a}	9,805 ± 50.7^{b}	9,793 ± 53.3^{b}	10,068 ± 58.5^{c}

Data are presented as the least squares means ± standard error of the mean (**SEM**).

[1]Values with different letters (a–d) differed significantly.

VLS: Vulvovaginal laceration score (0 = no laceration; 1 = laceration less than 2 cm at dorsal commissure of the vulva or at the lateral walls of the vulva/vagina, or both; 2 = laceration greater than 2 cm at dorsal commissure of the vulva or at the lateral walls of the vulva/vagina, or both; Vieira-Neto et al., 2016).

Culling. BW at first calving was associated with culling risk in the first lactation (P = 0.001; Figure 3). Compared with primiparous cows in BW_Q1 there was a reduced hazard risk for culling for cows in BW_Q2 (HR = 0.562; 95% CI 0.475 – 0.665; P = 0.001); BW_Q3 (HR = 0.614; 95% CI 0.518 – 0.727; P = 0.001), and BW_Q4 (HR = 0.524; 95% CI 0.438 – 0.626; P = 0.001). Culling reasons differed among the quartiles (P = 0.001). The number of cows being sold for dairy purpose was highest in BW_Q1 (27.6%) compared with all other quartiles (BW_Q2: 16.1%; BW_Q3: 17.5%; BW_Q4: 12.0%).

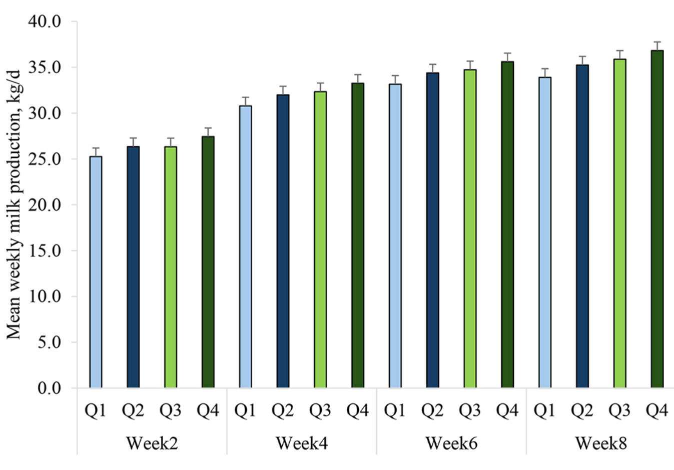

Figure 2. Mean (±SEM) weekly milk production (kg/d) at wk 2, 4, 6 and 8 of lactation of primiparous Holstein cows based on their body weight at first calving. Cows were categorized into 4 quartiles based on their body weight at first calving: BW_Q1(light blue): 394 – 564 kg; BW_Q2 (dark blue): 566 – 588 kg; BW_Q3 (light green): 589 – 612 kg; BW_Q4 (dark green): 614 – 768 kg. Least square estimates were derived from multivariable models accounting for age at first calving, year, and season of calving.

Lactation 2

Descriptive data including statistical analyzes from the second lactation for calving related events are summarized in Table 4.

Age and weight. There was an association of the secundiparous cows' age at second calving and BW quartile at first calving (P = 0.001; Table 4). Heavier cows from BW_Q4 were older than the cows from all other quartiles. There was an association of BW quartile at first calving and BW at second calving (P = 0.001; Table 4). Secundiparous cows from all quartiles differed from each other. Cows from BW_Q1 were lightest and cows from BW_Q4 were heaviest at second calving. Weight gain from first to second calving differed among all the quartiles (P = 0.001; Table 4). Cows from BW_Q1 gained 114.54 ± 2.03 kg within the first lactation. Cows from BW_Q4 had the lowest weight gain within the first lactation with 80.32 ± 2.17 kg. Consequently, there was an association between BW quartile at first calving and ADG within the first lactation (P = 0.001; Table 4). Cows from BW_Q1 had the highest average daily weight gain, compared with cows from BW_Q4.

Calves. There was an association between the dams' BW at first calving and sex of the calves at second calving (P = 0.020; Table 4). The proportion of female calves differed between BW_Q1 (66%) and BW_Q3 (73.7%). There was no difference between all other quartiles. The number of twin births was highest among secundiparous cows in BW_Q3 and lowest in cows from BW_Q4 (P = 0.005; Table 4). After accounting for the sex of the calf, there was no association between the dam's BW at first calving and BW of the calf at second calving (P = 0.680). There was an association between the ratio of the calves' birth weight and the dams' BW at second calving (P = 0.001; Table 4). Lighter secundiparous cows from BW_Q1 had calves that were heavier relative to their BW compared with heavier cows from all other quartiles that had lighter calves relative to their BW.

Gestation and birth. There was no association of the dam's BW at calving and gestation length (P = 0.648; Table 4). There was no association between the BW at first calving and the occurrence of calving related events, including stillbirth (P = 0.593; Table 4), dystocia (P = 0.374; Table 4), vaginal lacerations (P = 0.807; Table 4) or retained fetal membranes (P = 0.264; Table 4). However, there was an association between the incidence of metritis and BW quartile (P = 0.016). Cows from BW_Q3 showed the highest incidence for metritis compared with cows from the other BW quartiles (P = 0.016; Table 4).

Milk production. Milk production within the first 8 weeks of lactation 2 was associated with the BW quartile (P = 0.001) and time (P = 0.001). There was no interaction between quartile x time (P = 0.928; Figure 4). Overall, cows in BW_Q1 (44.4 ± 0.26 kg/d) produced less milk compared with all other quartiles (P = 0.001; BW_Q2 45.2 ± 0.25 kg/d; BQ_Q3 45.6 ± 0.27 kg/d; BW_Q4 46.4 ± 0.29 kg/d). There was no difference in milk production within the first 8 weeks between BW_Q2 and BW_Q3 (P = 1.000) and between BW_Q3 and BW_Q4 (P = 0.350). Cows in BW_Q2 differed from BW_Q4 (P = 0.012). Milk production increased (P = 0.001) from wk 2 (38.4 ± 0.13 kg/d), 4 (46.4 ± 0.17 kg/d), 6 (48.5 ± 0.17 kg/d), and 8 (48.3 ± 0.19 kg/d) of lactation.

Milk yield in lactation 2 at d 305 of lactation was not significantly associated with the body weight quartile (P = 0.091; Table 4). Nevertheless, adjusted least squares means indicated a numerical increase in milk yield among heavier cows. Specifically, lightest cows (BW_Q1) produced 11,797 ± 91.8 kg, whereas cows in BW_Q2, BW_Q3, and BW_Q4 produced 11,932 ± 84.8 kg, 11,996 ± 92.4 kg, and 12,107 ± 98.0 kg, respectively (all values adjusted to the mean AFC). This corresponds to an overall numerical difference of approximately 310 kg between BW_Q1 and BW_Q4.

Breeding in the 2nd lactation. There was no association between BW quartile and P/AI at first service d 32 (P = 0.809) and d 60 (P = 0.982; Table 4). In addition, pregnancy loss at first service was equally not associated with the BW quartile (P = 0.524).

Culling. Body weight at first calving was not associated with culling risk in the second lactation (P = 0.348). Culling reason did not differ among the different quartiles (P = 0.538).

DISCUSSION

The overall objective of this retrospective cohort study was to determine the association between BW at first calving with milk production, calving related events and transition cow health in in the first and second lactation from a commercial dairy herd.

The main findings of the present study were the following: (1) Cows that were lighter at their first calving, were lighter in body weight at birth; (2) Lighter cows had a greater pre-weaning morbidity, but did not show a difference in the proportion of calves with failed transfer of passive immunity (**FTPI**) in their group compared with heavier cows; (3) Lighter cows had a better reproductive performance when they were heifers compared with heavier cows; (4) Lighter cows showed reduced milk production in the first and second lactation compared with heavier cows; (5) Lighter cows had a greater risk of being culled in lactation 1 compared with heavier cows.

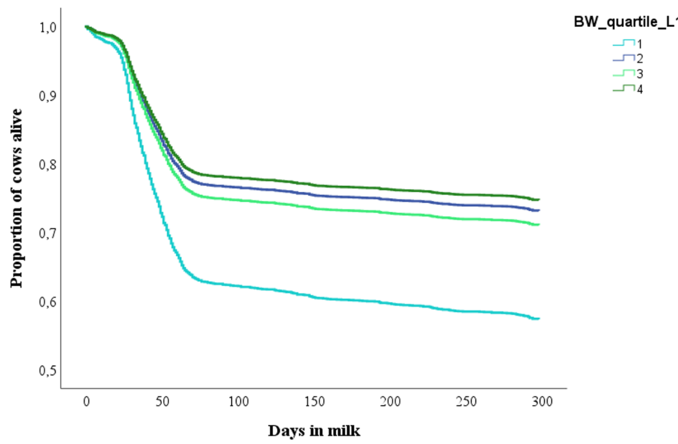

Figure 3. Probability of culling in the first lactation based on body weight at calving. Cows were categorized into 4 quartiles based on their body weight at first calving: BW_Q1 (light blue): 394 – 564 kg; BW_Q2 (dark blue): 566 – 588 kg; BW_Q3 (light green): 589 – 612 kg; BW_Q4 (dark green): 614 – 768 kg. Compared with primiparous cows in BW_Q1 there was a reduced hazard risk for culling for cows in BW_Q2 (HR = 0.562; 95% CI 0.475 – 0.665; P = 0.001); BW_Q3 (HR = 0.614; 95% CI 0.518 – 0.727; P = 0.001), and BW_Q4 (HR = 0.524; 95% CI 0.438 – 0.626; P = 0.001).

Heifer rearing

Birth weight was positively associated with BW at first calving, which agrees with a previous study from Coffey et al. (2006) who included 625 animals from a research farm in UK and detected a moderate correlation between BW at birth with BW at first calving, phenotypically (r = 0.25) and genotypically (r = 0.50). In a large data set including 57,868 birth weight records from German Holstein cows, genetic and phenotypic correlations between calf birth weight with either cow test-day traits and cow health traits, or with female fertility traits from heifers, were close to zero (Yin and König, 2018).

The overall pre-weaning morbidity (i.e., diarrhea, pneumonia, omphalitis) was 38.0% in our study, which is comparable to a cross-sectional study performed in Germany (Dachrodt et al., 2021) with an overall morbidity of 42.0% in pre-weaned dairy calves from 731 herds. However, these authors described a higher prevalence for diarrhea (18.5%) and omphalitis (20.9%) and a lower prevalence for respiratory disease (8.7%). While the overall morbidity among these 2 studies seems similar there might be a discrepancy in the definition of certain diseases. While we used disease records from a commercial dairy farm, disease incidences in Dachrodt et al.

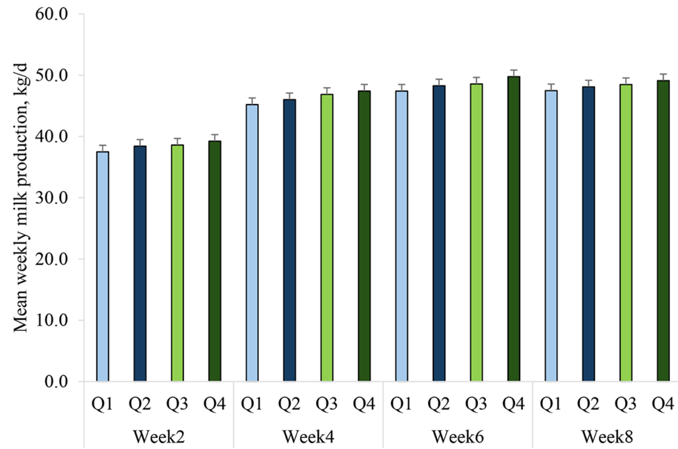

Figure 4. Mean (±SEM) weekly milk production (kg/d) at wk 2, 4, 6 and 8 of lactation of secundiparous Holstein cows based on their body weight at first calving. Cows were categorized into 4 quartiles based on their body weight at first calving: BW_Q1 (light blue): 394 – 564 kg; BW_Q2 (dark blue): 566 – 588 kg; BW_Q3 (light green): 589 – 612 kg; BW_Q4 (dark green): 614 – 768 kg. Least square estimates were derived from multivariable models accounting for age at first calving, year, and season of calving.

Table 4. Descriptive data for calving related events in lactation 2

	Body weight at first calving			
Item[1]	Q1	Q2	Q3	Q4
Number of cows	473	542	463	416
Age at second calving, d	1,031.24 ± 2.56[a]	1,030.87 ± 2.34[a]	1,031.19 ± 2.58[a]	1047.075 ± 2.73[b]
Body weight at second calving, kg	658.1 ± 2.09[a]	675.9 ± 1.96[b]	693.5 ± 2.12[c]	716.1 ± 2.23[d]
[2]Weight gain in lactation 1, kg	114.54 ± 2.03[a]	98.46 ± 1.9[b]	93.03 ± 2.05[b]	80.32 ± 2.17[c]
Average daily gain in lactation 1, kg/d	0.359 ± 0.006[a]	0.311 ± 0.006[b]	0.293 ± 0.006[b]	0.253 ± 0.006[c]
Number and sex of the calves, %				
Singleton Female	66.0	72.1	73.7	73.3
Singleton Male	33.3[a]	26.4[a, b]	24.6[b]	26.7[a, b]
Twins	0.6[a, b]	1.5[a, b]	1.7[b]	0.0[a]
Weight of the calf, kg				
Singleton Female	40.4 ± 0.26	40.9 ± 0.26	40.7 ± 0.28	41.1 ± 0.29
Singleton Male	44.3 ± 0.8	43.4 ± 0.9	44.5 ± 1	43.8 ± 1
Ratio of calf weight over cow weight, %	6.4 ± 0.04[a]	6.2 ± 0.04[b]	6.0 ± 0.04[b, c]	5.9 ± 0.04[c]
Gestation length, d	276.4 ± 0.23	276.4 ± 0.21	276.6 ± 0.23	276.8 ± 0.24
Stillbirth, %	0.4	1.1	1.1	1.2
Dystocia, %	16.9	13.1	14.3	14.2
Vulvovaginal laceration, %				
Score 0	26.2	30.3	29.8	30.8
Score 1	37.1	34.7	35.8	34
Score 2	36.7	34.9	34.5	35.2
Retained fetal membranes, %	5.5	3.5	5.6	3.8
Metritis, %	6.6[a, b]	5.0[a, b]	8.6[b]	3.8[a]
305 d milk yield, kg	11,797 ± 91.8[a,b]	11,932 ± 84.8[b]	11,996 ± 92.4[b]	12,107 ± 98.0[b,c]

Data are presented as the least squares means ± standard error of the mean (**SEM**).

[1]Values with different letters (a–d) differed significantly.

[2]Weight gain between the first and second calving, during lactation 1

VLS: Vulvovaginal laceration score (0 = no laceration; 1 = laceration less than 2 cm at dorsal commissure of the vulva or at the lateral walls of the vulva/vagina, or both; 2 = laceration greater than 2 cm at dorsal commissure of the vulva or at the lateral walls of the vulva/vagina, or both; Vieira-Neto et al., 2016).

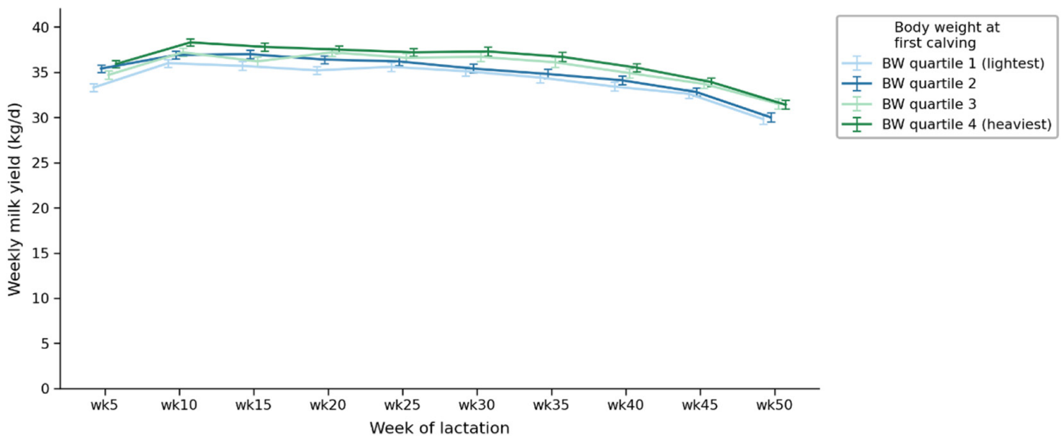

Figure 5. Mean (±SEM) weekly milk production (kg/d) from wk 5 until 50 of primiparous Holstein cows based on their body weight at first calving. Cows were categorized into 4 quartiles based on their body weight at first calving: BW_Q1(light blue): 394 – 564 kg; BW_Q2 (dark blue): 566 – 588 kg; BW_Q3 (light green): 589 – 612 kg; BW_Q4 (dark green): 614 – 768 kg. Least square estimates were derived from multivariable models accounting for age at first calving, year, and season of calving. SEM ranged from 0.35 to 0.56 across weeks and quartiles.

(2021) were based on diagnoses performed by veterinarians

While we detected no association between TPI categories and BW at first calving, this finding should be interpreted with caution, as TPI was assessed in some calves later than 72 h after birth, which may have reduced the accuracy of the classification. However, calves from BW_Q1 (7%) and BW_Q2 (7.5%) showed a greater incidence of diarrhea than calves from BW_Q4 (4.1%). Furthermore, calves from BW_Q1 (1.00 kg/d) had reduced pre-weaning ADG compared with calves from BW_Q4 (1.05 kg/d). It has been shown that pre-weaning diarrhea was associated with lower growth rates pre-weaning (−50 g/d) and lower milk production (−325 kg) in the first lactation (Abuelo et al., 2021). Contrary to another study with a similar study design (Lauber and Fricke, 2023), we observed no difference in bovine respiratory disease (**BRD**) incidence among the different BW quartiles. In that particular study, there was an association between BW quartile and the proportion of heifers with BRD in which Q1 cows had a 9 to 11 percentage point greater incidence of BRD as heifers than Q2, Q3, and Q4 cows. Due to differences in disease definition and possible survivorship bias, one must be careful when comparing outcomes among studies regarding the prevalence and the association of FTPI or pre-weaning diseases with BW at first calving. It has been shown that TPI (Sutter et al., 2023), pre-weaning BRD (Buczinski et al., 2021), and diarrhea (Urie et al., 2018) were associated with an increased risk of death or culling from birth until first calving. Therefore, it is difficult to draw conclusions from the cohort of heifers that survived these negative outcomes.

Interestingly, lighter heifers reached first calving at a younger age, which was largely driven by improved reproductive performance. Although all nulliparous heifers were first inseminated at approximately the same age, we observed that lighter heifers had greater P/AI at first service, required fewer inseminations, and had lower risk for pregnancy loss. These findings are consistent with previous work (Lauber and Fricke, 2023) and may reflect genetic differences or physiological factors not captured in this data set, such as body condition score or body fat and growth.

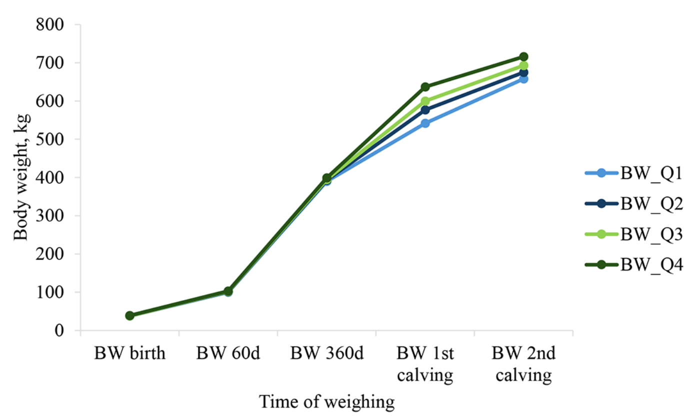

Figure 6. Mean body weight (BW) development of Holstein cows from birth to second calving. Cows were categorized into 4 quartiles based on their body weight at first calving: BW_Q1 (light blue): 394 – 564 kg; BW_Q2 (dark blue): 566 – 588 kg; BW_Q3 (light green): 589 – 612 kg; BW_Q4 (dark green): 614 – 768 kg. SEM for BW birth, BW 60d, BW 360d, BW 1st calving, BW 2nd calving were 0.14, 0.5, 0.6, 0.5, 1.96–2.23, respectively.

Lactation 1 and 2

In our study, lower body weight at first calving was associated with less favorable performance in lactation 1, including the incidence of metritis, reduced milk yield, and a higher risk of culling. Some of these associations, particularly milk production and growth, persisted into lactation 2.

Weight

At the time of first calving, the cows' weight ranged between 394 and 768 kg. Variations in weight at the time of first calving despite having uniform rearing conditions were also detected by Coffey et al. (2006). In their study, data from cows born between 1990 and 2002 on a farm in UK were analyzed. The suspected cause of this effect are genetic predispositions for growth. Lee et al. (1992) conducted a study on 1,266 Holstein cows born between 1972 and 1983, estimating the heritability of BW at first calving as 0.33, and the heritability of BW gain from 0 to 8 weeks of age as 0.24. Another possible explanation is suggested by Lauber and Fricke (2023). They pointed out that lighter heifers in their study conceived approximately 20 d earlier than heavier heifers. Thus, they had fewer days on feed and a shorter growth period.

Interestingly, AFC was not associated with milk production in the final models, nor did we detect an interaction between AFC and BW at first calving. Although AFC differed among BW quartiles by approximately 19 d, there was substantial variation in BW within individual AFC categories (Table 1). Consequently, heifers of the same calving age often differed considerably in body size and likely physiological maturity. This overlap may explain why AFC alone provided limited explanatory value once BW at first calving was included in the models. These findings suggest that BW at first calving may be a more informative indicator of developmental readiness for lactation than chronological age alone, particularly in herds where AFC is already maintained within a relatively narrow range.

Consequently, in lactation 2, we could see a long-term effect of body weight and age at first calving on growth and age at second calving, as well as a significant difference in body weight gain and average daily gain between lactation 1 and lactation 2, among the quartiles. While there is some compensatory growth in lighter cows in lactation 1, it is interesting to see that the differences in body weight and age at first calving remained at second calving. This observation potentially underscores the genetic predispositions for growth that were identified by Coffey et al. (2006) in their study.

Calf weight, sex and birth

An association was seen between heifer body weight at first calving and calf sex, with a higher proportion of female calves among lighter nulliparous heifers compared with heavier nulliparous heifers. In comparison, in lactation 2 no such associations were observed. However, the biological relevance of these differences appears limited, as reproductive management decisions, particularly the use of sexed semen, may significantly affect these findings. Sexed semen is often preferentially used at first service, when fertility is highest, to increase the likelihood of female offspring. Accordingly, Lauber et al. (2023) reported that the use of sexed semen decreased with increasing service number in nulliparous heifers.

The greater proportion of twin births in BW_Q1 (1.5%) was unexpected and has, to the authors' knowledge, not previously been associated with lower BW at first calving. In lactating cows, twinning is commonly linked to increased steroid metabolism associated with greater milk production, dry matter intake, and hepatic blood (Wiltbank et al., 2006). As primiparous cows generally have lower milk production and lower twinning rates than multiparous cows, the biological explanation for this finding remains unclear.

The association between the dams' body weight at first calving and the calves' birth weight is interesting. Lighter heifers from BW_Q1 have been observed to give birth to lighter calves, regardless of the calves' sex. This finding aligns with the results reported in a previous study (Yin and König, 2018). In their study they analyzed the heritability of calf birth weight and the dam's body weight at first insemination. They found a positive correlation between BW at calving and calf birth size traits, but didn't see an impact of calf weight on calving difficulties.

Further, in our study we detected that the gestation length of lighter heifers in BW_Q1 (274.5 d) was significantly shorter than the gestation length of heavier heifers from BW_Q4 (275.5 d). Although, we can see statistically significant differences in birth weight and gestation length between the quartiles, it remains speculative whether a one-day difference in gestation length causes a biologically significant difference in calf birth weight. Interestingly, in the second lactation an association between the birth weight of the calves and the body weight quartile was not observed. This finding suggests the possibility that the observed association in lactation 1 may be more indicative of a coincidental phenomenon than caused by the length of gestation. In addition, it should be noted that there was no difference observed in gestation length among the body weight quartiles in lactation 2.

Calving related events

Our study demonstrated an association between the dams' body weight at first calving and the occurrence of calving-related events. There was a significantly greater incidence of RFM and PM among lighter primiparous cows compared with the incidence among heavier cows. In a study by Johanson and Berger (2003), the calves' body weight at birth was put into ratio to the dams' body weight at calving. In our study, calves from lighter primiparous cows (BW_Q1 7.2%) were relatively heavier compared with the dams' body weight than calves from heavier cows (BW_Q4 6.3%). This observation might offer a potential explanation for the increased prevalence of calving-related events among lighter primiparous cows in our study. Another reason for the higher incidence of PM and RFM among lighter primiparous cows could be the occurrence of twin births. In their study from 2004, Sheldon and Dobson analyzed the postpartum uterine health in cattle and identified the risk factors for uterine bacterial diseases. They suspected uterine damage to be one of the risk factors and mentioned twin births, stillbirths, dystocia, and others as causes of uterine diseases, such as PM. Accordingly, our study showed that the highest incidence of PM coincided with the highest number of twin births in the same quartiles, both in lactation 1 (BW_Q1) and lactation 2 (BW_Q3). This suggests a possible association between twin births and the occurrence of metritis, consistent with the findings by Sheldon and Dobson (2004).

Interestingly, in lactation 1 and 2 we couldn't see an association between the dams' body weight at first calving and the occurrence of other calving-related events, such as stillbirth, dystocia or VLS. However, similar to the findings of Vieira-Neto et al. (2016), the majority of heifers in our study in lactation 1 had VLS2, while fewer cases of VLS1 and VLS0 occurred. In their study Vieira-Neto et al. (2016) found that primiparous cows were more likely to have a higher VLS than multiparous cows (OR = 7.6). This finding aligns with the results of our study. The occurrence of the VLS 1 - 3 among multiparous cows from all quartiles in lactation 2 was approximately uniform (on average: 33.3%).

Milk yield

We detected an association between BW at first calving and milk yield during early lactation, with lighter primiparous cows producing less milk than heavier cows. Lauber and Fricke (2023) also observed this trend among primiparous cows in their study and hypothesized that lighter primiparous cows allocate more energy to growth than to milk production. This hypothesis can be supported by our study, as lighter primiparous cows showed greater weight gain and ADG between lactation 1 and lactation 2 compared with heavier cows. Undersized heifers will partition more of the consumed nutrients toward growth than for lactation functions (van Amburgh et al., 1998; Fox et al., 1995). According to a previous review, a heifer that is lighter at calving will need a higher ADG during the first lactation to achieve the target BW for the next lactation (van Amburgh et al., 2019). These authors compared ADG, metabolizable energy (**ME**) and metabolizable protein (**MP**) requirements for 2 heifers differing in their BW at calving (540 kg vs. 615 kg) using the Cornell Net Carbohydrate and Protein System (van Amburgh et al., 2015). The ADG (0.39 kg/d vs. 0.19 kg/d), the ME (2 Mcal/d vs. 3.8 Mcal/d) and MP (133g/d vs. 74 g/d) requirement for growth was greater in the undersized heifer. This difference in ME and MP required for growth would come at the expense of milk yield and is equal to approximately 1 kg of milk/d, not accounting for the dry matter intake (**DMI**) difference that would exist between the heifers of at least 1.5 to 2 kg/d due to the BW difference. Thus, for every 0.1 kg of BW gain required per day, daily ME and MP requirements for growth during lactation would increase by approximately 1 Mcal and 30g, respectively (van Amburgh et al., 2015).

The reduced milk production among lighter primiparous cows in lactation 1 was also observed during lactation 2. This supports the hypothesis from Lauber and Fricke (2023) and van Amburgh et al. (1998), that lighter heifers/ cows allocate a greater proportion of energy to growth than to milk production. Furthermore, this finding aligns with the results reported by van Amburgh et al. (2015) that an increased energy requirement for growth comes at the expenses of milk yield.

Differences in milk yield between BW quartiles were also evident across the full first lactation, particularly during early and mid-lactation. However, milk production later in lactation should be interpreted with caution, as group composition may be increasingly influenced by pregnancy status, dry-off timing, culling, and survivorship bias. For example, cows with greater reproductive success may have been dried off earlier, whereas cows remaining in milk later in lactation may represent a more selected subset of animals. Therefore. the early-lactation analyses likely provide the most biologically relevant assessment of the relationship between BW at first calving and milk production.

A limitation of the milk production analyses is that pregnancy- and calving-related factors known to influence lactation performance, such as gestation length or calf characteristics, were not included in the final models. These variables may explain part of the residual variation in milk production; however, because they may also be biologically linked to maternal BW at calving, their inclusion could have complicated interpretation of the primary exposure effect.

Reproduction. Lighter nulliparous heifers in our study showed significantly greater P/AI compared with heavier heifers in our study. Lauber and Fricke (2023) attributed greater P/AI among lighter heifers in their study to genetic predispositions. Taking genetic predispositions as an influential factor, one might expect P/AI to be the same among primiparous cows as among nulliparous heifers. However, in our study this association was not observed among first-lactation cows. Frenkel et al. (2024) observed an association between transition cow health, P/AI, and pregnancy loss using a Double-Ovsynch protocol. They found that inflammatory disorders (e.g., RFM, PM, mastitis) negatively impacted P/AI. In our study, we detected a greater incidence of metritis and retained fetal membranes among lighter cows. This could have impacted fertility outcomes, though we couldn't establish a relationship with primiparous cows' BW.

Culling. Furthermore, the risk of culling was significantly increased during the first lactation among heifers with a lower body weight at first calving. Culling can occur voluntarily due to low milk production, behavioral conditions and market prices, or involuntarily due to conformation, disease, injury, infertility or death (Fetrow et al., 2006). In their review, de Vries and Marcondes (2020) described PM and low milk production, among other factors, as causes of culling. In our study, primiparous cows with a lower weight at first calving were more likely to suffer from PM and had lower milk yield in the first lactation than heavier cows. These 2 factors could explain the increased culling risk among lighter primiparous cows in our study. Pinedo et al. (2014) also emphasized that various factors such as disease, milk yield, and reproductive success, have an impact on culling risk. In lactation 2, however, no association was observed between body weight and the risk of culling, despite the lower milk production among lighter cows.

Study limitations and future directions

This data set provides insights into the association between body weight at first calving and various outcomes related to the heifer rearing phase, as well as the first and second lactation, including milk production, reproductive performance, health, and culling risk. However, this study has some limitations that should be acknowledged. First, the observed data set was taken from a single commercial dairy farm. While this ensured consistent management and environmental conditions, it limits the external validity of the findings. Second, although major variables were captured, potentially relevant factors such as genetic predispositions or environmental influences (e.g., heat stress) were not measured. Third, information on BCS or skeletal body size was not available in the data set. Therefore, we cannot distinguish whether differences in BW were primarily related to frame growth or body fat deposition. Further, due to this study being a retrospective data analysis, some outcomes may be influenced by survivorship bias, as only animals that survived until first calving were included and cows during lactation were affected by culling which impacted 305 d milk yield. Although several relevant variables were included in the statistical models, there is potential for residual confounding, as unmeasured factors such as genetic predisposition, growth efficiency, feeding behavior, skeletal size, or other management-related influences may have affected both BW at first calving and subsequent health, reproductive, and production outcomes. Therefore, the observed associations should not be interpreted as causal relationships. Instead, BW at first calving may partly represent a proxy for underlying biological or management-related factors associated with long-term performance. Another important limitation is that the study population had a comparatively early AFC, with mean AFC ranging from approximately 21.5 to 22.1 mo. Therefore, these findings may not be directly generalizable to herds targeting later AFC.

Randomized-controlled studies are needed to further understand the effects of body weight at first calving, milk yield and reproductive performance, calving-related disease incidence, heifer growth and survivability.

CONCLUSIONS

In conclusion, body weight at first calving was associated with growth and reproductive performance of heifers, as well as with ADG and milk yield during the first and second lactation. Lower BW at first AI in heifers was positively associated with P/AI, as lighter heifers showed a greater P/AI at first insemination compared with heavier heifers, although no such association was observed among primiparous and secundiparous cows. Further, the incidence of postpartum metritis and retained fetal membranes was positively associated with lower BW at first calving. Therefore, lightest primiparous cows showed a greater incidence of such events compared with heavier primiparous cows. However, no such association with body weight at first calving was detected in multiparous cows. Regarding growth and productivity, lower BW at first calving was positively associated with ADG between lactation one and 2 as lighter primiparous cows achieved the greatest ADG between these 2 lactations. However, lower BW was negatively associated with milk yield during the first and second lactations.

NOTES

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Abbreviations: AFC = Age at first calving; AI = Artificial insemination; BRD = Bovine respiratory disease; BW_Q1 - BW_Q4 = Body weight Quartile 1 – Body weight Quartile 4; CIDR = Controlled internal drug release; CL = Corpus luteum; FTPI = Failed transfer of passive immunity; HR = Hazard ratio; MBS = Mature body size; NASEM = National Academies of Sciences, Engineering, and Medicine; OR = Odds ratio; P/AI = Pregnancy per artificial insemination; P4 = Progesterone; PM = Puerperal metritis; RFM = Retained fetal membranes; SPSS = Statistical package for the social sciences; TAI = Timed artificial insemination; TPI = Transfer of passive immunity; VL = Vulvovaginal laceration; VLS = Vulvovaginal laceration score; Wk = Week

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