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Invited review: The welfare of dairy cattle housed in tiestalls compared to less-restrictive housing types: A systematic review

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ABSTRACT

Many dairy cattle worldwide are housed in tiestalls, meaning that they are tethered by the neck to individual stalls. On some farms, tied cattle are permitted seasonal access to pasture, but otherwise their movements are restricted compared with cows housed in freestall barns or other loose housing systems. The aim of this systematic review is to summarize the scientific literature pertaining the welfare of tied dairy cattle through comparison with less-restrictive housing systems. Articles identified by PubMed and Web of Science underwent a 5-phase screening process, resulting in the inclusion of 102 papers. These papers addressed measures of welfare related to affective state, natural behavior, and health (with the lattermost category subdivided into hoof and leg disorders, lameness, mastitis, transition disease, and other diseases or conditions). Health was the most researched topic (discussed in 86% of articles); only 19% and 14% of studies addressed natural behavior and affective state, respectively. Our review highlights different health benefits for tethered and loose cattle. For example, tied cattle experience reduced prevalence of white line disease and digital dermatitis, whereas loose cattle experience fewer leg lesions and injuries. The prevalence of mastitis, transition diseases, and other conditions did not differ consistently across housing types. We found that the expression of certain natural behaviors, particularly those associated with lying down (e.g., time spent kneeling, unfulfilled intentions to lie down), were impaired in tiestalls. Articles addressing affective state found benefits to loose housing, but these studies focused almost exclusively on (1) physiological measurements and (2) cow comfort, a concept that lacks a consistent operational definition across studies. We call for future research into the affective state of tied cattle that extends beyond these explorations and employs more sophisticated methodologies.

Key words: confinement housing, animal well-being, biological functioning

INTRODUCTION

Tiestall housing, in which dairy cattle are tethered to individual stalls, remains prevalent in many parts of the world. In North America, 74% of Canadian dairy farms and 39% of US dairy farms use tiestall facilities as their primary housing type (USDA, 2016; CDIC, 2019), and the popularity of this housing system is echoed in other regions in the northern hemisphere such as Austria (82%) and Switzerland (40%) (Directorate-General for Health and Food Safety, 2017; Swiss Federal Statistical Office 2016, as cited by Bernhard et al., 2020). Exercise is sometimes permitted for tethered dairy cattle, although the percentage of tiestall farms allowing exercise varies widely by country. For example, 73% of tiestall farms in the United States offer pasture access for at least part of the year (USDA, 2016); whereas, this value appears to be closer to 30% in Canada (15–50% depending upon region; Denis-Robichaud et al., 2016).

Confinement housing for other farmed species has sparked controversy among the public, as evidenced by widespread legislative response to gestation crates and battery cages (von Keyserlingk and Hötzel, 2015). This strong opposition is likely driven by the visible restriction to even the rudimentary freedoms outlined in the Brambell (1965) report (e.g., ability to turn around). Robbins et al. (2019) report that the public are mostly unaware of the existence of tiestalls (54% of those initially surveyed), which may explain why this housing type has received less attention than restrictive housing systems for other farmed species. Despite the relative lack of awareness, globally the use of tiestalls continues to decline (Barkema et al., 2015), with some countries such as Sweden prohibiting the construction of new tiestall facilities (Simensen et al., 2010; Lundmark Hedman et al., 2018) and others (Denmark and

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Norway) imposing an outright ban on tethering. The ban in Denmark will be enforced in 2027 (Miljø- og Fødevareministeriet, 2017); until that time, cows housed in tiestalls must have summer pasture access for a minimum of 150 d. In Norway, the ban will come into force in 2034 (Landbruks- og matdepartementet, 2004), with increased grazing time (a minimum of 16 wk in summer) required for farms continuing use tethering past 2024.

Scientific opinion on the welfare of tied dairy cattle varies, ranging from staunch opposition (e.g., "tie-stall housing can endanger the welfare of animals, and it is hoped that this farming system will be abandoned in the future"; Tarantola et al., 2016, p. 103) to general approval (e.g., "[a] well-designed tie-stall may be able to limit the physical and behavioural problems linked to an animal's lack of freedom"; Corazzin et al., 2010, p. 310). These differences may be attributed to varying welfare definition and disparate weightings of welfare components (Fraser et al., 1997). Thus, we conducted a systematic review of the available scientific evidence to evaluate the welfare of tethered cattle (in comparison with less-restrictive housing types) using the 3-sphere conception of welfare that considers basic health and biological functioning, natural behavior, and affective state (Fraser et al., 1997).

MATERIALS AND METHODS

Summary of Inclusion and Exclusion Criteria

Inclusion and exclusion criteria for the systematic review were determined a priori. Articles were considered eligible if they were peer-reviewed, reported original data, and if a full text in English was available. Further, articles were only included if they provided a direct comparison between dairy cattle housed in tiestall or stanchion barns and less-restrictive housing types (including freestall, pasture, yard, bedded pack, or tiestall systems with at least partial access to one of these other systems). Studies in which dairy cattle were transferred to, or from, tiestalls to less-restrictive housing were also considered.

To meet inclusion criteria, studies must have provided at least 1 inferential, statistical comparison between welfare-related measures. These measures were categorized according to the definition of animal welfare provided by Fraser et al. (1997). That is, articles were considered welfare related if they empirically addressed one or more of the following topics: basic health and biological functioning (e.g., mastitis or lameness), natural behavior [the animal-based component of Fraser et al.'s (1997) "natural living," e.g., lying down or ruminating], or affective state (e.g., fearful or frustrated). Studies were included in multiple sections if they addressed more than one type of measure.

Studies addressing herd-level measurements were only included if they discussed individual animal welfare implications. For example, studies addressing bulk-tank SCC or SCS were only included if they made a direct link between these measures and mastitis or IMI. Studies reporting on claw conformation (i.e., traits relating to the anatomical structure of the hoof) were only considered if the relationship to lameness was discussed. Similarly, articles addressing physiological parameters such as cortisol were only included if the authors provided a conclusion or hypothesis regarding the animals' affective state. Finally, we did not include studies that exclusively addressed resource-based welfare measures, or studies in which resource-based and animal-based measures were presented collectively and could not be disentangled. No restrictions were placed upon publication year, sample size, or methodology. A quality assessment of the included studies is presented in the Supplemental Files (http://dx.doi.org/10.6084/m9.figshare.14769567; Beaver et al., 2021).

Search Strategy

Systematic searches were conducted in Web of Science (**WoS**) and PubMed. The following terms were used to search the WoS Core Collection, with an asterisk denoting wildcard truncations and quotation marks representing exact phrases: dairy AND (cow* or cattle) AND (tiestall* OR "tie-stall*" OR "tie stall*" OR stanchion*) AND (freestall* OR "free-stall*" OR "free stall*" OR cubicle OR pasture OR pack OR outdoor OR drylot OR "dry lot").

Searches in PubMed were slightly modified to account for medical subject heading terms: dairy AND cow AND (tiestall OR tie-stall OR "tie stall" OR "tie stalls" OR stanchion) AND (freestall OR free-stall OR "free stall" OR "free stalls" OR cubicle OR pasture OR pack OR outdoor OR drylot OR "dry lot" OR "dry lots"). Final searches were conducted on June 1, 2020 (PubMed) and June 2, 2020 (WoS).

Selection Process

Articles were selected for final inclusion using a 5-phase screening process:

- Phase 1: Duplicates across PubMed and WoS were excluded, and a list of unique articles was compiled.
- Phase 2: Articles written in languages other than English, review articles, and conference abstracts were excluded. The titles of all articles were

evaluated, and articles were filtered for relevance. Papers addressing species other than adult dairy cattle were also removed at this stage.

- Phase 3: Abstracts of the remaining articles were read to assess whether or not a direct comparison was made between tiestalls or stanchions and a less-restrictive housing type. Only articles meeting this criterion were retained.
- Phase 4: Full texts were read in detail, and further articles were excluded based upon whether the comparison between tiestalls or stanchions and other housing types actually addressed a welfare measure. Any full texts that were not available online or within The University of British Columbia's library system were requested by means of interlibrary loan or by contacting the authors via ResearchGate.
- Phase 5: The reference lists of the remaining papers were mined to identify additional papers. To facilitate this process, we searched for titles that contained the words: "tiestall" (or other spelling variants such as "tie-stall"), "tether" (or other spelling variants such as "tethered"), or "stanchion." We also searched for the key words "housing," "risk," or "management" to identify relevant cross-sectional studies. Once potential articles were identified, they were evaluated beginning at phase 3.

The articles retained after phase 5 were included in the systematic review, in multiple sections if eligible. A bias assessment of the systematic review protocol is provided in Supplemental File S1 (http://dx.doi.org/10.6084/m9.figshare.14769567; Beaver et al., 2021).

Data Extraction

For each article, where applicable, we recorded authorship, publication year, country of study, number of herds, number of cattle, tiestall (or stanchion) dimensions, dimensions of other housing, the welfare sphere addressed (i.e., basic health and biological functioning, natural behavior, or affective state), outcome measure(s), the authors' conclusion, and the direction of the conclusion (with "+" indicating a positive welfare effect in tie stalls, "−" indicating a negative effect, and "=" indicating no difference at the $P < 0.05$ threshold). Following data extraction by the study authors, the data were also extracted by an additional researcher to improve validity. Any discrepancies in the extracted data were reviewed among authors. Discrepancies most commonly arose in regard to sample sizes, due to subject attrition or change in sample sizes across years; clarifying footnotes have been added to relevant tables.

RESULTS

Full results from the selection process are detailed in Supplemental Figure S1 (http://dx.doi.org/10.6084/m9.figshare.14769567; Beaver et al., 2021). In summary, the initial searches yielded 264 unique articles, 62 of which met our inclusion criteria. An additional 40 were added from reference lists, resulting in a final list of 102 articles. The research predominantly described results relevant to basic health and biological functioning, with 88 of the 102 total studies (86%) addressing this welfare sphere (Figure 1). Nineteen studies (19%) addressed results relevant to the natural behavior welfare sphere, and 9 of these (47%) also addressed basic health and biological functioning. Finally, 14 studies (14%) described results relevant to the affective state welfare sphere, with 7 of these (50%) also addressing other welfare spheres. Of the 88 articles addressing basic health and biological functioning, 41 (40%) referenced "welfare," despite the vast majority considering health or production exclusively (Figure 1).

Of the 102 total articles, publication years ranged from 1981 to 2020 (median of 2006), with the amount of research increasing across the decades (Supplemental Figure S2; http://dx.doi.org/10.6084/m9.figshare.14769567; Beaver et al., 2021). The number of herds included in each study ranged from 1 to 2,728, and the number of cows from 7 to 132,721. The majority of studies were conducted in Scandinavia (n = 36; 22 in Sweden, 5 in Norway, 7 in Denmark, and 2 in Finland) and North America (n = 31; 20 in Canada and 11 in the United States). Other countries represented were Italy (n = 8), Switzerland (n = 7), France (n = 3), Austria and Germany (n = 2), Estonia (n = 2), Romania (n = 2), Japan (n = 1), Ireland (n = 1), Poland (n = 1), Serbia (n = 1), Turkey (n = 1), and Tanzania (n = 1), in addition to 5 studies that did not specify a country (Supplemental Figure S3; 10.6084/m9.figshare.14769567; Beaver et al., 2021).

Basic Health and Biological Functioning

Foot and Leg Disorders. Studies addressing the effect of tiestalls on foot and leg disorders are shown in Table 1. Of the 23 studies included in this section, 8 compared tiestall to freestall or other loose housing, 9 compared tiestalls with different levels of outdoor access, and 5 addressed both of these aspects. One study investigated the move from tiestall to freestall or loose housing. A variety of foot and leg disorders were addressed, including noninfectious foot lesions (such as sole ulcers and white line disease), infectious foot lesions [such as digital dermatitis (**DD**) and heel-horn erosion], leg lesions (such as knee and hock lesions), and foot and leg conformation traits. Many articles spanned

multiple categories, with the majority of studies investigating both infectious and noninfectious lesions.

Offering outdoor access to tied cattle (pasture or paddock) was associated with reduced prevalence of knee and hock lesions (Gustafson, 1993; Popescu et al., 2013), reduced odds of carpal ulceration and tarsal swelling (Bernhard et al., 2020) and improved claw conformation traits (Loberg et al., 2004; Corazzin et al., 2009, 2010). The associations between outdoor access and infectious and noninfectious lesions were sometimes neutral (e.g., Cramer et al., 2009 for sole ulcer and heel-horn erosion; Loberg et al., 2004 for white line fissures), but sometimes indicated reduced lesion prevalence when outdoor access was withheld (e.g., Cramer et al., 2009 for DD and white line separations; Gustafson, 1993 for sole ulcers; Bielfeldt et al., 2005 for interdigital disorders).

Cattle housed in tiestalls compared with loose housing had a higher prevalence of knee and hock lesions (Krohn and Munksgaard 1993; Regula et al., 2004; Mattiello et al., 2009) but appeared to fare better in terms of some types of infectious and noninfectious foot lesions, most notably DD (Bergsten and Herlin, 1996; Sogstad et al., 2005; Cramer et al., 2008) and white line disease (Sogstad et al., 2005; Cramer et al., 2008; Solano et al., 2016). For several other hoof lesions there was either no evidence of difference (e.g., sole ulcers: Alban, 1995; Bergsten and Herlin, 1996; Vaarst et al., 1998; Sogstad et al., 2005; and Solano et al., 2016) or mixed evidence (e.g., heel-horn erosion: Bergsten and Herlin, 1996; Bielfeldt et al. 2005; Sogstad et al., 2005; Cramer et al., 2008).

Lameness. Studies addressing the effect of tiestall housing on lameness are shown in Table 2. Of the 15 studies included in this section, 7 compared tiestall to freestall or other forms of loose housing, 3 compared tiestalls with different levels of outdoor access, and 3 addressed both of these aspects. Two studies evaluated lameness in cattle as they moved housing types. The most common scoring systems used to assess lameness were that of Sprecher et al. (1997; used in 5 studies), the Welfare Quality Assessment (**WQA**) Protocol for cattle (Welfare Quality, 2009; 4 studies), and Manson and Leaver (1988; 3 studies).

The effect of outdoor access on locomotion score was favorable, with all relevant studies reporting improved or unchanged locomotion scores (Regula et al., 2004; Bielfeldt et al., 2005; Mattiello et al., 2005; Mattiello et al., 2009; Corazzin et al., 2010; Popescu et al., 2013). The comparison between freestall and tiestall housing was less clear: 2 studies found improved locomotion scores in freestalls compared with tiestalls (Kara et al., 2011; Ostojić-Andrić et al., 2011), 3 found neutral effects (Wells et al., 1993; Olechnowicz et al., 2010; Popescu et al., 2014), and 2 found positive effects of tiestall housing (Cook, 2003 and Sogstad et al., 2005). After a move from tiestalls to freestalls, Tarantola et al. (2016) found no change in lameness. Enriquez-Hidalgo et al. (2018) tracked locomotion scores as cattle transitioned from pasture, to tiestalls, and back, and noted that scores worsened after confinement.

Udder Health. Studies addressing the effect of tiestall housing on udder health are shown in Table 3. The 34 studies addressed topics such as mastitis, clini-

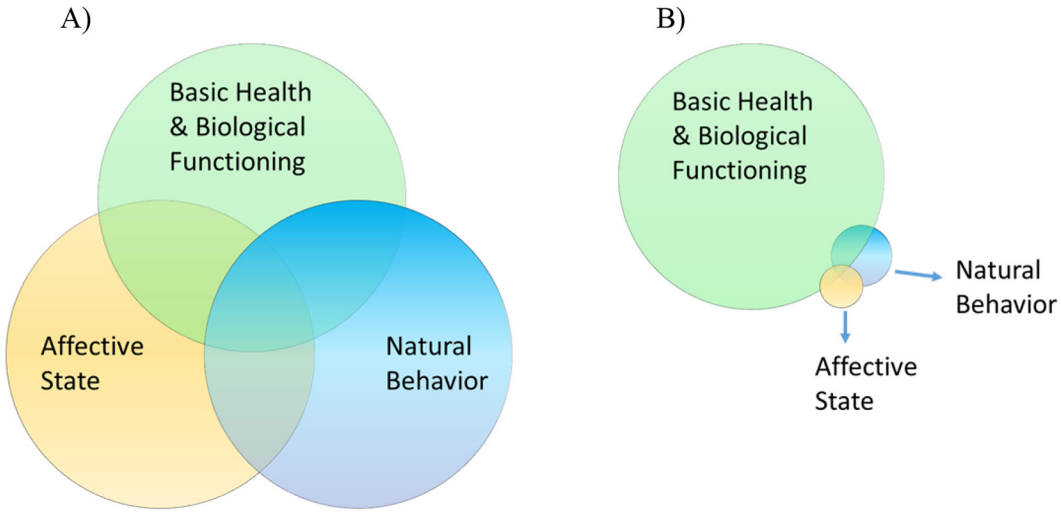

Figure 1. Panel A shows the 3 spheres of welfare as defined by Fraser et al. (1997). Panel B shows the 3 spheres of welfare but rescaled according to their representation in the literature on tiestalls versus less-restrictive housing types. Figure modified from Beaver et al. (2019), with permission.

Table 1. Articles comparing foot and leg disorders in tiestalls versus less-restrictive systems [listed for each study are country, condition, number of herds and total number of cows, the housing systems compared, the results (with "no difference" implying $P \geq 0.05$), and the direction of these results]

Study (country)	Condition	No. of herds (no. of cows)	System comparison[1]	Results	Effect[2]
Corazzin et al., 2009 (Italy)	Claw conformation	24 (NA[3])	Tiestalls [mean (min, max) stall width = 1.1 m (0.8, 1.8); length = 1.7 m (1.1, 2.0)] with vs. without summer grazing on mountain pasture	Percentage of cows with poor claw conformation lower with summer grazing; percentage of unspecified injuries also lower.	−
Corazzin et al. 2010 (Italy)	Claw conformation	24 (NA)	Tiestalls [mean (min, max) stall width = 1.1 m (0.8, 1.8); length = 1.7 m (1.5, 2.0)] with vs. without summer grazing on mountain pasture (for mean ± SD of 93 ± 6 d)	Percentage of cows with poor claw conformation decreased during grazing and was also lower after grazing.	−
Loberg et al. 2004 (Sweden)	Claw length	1 (52)	Cattle in tiestalls (1.2 × 1.75 m; rubber mats + chopped straw) with either: exercise for 1 h/d on outdoor paddocks (either 3,220 or 2,040 m^2; E7); exercise 2 times/wk (E2), exercise 1 time/wk (E1), or no exercise (E0)	Cows in E7 had shorter claws before spring trimming and less net growth. Cows in E7 and E1 had decreased claw angles before trimming and less net change in claw angle. Cows in E7 and E2 had shorter diagonal before trimming and less net growth. E1 also had less net growth of the diagonal.	−
	Foot lesions			Tendency[4] for lower risk of heel-horn erosion for exercised cows. Cows in E7 tended[4] to have more laminitis lesions and dermatitis vs. other groups. No difference in white line fissures.	=
Olechnowicz et al., 2010 (Poland)	Foot and leg conformation traits	2 (142)	Tiestalls + year-round pasture (farm 1); freestalls (farm 2)	Tied cows had lower RLSV[5] scores compared with freestall cows and lower FA[6] scores; no difference in RLRV[7]	+/=
Hultgren, 2002 (Sweden)	Foot and leg disorders	196 (NA)	Cows moved from short tiestalls or long tiestalls (0.4–0.5 m longer) to cubicles or indoor straw yards	After move from long tiestalls to cubicles, monthly herd IR[8] of foot and leg disorders increased; no difference after 18 mo. After move from short tiestalls to cubicles, monthly herd IR increased. No difference from mo 0–18 after relocation from long or short tiestalls to straw yard.	+/=
Alban, 1995 (Denmark)	Foot and leg disorders	165 (9,762)	Tied vs. loose housing	After inclusion in the multivariable model, housing system did not affect the risk of lameness (including arthritis, contusion, foul in the foot, interdigital dermatitis, laminitis, sole ulcers, swollen hock, arthritis, and other lameness).	=
Vaarst et al., 1998 (Denmark)	Foot lesions	13 (974)	4 types of housing compared: loose housing with slatted floor, deep litter, and tiestalls with and without straw bedding	Type of housing was not a risk factor for the outcomes investigated: acute hemorrhage, sole ulcer in 1 leg, or sole ulcer in ≥2 legs.	=
Cramer et al., 2008 (Canada)	Foot lesions	204 (13,530)	Tiestalls, freestalls, bedded pack, and others[9]	Herd and cow-level prevalence improved in tiestalls vs. freestalls for the following: Foot lesions [DD,[10] hoof-horn lesions (ulcers, white line separations, abscesses), other lesions (korn, thin soles, vertical wall cracks)], and nonfoot lesions. Cow and herd-level prevalence of any lesion were lower in tiestalls. No difference in herd-level prevalence of foot rot, heel-horn erosion, or deep sepsis. No cow-level difference for foot rot or heel-horn erosion.	+/=
Cramer et al., 2009 (Canada)	Foot lesions	134 (5,582)	Tiestalls with seasonal, year-round, or no outdoor access (freestalls also considered but not directly compared with tiestalls)	PR[11] for DD, white line separations, and interdigital fibroma higher with year-round vs. no outside access. No differences in PR for these lesions when cattle had seasonal vs. no outdoor access. No difference between the 3 levels of outdoor access for any other lesion types (sole ulcer, sole hemorrhage, heel-horn erosion, white line abscess).	+/=

Continued

Table 1 (Continued). Articles comparing foot and leg disorders in tiestalls versus less-restrictive systems [listed for each study are country, condition, number of herds and total number of cows, the housing systems compared, the results (with "no difference" implying $P \geq 0.05$), and the direction of these results]

Study (country)	Condition	No. of herds (no. of cows)	System comparison[1]	Results	Effect[2]
Gustafson, 1993 (Sweden)	Foot lesions	1 (65)	Cows either permitted outdoor access (2–3 km/d from May to Oct.; 400–800 m/d for rest of year) or remained in tiestalls (1.2 × 2.15 m + rubber mats and 2 kg chopped straw and sawdust per day); for behavioral recording, cattle in both groups were moved to an individual stall	Exercised cows had a higher score for sole ulcers during the first observation period (yr 1). No differences in yr 2, 3, or 4 of the study.	+/=
	Hock lesions			Tied cows without exercise had higher scores for hock lesions.	−
Solano et al., 2016 (Canada)	Foot lesions	156 (23,014)	Tiestalls vs. freestalls	Compared with freestalls, tied cattle had decreased odds of white line disease. No difference for DD or sole ulcers.	+/=
Bergsten and Herlin, 1996 (Sweden)	Foot lesions	1 (245)	Tiestalls (1.8 × 1.3 m + in-stall milking + concrete floor with rubber mats and 0.5 kg/d chopped straw and 2 kg/d sawdust) vs. cubicles (2.2 × 1.3 m each, + an extra 76 m space in front. Concrete floors with rubber mats and 3–4 kg sawdust 2 times/wk. Two cubicle rows on either side of a manger with a short step in front. Parlor milking.) Feeding regimens differed slightly between groups.	Both increases and decreases in white line hemorrhages and heel erosion were observed in cubicle-housed cattle compared with tied cattle depending upon year, parity, and claw region.[12] No difference in sole hemorrhages.	+/=/−
Bernhard et al., 2020 (Switzerland)	Foot lesions	27 (609)	Tiestalls with varying levels of outdoor exercise, ranging from <13 to >15 d/mo	More frequent exercise was associated with reduced odds of hair loss at the carpus and tarsus in addition to reduced odds of ulceration at the carpus and swelling at the tarsus.	−
Faye and Lescourret, 1989 (France)	Foot lesions	80 (NA)	Winter housing: tiestall [short (TS) or long (TL); with (TO) or without (TN) half-open air] vs. loose housing [with (LO) or without (LN) half-open air; with earth floor (LE) or concrete (LC)]. Feeding regimens differed slightly between groups.	Functional, metabolic, infectious, and traumatic foot diseases evaluated. Factor analysis showed loose housing associated with high incidence of infectious foot lesions. Overall incidence of all foot diseases lower in TO vs. LN and LO. No difference between TN and other categories. Incidence lower in LE vs. TS. TS had lower incidence than LC. No difference between TL and other categories.	+/=/−
Bielfeldt et al., 2005 (Switzerland)	Foot lesions	290 (4,621)	Tiestalls without exercise (T1); with exercise (T2); or loose housing with exercise (L2). Exercise consisted of 13d/mo in a yard or pasture in winter or 26 d/mo in vegetation period.	Compared with L2, cattle in T1 had greater odds of heel-horn erosion. Compared with L2, cattle in T2 had a greater odds of heel erosion. Cattle in T1 had lower odds of interdigital disorders compared T2. L2 had lowest number of cattle with sole disorders and more white line disorders.[13]	−/+
Alban et al., 1995 (Denmark)	Foul in the foot	171 (9,520)	Loose vs. tied-up housing	Risk of foul in the foot higher in loose-housed vs. tied cattle.	+
Keil et al., 2006 (Switzerland)	Hock lesions	66 (NA)	Different frequencies and durations of outdoor exercise compared, in addition to length of lying areas, for cattle housed in tiestalls	Prevalence of scabs and wounds negatively associated with duration of outdoor access and length of lying area. Prevalence of scabs and wounds positively associated with frequency of outdoor access.	−/+
Krohn and Munksgaard, 1993 (Denmark)	Knee and hock injuries	1 (48)	Cattle housed in either (1) loose housing + access to feeding table, deep bedding, yard and pasture, with milking 2 times/d; (2) tiestalls (1.25 × 1.8 m with neckbar tie), no exercise, concrete floor + 1 kg straw, 2 times/d milking; (3) tiestalls, rubber mats + 2 kg straw, 4 times/d milking, no exercise; (4) same as Group 3 but with 1 h daily exercise in the yard.	More hock inflammation in tiestalls compared with loose housing; no difference in knee inflammation between groups.	−/=

Continued

Table 1 (Continued). Articles comparing foot and leg disorders in tiestalls versus less-restrictive systems [listed for each study are country, condition, number of herds and total number of cows, the housing systems compared, the results (with "no difference" implying $P \geq 0.05$), and the direction of these results]

Study (country)	Condition	No. of herds (no. of cows)	System comparison[1]	Results	Effect[2]
Sogstad et al., 2005 (Norway)	Knee and hock lesions	112 (2,665)	Tiestalls vs. freestalls	More tied vs. loose cows had wounds or swelling on carpal joints and tarsal joints.	−
	Foot lesions			Fewer tied vs. loose cows had ≥1 claw lesion. Most lesions (dermatitis, white line and sole hemorrhages, heel-horn erosions, and white line fissures) were more prevalent in freestalls. No difference for sole ulcers.	+
Regula et al., 2004 (Switzerland)	Knee and hock lesions	134 (NA)	Tiestalls + summer outdoor exercise; tiestalls + year-round outdoor exercise; loose housing + year-round outdoor exercise	Prevalence of alterations at hock joints lower in loose housing vs. tiestalls with only summer exercise. Presence of callosities at carpal joints also lower.	−
Popescu et al., 2013 (Romania)	Leg lesions	80 (3,192)	Tiestalls (160–250 cm × 85–190 cm) with straw or sawdust (≤1.5 kg/head per day) with regular outdoor exercise (paddock, pasture, or both) vs. no exercise.	Percentage of cows with lesions lower with exercise; percentage of cows with a hairless patch lower with exercise.	−
Mattiello et al., 2009 (Italy)	Leg lesions	14 (185)	Cubicles vs. tiestalls (with and without access to mountain pasture in summer)	Higher percentage of cattle in tiestalls vs. freestalls had leg and heel lesions (and neck lesions); no difference based on access to summer pasture.	−/=
Bendixen et al., 1986 (Sweden)	Inflammatory and noninflammatory hoof disease	900 (NA)[14]	Swedish red and white (SRB) and Swedish Friesian (SLB) kept tied year-round, or tied during winter with summer pasture access	Cows of both breeds with pasture access had higher risk of hoof inflammation while on pasture. When adjustments were made for herd size distribution, zero-grazing SRB had a decreased risk of hoof inflammation. SRB cows with pasture access had higher risk of noninflammatory hoof disease during the pasture period. When herd-size adjustments were made, zero-grazing SLB cows had decreased risk.	+

[1]Housing types being compared in each study. Stall dimensions and other characteristics are specified for all housing types if this information is provided in the article.

[2]Where + indicates a beneficial effect of tiestall housing, − indicates a negative effect, and = indicates no statistical different at $P \geq 0.05$ unless otherwise specified.

[3]NA indicates information is either not applicable or has not been provided.

[4]Tendencies are defined at the $P < 0.01$ threshold and are not significant at $P < 0.05$.

[5]RSLV = rear legs set side view.

[6]FA = intermediate foot angle.

[7]RLRV = rear legs set rear view.

[8]IR = incidence rate.

[9]Analyzed results pertain only to tiestalls and freestalls.

[10]DD = digital dermatitis.

[11]PR = prevalence ratio.

[12]In yr 1 and 3, primiparous cows in cubicles had higher mean scores for white line hemorrhages (medial foreclaw) vs. tied cows. In yr 3, cubicle-housed cattle had lower scores in medial hind claws. In yr 1 and 3, multiparous cows in cubicles had higher scores (both fore and hind claws, both medial and lateral). In yr 1 and 2, primiparous cows in cubicles had higher mean scores for heel erosion in the foreclaws vs. tiestalls. Multiparous cows in cubicles had higher mean scores for heel erosion in foreclaws in yr 1 and lower heel erosion in hind claws in yr 2. This study also considered clinical lameness, which was higher in freestalls, but no statistical comparison was provided.

[13]Not tested statistically.

[14]The number of herds varied from 900 to 1,021 across 4 yr of study.

Table 2. Articles comparing lameness in tiestalls versus less-restrictive systems [listed for each study are country, condition, number of herds and total number of cows, comparison of housing systems being made, results (with statements referencing "no difference" representing $P \geq 0.05$), and the direction of these results]

Study (country)	No. of herds (no. of cows)	System comparison[1]	Lameness scoring system	Results	Effect[2]
Sogstad et al., 2005 (Norway)	112 (2,665)	Tiestalls vs. freestalls	Assessed during the move to trimming chute as either: none, moderate (asymmetric gait but bearing weight on all limbs) or severe (avoiding weight on ≥1 limb)	Higher prevalence of lameness in front and hind limbs in freestall vs. tied cattle.	+
Cook, 2003 (US)	27 (2,621)[3]	Tiestalls vs. freestalls	Scored on 4-point scale according to Sprecher et al. (1997), Wells et al. (1993), and Manson and Leaver (1988). Tied cattle scored when released after morning milking; freestall cows scored leaving milking parlor. Both groups scored on concrete surfaces.	Lameness prevalence higher in freestalls with non-sand bedding vs. tiestalls with sand bedding (in both summer and winter) and non-sand bedding (in winter). No difference in lameness prevalence between sand-bedded tiestalls and sand-bedded freestalls.	+/=
Mattiello et al., 2009 (Italy)	14(185)	Cubicles vs. tiestalls (with and without access to mountain pasture in summer)	Scored according to Welfare Quality (2009)	No difference in prevalence of lame cows in tiestalls vs. cubicles, or in herds with vs. without access to summer pasture.	=
Olechnowicz et al., 2010 (Poland)	2(142)	Tiestalls + year-round pasture (farm 1); freestalls (farm 2)	Scored according to Sprecher et al. (1997). Scores ≥3 defined as clinical lameness.	No difference in locomotion scores before or after hoof trimming.	=
Popescu et al., 2014 (Romania)	60 (2,624)	Tiestalls (160–250 cm × 85–190 cm; most with straw or sawdust bedding (≤1.5 kg/d); some had access to pasture or paddocks); cubicles (sawdust bedding); straw yards	Scored according to Welfare Quality (2009)	No difference in lameness between the housing types.	=
Tarantola et al., 2016 (Italy)	1 (15)	Reared in tiestalls (concrete + straw) then moved to freestalls (2.6 × 1.2 m cubicles, concrete + straw, 4 m^2 total stall surface)	Scored on 4-point scale according to Sprecher et al. (1997). Tied cows scored when released after morning milking; freestall cows scored leaving milking parlor. Both groups scored on concrete surfaces.	No change in lameness prevalence before and after the move.	=
Wells et al., 1993 (US)	16 (851)[4]	Stanchions or tiestalls vs. freestalls or dry lots	Scored on a 5-point scale, which ranged from no gait abnormality to nonambulatory (recumbent). Scores of ≥2 (moderate gait asymmetry or gate abnormality) were classed as "clinically lame."	Prevalence of clinical lameness was studied in spring and summer, but no differences were found between housing types.	=
Corazzin et al., 2010 (Italy)	24 (NA[5])	Tiestalls [mean (min, max) stall width = 1.1 m (0.8, 1.8); length = 1.7 m (1.5, 2.0)] with vs. without summer grazing on mountain pasture (for mean ± SD of 93 ± 6 d)	Cattle on pasture scored according to Sprecher et al. (1997) and modified by Breuer et al. (2000). Animals divided into lame and not lame for analysis. Tied cows scored according to Leach et al. (2009)	Percentage of lame cows did not differ between cows after summer grazing vs. without summer grazing; however, proportion decreased during grazing.	=/−
Regula et al., 2004 (Switzerland)	134 (NA)	Tiestalls + summer outdoor exercise; tiestalls + year-round outdoor exercise; loose housing + year-round outdoor exercise	Scored on 5-point scale according to Manson and Leaver (1988). Tied cows scored outdoors; loose-housed cows scored outdoors or in a concrete walking area.	Lameness prevalence lower with year-round exercise vs. only summer exercise. No difference in prevalence between loose housing and tiestalls with summer exercise. Lameness increased in short vs. medium stalls.	−/=

Continued

Table 2 (Continued). Articles comparing lameness in tiestalls versus less-restrictive systems [listed for each study are country, condition, number of herds and total number of cows, comparison of housing systems being made, results (with statements referencing "no difference" representing $P \geq 0.05$), and the direction of these results]

Study (country)	No. of herds (no. of cows)	System comparison[1]	Lameness scoring system	Results	Effect[2]
Bielfeldt et al., 2005 (Switzerland)	290 (4,621)	Tiestalls without exercise (T1); with exercise (T2); or loose housing with exercise (L2). Exercise was at least 13 d/mo in a yard or pasture in winter or at least 26 d/mo in vegetation period	Scored on 5-point scale according to Manson and Leaver (1988) and modified by Lischer et al. (2000): 0 = normal; 1 = splayfoot; 2 = uneven gait; 3 = mildly lame, possibly arched back; 4 = obviously lame, impaired movement, arched back; 5 = severely lame, difficulty rising, back heavily arched	Compared with L2, cattle in T1 had greater odds of lameness. No difference in odds between T2 and L2. (L2 also had lowest number of cattle with disturbed locomotion).[6]	–
Enriquez-Hidalgo et al., 2018 (Ireland)	1(48)	Moved from pasture to tiestall (1.35 × 1.2 m for 12 d) then back to pasture.	Scored according to O'Driscoll et al. (2010).	Lower locomotion score in preconfinement than immediately after confinement (d 12) or after confinement (d 16).	–
Kara et al., 2011 (Turkey)	28 (709)	Tiestalls vs. freestalls (both with concrete flooring)	Scored using 4-point scale from Sprecher et al. (1997) and dichotomized into sound (score 0) and lame (score 1–3) for analysis.	Locomotion score improved in freestalls vs. tiestalls.	–
Mattiello et al., 2005 (Italy)	47 (NA)	Tiestalls with varying dimensions and durations of spring and fall grazing; majority of herds allowed <30 d of grazing each season; stalls ranged from 96 to 150 cm wide × 145–203 cm long; almost all stalls had concrete floor with straw or sawdust (1.5–2.5 kg/d)	Based upon farmer estimation	Increased duration of grazing associated with reduced frequency of lameness.	–
Ostojić-Andrić et al., 2011 (Serbia)	6 (400)	Tied without exercise vs. loose housed with and without grazing	Scored according to Welfare Quality (2009)	Higher percentage of lame cows identified in tied systems in addition to a higher percentage of severely lame and moderately lame cows.	–
Popescu et al., 2013 (Romania)	80 (3,192)	Tiestalls (160–250 cm × 85–190 cm) with straw or sawdust (≤1.5 kg/head per day) with regular outdoor exercise (paddock, pasture or both) vs. no exercise	Scored according to Welfare Quality (2009)	Percentage of lame cows lower when permitted exercise.	–

[1]Housing types being compared in each study; stall dimensions and other characteristics are specified for all housing types if this information is provided in the article.

[2]Where + indicates a beneficial effect of tiestall housing, − indicates a negative effect, and = indicates no statistical different at $P \geq 0.05$ unless otherwise specified.

[3]In the first year, 30 herds (with 3,621 cows) were scored, but only 29 herds were included in analysis. During the second year, 27 herds were scored (with an unspecified number of cows).

[4]Numbers reflect total of herds and cattle observed in the spring. In the previous summer, a greater number of cattle (853) and herds (16) were observed.

[5]NA indicates information is either not applicable or has not been provided.

[6]Not tested statistically.

cal mastitis (**CM**), SCC, SCS, IMI, and teat injuries. Twenty of these studies reported differences in cattle housed in tiestalls versus freestalls or loose housing, 4 studies evaluated the effect of outdoor access for tied cattle, and 5 studies addressed both aspects. Five additional studies evaluated the effects of moving cattle between systems.

In the studies reporting specific bacterial causes of IMI and mastitis, higher prevalence of *Streptococcus* species (Bartlett et al., 1992; Ferguson et al., 2007; Olde Riekerink et al., 2008) and both aureus and non-*aureus Staphylococcus* species (Whist et al., 2006; Olde Riekerink et al., 2008; Ericsson Unnerstad et al., 2009; Condas et al., 2017; Taponen et al., 2017) were identified in tiestalls compared with less-restrictive housing types. Conversely, *Escherichia coli* (Whist et al., 2006; Ericsson Unnerstad et al., 2009; Taponen et al., 2017) was more common in loose housing.

Despite differences in prevalence caused by different bacteria, several studies found that the overall prevalence of IMI and rate of CM did not differ between housing types (Kalmus et al., 2006; Whist et al., 2006; Ferguson et al., 2007; Kivaria et al., 2007; Simensen et al., 2010; Ostojić-Andrić et al., 2011; Levison et al., 2016; Condas et al., 2017). In contrast, some articles identified differences in mastitis prevalence and SCS or SCC; 3 studies identified reduced risk in tiestalls (compared with freestalls: Bielfeldt et al., 2004 and Ericsson Unnerstad et al., 2009; compared with straw yards: Barnouin et al., 2005) and 6 others identified increased risk in tiestalls (Bakken, 1981; Valde et al., 1997; Olde Riekerink et al., 2008; Sabbioni et al., 2012; Popescu et al., 2014).

The effect of outdoor access was largely positive for tied cattle, with reductions in mastitis (Popescu et al., 2013), SCC in the first month after calving (Gustafson, 1993), and teat injuries (Bendixen et al., 1998a; Krohn and Munksgaard, 1993; Regula et al., 2004). Several studies, however, reported mixed results (Bendixen et al., 1998b; Bendixen et al., 1986). The effects of housing change on SCC, mastitis rates, and teat injuries were also mixed (Varner et al., 1983; Hultgren, 2002; Bielfeldt et al., 2004; Hovinen et al., 2009; Nyman et al., 2009).

Transition Diseases. The 10 studies reporting the effect of tiestall housing on transition disease are shown in Table 4. Conditions studied were ketosis, dystocia, abomasal displacements, and metritis. Vulvar discharge was also included in this section due to its association with metritis. Four studies compared tiestall to loose housing, 5 compared tiestall with different levels of outdoor access, and 1 addressed both of these aspects. Less-restrictive housing and outdoor access had mostly positive or neutral effects on disease rates, prevalence, and treatments; however, 3 studies found some mixed-positive effect of tethering (Bendixen et al., 1986; Corazzin et al., 2010; Ostojić-Andrić et al., 2011).

Other Diseases and Conditions. Studies addressing the effect of tiestall housing on other diseases and conditions (excluding transition diseases, lameness, hoof lesions, and udder health conditions) are shown in Table 5. Of the 23 studies included in this section, 16 compared tiestalls with freestalls or loose housing, 4 investigated the effects of outdoor access for tied cattle, and 3 addressed both aspects. One additional study evaluated the move from tiestall to loose housing. The most commonly assessed outcomes were mortality and culling risk (n = 8), respiratory disorders (including coughs, nasal discharge; n = 5), Johne's disease (n = 4), and diarrhea and enteric health (n = 4). Winter dysentery, *Giardia*, cattle lice, injuries, integument alterations, bloat, and veterinary treatments were also addressed.

Outdoor access was associated with lower mortality for tied cattle (Dechow et al., 2011; Popescu et al., 2013), decreased prevalence of injuries (Corazzin et al., 2010), and fewer treatments for bloat (Gustafson, 1993). There was no effect of outdoor access on the prevalence of respiratory disorders (Popescu et al., 2013), or ocular/nasal discharge (Corazzin et al., 2009), although the proportion of cows with a cough decreased during grazing (Corazzin et al., 2010).

Effects of housing type were mixed or neutral in reference to mortality (Alvåsen et al., 2012; Popescu et al., 2014; Reimus et al., 2020), diarrhea (Mattiello et al. 2009; Ostojić-Andrić et al. 2011; Popescu et al. 2014), and respiratory disorders (Mattiello et al., 2009; Ostojić-Andrić et al., 2011; Popescu et al., 2014). One of 4 studies addressing Johne's disease found a beneficial effect of tiestall housing on environmental prevalence of *Mycobacterium avium* ssp. *paratuberculosis* (Corbett et al., 2018a). Conversely, tiestalls and stanchions were associated with increased odds of joint injuries (Busato et al., 2000), cattle lice (Geden et al., 1990), and higher risk of winter dysentery outbreaks (Smith et al.,1998). The effects of housing on *Giardia* prevalence was mainly neutral, although Wade et al. (2000) found higher infection risk for lactating cows in tiestalls compared with loose housing.

Fertility and Reproductive Performance. As fertility is an indirect welfare metric, the results are provided in Supplemental Table S1 (http://dx.doi.org/10.6084/m9.figshare.14769567; Beaver et al., 2021). Eleven studies were included in this section. Ten of these reported that reproduction parameters were more favorable, or at least equivalent, in less-restrictive housing systems compared with tiestalls. The evaluated parameters included, among others, pregnancy risk,

Table 3. Articles comparing udder health in tiestalls versus less-restrictive systems [listed for each study are condition, country, number of herds and total number of cows, comparison being made, results (with statements referencing "no difference" representing $P \geq 0.05$), and the direction of these results]

Study (country)	Condition[1]	No. of herds (no. of cows)	System comparison[2]	Results	Effect[3]
Taponen et al., 2017 (Finland)	IMI	4,173 (29,969)	Tiestalls vs. freestalls with either conventional or automatic milking systems	*Staph. aureus* IMI most common in tiestalls. *Corynebacterium bovis* and *Escherichia coli* IMI more common in parlor milking compared with tiestalls (and no difference between parlor milking and automatic milking systems).	−/+
Bartlett et al., 1992 (US)	IMI	48 (NA[4])	Tiestalls, freestalls, other loose housing, or pasture, considered in summer and winter	Winter housing in tiestalls associated with highest prevalence of environmental streptococci IMI, and loose housing types in winter (primarily freestalls) associated with a lower prevalence. No summer differences.[5]	−/=
Ferguson et al., 2007 (Italy/Sicily)	IMI	101 (5,261)	Tiestalls; bedded pack; freestalls; paddock	Prevalence of *Streptococcus* IMI was highest in tiestalls and lowest in paddock housing. No difference IMI prevalence for other bacteria.	−/=
Condas et al., 2017 (Canada)	NAS IMI	89 (98,233 samples; 5,149 cows)	Tiestalls; freestalls; bedded pack	Overall prevalence of NAS IMI similar across barn types; however, tiestalls had higher prevalence of *Staphylococcus simulans*, *Staphylococcus xylosus*, *Staphylococcus cohnii*, *Staphylococcus capitis*, *Staphylococcus arlettae*, and *Staphylococcus saprophyticus* IMI compared with freestalls. Prevalence of *Staph. simulans*, *Staph. xylosus*, *Staphylococcus epidermidis*, and *Staph. cohnii* IMI higher in tiestalls vs. bedded packs.	−/=
Nyman et al., 2009 (Sweden)	Mastitis	70 (1,189)	Freestalls with potential relocation to tiestalls	Housing first-parity cows in tiestalls 1 mo before calving reduced number of CM[6] treatments from −10 to 60 d around calving.	+
	SCC			No difference in number of first-parity cows with SCC ≥200,000 cells/mL at first test-day postpartum and no difference in log(SCC).	=
Ericsson Unnerstad et al., 2009 (Sweden)	Mastitis	571 (734)	Tiestalls with different dimensions vs. loose housing	Reduced odds of isolating *Escherichia coli* in short tiestalls vs. loose housing. Higher odds of isolating *Staphylococcus aureus* in tiestalls vs. cold cubicle housing. No difference for CNS, *Klebsiella* spp., *Arcanobacterium pyogenes*, *Streptococcus dysgalactiae*, or *Streptococcus uberis*.	+/−/=
Barnouin et al., 2005 (France)	Mastitis	297 (20,084)	Tiestalls; freestalls; straw yard	Housing system was a predictor of CM; freestalls did not differ from tiestalls; relative risk was highest in straw yards.	=/+
Svensson et al., 2006 (Sweden)	Mastitis	107 (2,126)	Comparison of (1) straw-bedded group pen; (2) cubicles with concrete alleys; (3) long tiestalls (cows can rise/lie when lockable feeding barriers are closed); (4) short tiestalls (cows have unlimited access to feeding table; space above table is needed for unrestricted rising/lying); (5) "other"	Housing in the period of 2 mo prepartum predicted veterinarian-treated CM at −7 to 30 d postpartum. Differences between groups not reported (lowest percentage of animals with veterinary treated CM found in long tiestalls and "other" housing, and highest percentage in the cubicle system). Housing variable not included in multivariable analyses.	=/+
Bendixen et al., 1986 (Sweden)	Mastitis	900 (NA)[7]	Swedish red and white (SRB) and Swedish Friesian (SLB) kept tied year-round, or tied during winter with summer pasture access	Cows of both breeds with pasture access had a lower risk of mastitis while on pasture; however, when adjustments were made for herd size distribution, zero-grazing SRB cows had a decreased risk of mastitis.	−/+
	Teat injuries			Cows of both breeds with pasture access had lower risk of tramped teat while on pasture; however, when adjustments were made for herd size distribution, zero-grazing SRB cows had a decreased risk of tramped teat.	−/+

Continued

Table 3 (Continued). Articles comparing udder health in tiestalls versus less-restrictive systems [listed for each study are condition, country, number of herds and total number of cows, comparison being made, results (with statements referencing "no difference" representing $P \geq 0.05$), and the direction of these results]

Study (country)	Condition[1]	No. of herds (no. of cows)	System comparison[2]	Results	Effect[3]
Hovinen et al., 2009 (Finland)	Mastitis	182 (NA)	Moved from tiestall or loose housing + conventional milking to loose housing with either automatic or conventional milking.	In herds with automatic milking systems, mastitis treatments decreased when cows were moved loose housing but increased in conventional-milking herds.	−/+
	SCC			Before housing change, lower log(SCC) in tiestalls vs. loose housing. Increase in new high SCC cows after the change, but no difference in percentage of high SCC cows.	+/=
Olde Riekerink et al., 2008 (Canada)	Mastitis	106 (3,033 samples)	Tiestalls, freestalls, and others (straw pack, combined, or unknown)[8]	Higher IR[9] of CM in tiestalls for *Staph. aureus*, *Strep. uberis*, CNS, and *Streptococcus* spp. Lower IR for *Klebsiella* spp. in tiestalls. In sum, the overall IR was higher in tiestalls.	−/+
Gustafson, 1993 (Sweden)	Mastitis	1 (65)	Cows either permitted outdoor access (2–3 km/d from May to Oct.; 400–800 m/d for rest of year) or remained in tiestalls (1.2 × 2.15 m + rubber mats and 2 kg chopped straw and sawdust/d); for behavioral recording, cattle in both groups were moved to an individual stall	No difference between groups in total # of mastitis treatments. Tied cows without exercise had higher frequency of treatments 0–2 mo after calving (which coincided with high milk SCC for untreated cows in this group). Exercised cows had higher frequency of treatments in mid-lactation (but this did not coincide with higher SCC for untreated cows in this group).	=
	SCC			Excluding cows treated for mastitis, tied cows without exercise had greater SCC in first month after calving. No differences after first mo.	−/=
Kalmus et al., 2006 (Estonia)	Mastitis	11 (1,063)	Freestalls, short tiestalls (≤175 cm), long tiestalls (>175 cm)	Moving heifers from tiestalls to calving area <14 d before calving increased CM risk at parturition. No difference in CM rate in freestall and tied cattle	=
Levison et al., 2016 (Canada)	Mastitis	59	Tiestalls vs. loose housing (freestalls or bedded pack)	IR of CM not different between tiestalls and loose housing	=
Ostojić-Andrić et al., 2011 (Serbia)	Mastitis	6 (400)	Tied without exercise vs. loose housed with and without grazing	No difference in percentage of cattle with mastitis in the different housing systems	=
Whist et al., 2006 (Norway)	Mastitis	164 (784 samples from CM cases)	Tiestalls vs. freestalls	Trend for more cases of CM caused by *E. coli* and fewer caused by *Staph. aureus* in freestalls vs. tiestalls, but the differences were not significant.	=
Hultgren, 2002 (Sweden)	Mastitis	196 (NA)	Cows moved from short tiestalls (+ 24 h access to feed manger) or long tiestalls (0.4–0.5 m longer + lockable feeding barriers and elevated manger) to cubicles or indoor straw yards.	After transition from long tiestalls to cubicles, monthly herd IR of CM decreased in the period of >18 mo after relocation.[10] After relocation from long tiestalls to straw yards, monthly herd IR[8] of CM[4] decreased in the period of >6–12 mo.[11]	−/=
	SCS			After relocation from short tiestalls to cubicles, monthly herd prevalence of high SCCs decreased for a period of 12 mo.[12]	−/=
	Teat injuries			After relocation from long tiestalls to straw yards, monthly herd IR[7] of teat injuries decreased in the period of >18 mo.[13] After relocation from short tiestalls to cubicles, monthly herd-incidence rate of teat injuries decreased after 12 mo.[14] After relocation from short tie stalls to straw yards, monthly herd IR[8] of teat injuries decreased.	−/=
Kivaria et al. 2007 (Tanzania)	Mastitis	87 (317)	Presence or absence of tethering	Tethered animals had higher odds of first occurrence of CM.[4] Housing type did not appear to contribute to overall IR of CM.	−/=

Continued

Table 3 (Continued). Articles comparing udder health in tiestalls versus less-restrictive systems [listed for each study are condition, country, number of herds and total number of cows, comparison being made, results (with statements referencing "no difference" representing $P \geq 0.05$), and the direction of these results]

Study (country)	Condition[1]	No. of herds (no. of cows)	System comparison[2]	Results	Effect[3]
Simensen et al., 2010 (Norway)	Mastitis	812 (21,235)	Tiestall vs. freestall	For large herds (>45 cows), IR of mastitis was lower in freestalls. No differences when all herd sizes were considered together.	−/=
	SCC			For large herds (>45 cows), bulk milk SCC was higher in freestalls. No differences when all herd sizes considered together.	+/=
	Teat injuries			IR of teat injuries was lower in freestalls.	−
Bakken, 1981 (Norway)	Mastitis	343 (NA)	Tiestall vs. freestall; freestall cubicles were an average of 14 cm longer that tiestalls in the cowhouse; daily amount of litter was larger in the freestall systems	Lower incidence of CM and subclinical mastitis in loose-housed herds across the 3-yr study. Lower frequency of re-isolation of *Staph. aureus* and other bacteria in loose-housed herds, and lower new infection rate of healthy udders.	−
	Teat injuries			Lower incidence of tramped teat in loose-housed herds across the 3 yr study.	
Popescu et al., 2013 (Romania)	Mastitis	80 (3,192)	Tiestalls (160–250 cm × 85–190 cm; straw or sawdust bedding (<1.5 kg/d)) + regular outdoor exercise (paddock, pasture or both) vs. no exercise	Percentage of cows with mastitis increased without exercise.	−
Popescu et al., 2014 (Romania)	Mastitis	60 (2,624)	Tiestalls (160–250 cm × 85–190 cm; most with straw or sawdust bedding (≤1.5kg/d); some had access to pasture or paddocks); cubicles (sawdust bedding); straw yards	Percentage of cows with mastitis higher in tiestalls.	−
Valde et al., 1997 (Norway)	Mastitis	592 (NA)	Tiestalls vs. freestalls	Tiestalls had higher rate of CM.	−
Bendixen et al., 1988b (Sweden)	Mastitis		Details given in Bendixen et al., 1986 (see above)	Higher incidence of mastitis while housed vs. on pasture. Decreased incidence in loose-housed vs. zero-grazing cows in late lactation. No difference in early lactation.	−/=
Bielfeldt et al., 2004 (Switzerland)	SCS	1,674 (NA)	Tiestalls vs. loose housing; time interval in which housing changed from tied to loose (517 of the included farms)	SCS lower in tiestalls vs. loose housing. SCS also lower in tiestalls compared with the transition period to loose housing.	+
Varner et al., 1983 (not known)	SCC	2 (86)	2 herds of cattle moved from tiestalls to freestalls (including a change in diet); half the cattle from herd 1 remained in tiestalls and half were moved 100 m across a deep flush gutter; cattle from herd 2 were transported 7 km	CM was detected in 5 moved and 2 tied cattle within 3 wk after relocation.[15] SCC was lower in moved cows from herd 1 at 1 and 7d after relocation compared with tied controls, but no consistent effect was present.	−/=
Eckelkamp et al. 2016 (US)	SCC	214 (NA)	Tiestalls, compost bedded-pack barns, freestalls, conventional bedded-pack barns, or pasture	SCC not different among herds using compost bedded pack, freestalls, and tiestalls.	=
Dechow et al., 2011 (US)	SCS	314 (NA)	Freestalls + no outdoor access; freestalls + outdoor access; tiestalls + no outdoor access; tiestalls + outdoor access and TMR; tiestalls + outdoor access (but no TMR)	Tiestalls with outdoor access + no TMR had lower SCSs than other housing types.	+/−
Sabbioni et al., 2012 (Italy)	SCS	7 (470)	Freestalls + TMR vs. tiestalls + "traditional feeding"	SCS was lower in freestalls vs. tiestalls.	−
Dohoo et al., 1984 (Canada)	Teat injuries	32 (NA)	Tiestall vs. loose housing; in both treatments, 2/3 of farmers exercised cows outside in winter; all farmers exercised cows in summer	After controlling for frequency of ration balancing on the farms, there was a negative association between tiestall housing and lactational IR of teat injury.	+

Continued

Table 3 (Continued). Articles comparing udder health in tiestalls versus less-restrictive systems [listed for each study are condition, country, number of herds and total number of cows, comparison being made, results (with statements referencing "no difference" representing $P \geq 0.05$), and the direction of these results]

Study (country)	Condition[1]	No. of herds (no. of cows)	System comparison[2]	Results	Effect[3]
Krohn and Munksgaard, 1993 (Denmark)	Teat injuries	1 (48)	Cattle housed in either (1) loose housing + access to feeding table, deep bedding, yard and pasture, with milking 2 times/d; (2) tiestalls (1.25 × 1.8m with neckbar tie), no exercise, concrete floor + 1 kg straw, 2 times/d milking; (3) tiestalls, rubber mats + 2 kg straw, 4 times/d milking, no exercise; (4) same as group 3 but with 1 h daily exercise in the yard.	More teat injuries in the confined tiestalls with 1 kg of straw vs. loose housing and less restrictive tiestalls. Teat injuries were higher in tiestalls with no exercise and 2 times/d milking than in all other housing systems.	−
Bendixen et al., 1988a (Sweden)	Teat injuries	640 (11,653 episodes)	Tiestalls with pasture; tiestalls without pasture; loose housing	For cows of the Swedish Red and the Holstein Friesian breed, loose-housed cows and tied cows with pasture had a lower incidence of tramped teat compared with tied cows with no pasture.	−
Mattiello et al., 2005 (Italy)	Teat injuries	47 (NA)	Tiestalls with varying dimensions and durations of grazing during spring and fall; majority of herds allowed <30 d of grazing each season; stalls ranged from 96–150 cm wide × 145–203 cm long; almost all stalls had concrete floor with straw or sawdust (1.5–2.5 kg/d)	Teat injuries more common in narrower tiestalls.	−
Regula et al., 2004 (Switzerland)	Teat injuries	134 (NA)	Tiestalls + summer outdoor exercise; tiestalls + year-round outdoor exercise; loose housing + year-round outdoor exercise	Teat injuries less frequent in loose housing compared with tiestall + summer exercise and in tiestalls with year-round exercise compared with summer exercise.	−

[1]Studies addressing multiple conditions have been included within the "mastitis" subsection.

[2]Housing types being compared in each study; stall dimensions and other characteristics are specified for all housing types if this information is provided in the article.

[3]+ indicates a beneficial effect of tiestall housing, − indicates a negative effect, and = indicates no statistical different at $P \geq 0.05$ unless otherwise specified.

[4]NA indicates information is either not applicable or has not been provided.

[5]Freestalls in winter were associated with higher coliform IMI; however, this result could not be interpreted due to the grouping of other loose housing types with tiestalls.

[6]CM = clinical mastitis.

[7]The number of herds varied from 900 to 1,021 across 4 yr of study.

[8]We only report the results pertaining to tiestalls and freestalls, because the "other" housing category may have included farms with both tied and loose housing.

[9]IR = incidence rate.

[10]No difference before this period; also no difference when cows were relocated from short tiestalls to straw yards.

[11]No differences in other periods, and no differences when cows were relocated from short tiestalls to cubicles.

[12]No differences were observed earlier than 12 mo; also no differences when cows were relocated from short tiestalls to straw yards, or long tiestalls to cubicles or straw yards.

[13]No difference before this period; also no difference when cows relocated from short tiestalls to straw yards.

[14]No differences were observed earlier than 12 mo.

[15]Not tested statistically.

Table 4. Articles comparing transition diseases tiestalls versus less-restrictive systems [listed for each study are the country, number of herds and total number of cows, the comparison of housing systems being made, dimensions and feeding regimens of the tiestall herds and the other housing type(s), the results (with statements referencing "no difference" representing $P \geq 0.05$), and direction of these results]

Study (country)	No. of herds (no. of cows)	System comparison[1]	Results	Effect[2]
Corazzin et al., 2010 (Italy)	24(NA[3])	Tiestalls [mean (min, max) stall width = 1.1 m (0.8, 1.8); length = 1.7 m (1.5, 2.0)] with vs. without summer grazing on mountain pasture (for a mean ± SD of 93 ± 6 d)	No difference in percentage of cows with vulvar discharge between tiestall systems with vs. without grazing; however, the percentage of cows increased after vs. during grazing.	=/+
Ostojić-Andrić et al., 2011 (Serbia)	6 (400)	Tied without exercise vs. loose housed with and without grazing	No difference in percentage of cows with vulvar discharge, but higher percentage of cows with dystocia in loose housing.	=/+
Gustafson, 1993 (Sweden)	1 (65)	Cows either permitted outdoor access (2–3 km/d from May to Oct.; 400–800 m/d for rest of year) or remained in tiestalls (1.2 × 2.15 m + rubber mats and 2 kg chopped straw and sawdust per d); for behavioral recording, cattle in both groups were moved to an individual stall	No difference in number of treatments for ketosis or distribution on ketone classes 1–3.	=
Bendixen et al., 1986 (Sweden)	900 (NA)[4]	Swedish red and white (SRB) and Swedish Friesian (SLB) kept tied year round, or tied during winter with summer pasture access	Cows of both breeds with pasture access had a lower risk of dystocia and ketosis during the pasture period. SRB cows had increased risk of retained placenta and parturient paresis during the pasture period.	−/+
Dohoo et al., 1984 (Canada)	32 (NA)	Tiestall vs. loose housing. In both treatments, 2/3 of farmers exercised cows outside in winter; all farmers exercised cows in summer	After controlling for frequency of ration balancing, there was a positive association between tiestall housing and lactational IR[5] of dystocia. Also, a positive association between tiestall housing and lactational IR[4] of abomasal displacements and of clinical and subclinical ketosis; however, for these latter associations, manure handling procedures used as a proxy for housing type in analysis.	−/=
Popescu et al., 2013 (Romania)	80 (3,192)	Tiestalls [160–250 cm × 85–190 cm with straw or sawdust bedding (≤1.5kg/head per d)] + regular outdoor exercise (paddock, pasture, or both) vs. no exercise.	Percentage of dystocic cattle was higher with no exercise. No difference in percentage of cows with vulvar discharge.	−/=
Popescu et al., 2014 (Romania)	60 (2,624)	Tiestalls [160–250 cm × 85–190 cm; most with straw or sawdust bedding (≤1.5 kg/d); some had access to pasture or paddocks]; cubicles (sawdust bedding); straw yards	Percentage of dystocic cattle was higher in tiestalls. No difference in percentage of cows with vulvar discharge.	−/=
Bruun et al., 2002 (Denmark)	2,144 (102,060)	Herd-level variables were evaluated, such as housing type (tiestall, cubicle, or deep bedded) and grazing (yes, no, grazing for dry cows only, or exercise possibility)	No effect of housing type on the odds of metritis. (Odds of metritis were lower for grazing cows, vs. zero-grazing or dry-cow-only grazing; however, the interaction between housing type and grazing level was not evaluated.)	=
Simensen et al., 2010 (Norway)	812 (21,235)	Tiestalls vs. freestalls	Compared with tiestalls, IR was lower in freestalls for ketosis and other diseases.	−
Valde et al., 1997 (Norway)	592 (NA)	Tiestalls vs. freestalls	Tiestalls had higher ketosis risk.	−

[1]Housing types being compared in each study. Stall dimensions and other characteristics are specified for all housing types if this information is provided in the article.

[2]Where + indicates a beneficial effect of tiestall housing, − indicates a negative effect, and = indicates no statistical difference at $P \geq 0.05$ unless otherwise specified.

[3]NA indicates information is either not applicable or has not been provided.

[4]The number of herds varied from 900 to 1,021 across 4 yr of study.

[5]IR = incidence rate.

Table 5. Articles comparing other diseases or conditions in tiestalls versus less-restrictive systems [listed for each study are the disease or condition, the country, number of herds and total number of cows, the comparison of housing systems being made, dimensions and feeding regimens of the tiestall herds and the other housing types, results (with statements referencing "no difference" representing $P \geq 0.05$), and direction of these results]

Study (country)	Condition	No. of herds (no. of cows)	System comparison[1]	Results	Effect[2]
Ostojić-Andrić et al., 2011 (Serbia)	Ocular/nasal discharge, respiratory rate, cough	6 (400)	Tied without exercise vs. loose housed with and without grazing	Percentage of cattle with nasal or ocular discharge higher in tied cattle. Frequency of coughing/15 min higher in loose cattle. No difference in percentage of cows with increased respiratory rate.	−/+/=
	Integument alterations			Percentage of cows with at least 1 lesion was lower in loose systems. Percentage of cows with a least 1 hairless patch (and no lesion) was also lower.	−
	Mortality			Reduced mortality percentage in loose housing but a higher percentage of down cows.	−/+
	Diarrhea			No difference in percentage of cows with diarrhea in the different systems.	=
Gustafson, 1993 (Sweden)	Bloat	1(65)	Cows either permitted outdoor access (2–3 km/d from May to Oct.; 400–800 m/d for rest of year) or remained tied (1.2 × 2.15 m + rubber mats and 2 kg chopped straw and sawdust per d)	Tied cows without exercise more frequently treated for bloat.	−
	Veterinary treatments			Cows without exercise required more vet treatments in the 2 wk after calving. Difference between groups increased with lactation number. Exercised cows tended[3] to recover faster from parturient paresis after treatment. No differences after 2 wk.	−/=
Geden et al., 1990 (US)	Cattle lice	21 (210)	Stanchion vs. freestall housing	Cattle housed in stanchion barns more likely to be infested with cattle lice (Anoplura and Mallophaga).	−
Uehlinger et al., 2011 (Canada)	*Giardia duodenalis*	20 (596)	Tiestall vs. freestall	No difference in prevalence rate among housing types.	=
Wade et al., 2000 (US)	*Giardia* sp.	109 (2,943)	Tiestall vs. freestall, and "other" housing[4]	For milking cows, summer housing in tiestalls associated with infection risk compared with "other" housing. For bred heifers, there was no difference between freestall and tiestall on risk of infection.	−/=
Mattiello et al., 2009 (Italy)	Integument alterations	14 (NA)	Cubicles vs. tiestalls (with and without access to mountain pasture in summer)	No differences between tiestalls and freestalls in presence of hairless areas, but presence was higher in cattle with summer pasture access (hypothesized to be related to parasitic infection).	= /+
	Ocular/nasal discharge, cough			No difference between tiestalls and freestalls in percentage of cattle with ocular or nasal discharge or coughing.	=
	Diarrhea			No difference between tiestalls and freestalls in percentage of cattle with diarrhea.	=
Corbett et al., 2018a (Canada)	Johne's disease	362 (NA)	Tiestall vs. freestall, bedded pack, and others	Environmental prevalence of MAP[5] was lower in tiestalls compared with freestalls.	+
Corbett et al., 2018b (Canada)	Johne's disease	148 (NA)	tiestall, freestall, loose housing, or other	No difference in environmental prevalence of MAP between tiestalls and freestalls across 2 sample periods. Tiestalls not compared with loose housing.	=
Wolf et al., 2014 (Canada)	Johne's disease	526 (NA)	Tiestall vs. freestall or loose housing	No difference in environmental herd-level MAP prevalence between tiestalls and other housing. Because tiestall housing was confounded with herd size, a separate analysis compared herds with <100 cows; again, no difference between tiestalls and other housing types for these small herd sizes.	=

Continued

Table 5 (Continued). Articles comparing other diseases or conditions in tiestalls versus less-restrictive systems [listed for each study are the disease or condition, the country, number of herds and total number of cows, the comparison of housing systems being made, dimensions and feeding regimens of the tiestall herds and the other housing types, results (with statements referencing "no difference" representing $P \geq 0.05$), and direction of these results]

Study (country)	Condition	No. of herds (no. of cows)	System comparison[1]	Results	Effect[2]
Wolf et al., 2015 (Canada)	Johne's disease	601 (5,588 samples)	Tiestall, freestall, or loose housing	No difference in MAP culture results for lactating-cow housing areas.	=
Regula et al., 2004 (Switzerland)	Medical treatments	134 (NA)	Tiestall + summer outdoor exercise; tiestall + year-round outdoor exercise; loose housing + year-round outdoor exercise	Farms with loose housing had a lower incidence of medical treatments compared with those with tiestalls and only summer exercise.	−
Thomsen et al., 2006 (Denmark)	Mortality	6,839 (NA)	Tiestall; freestall (cubicles); freestall with deep litter	Tiestalls were associated with highest mortality risk in the first 100 d of lactation compared with freestalls with cubicles). Freestalls with deep litter were associated with lowest risk.	−
Reimus et al., 2020 (Estonia)	Mortality	212 (79,767)[6]	Tiestall, freestall, or combined	Herds using tiestalls had higher mortality rates compared with herds using freestalls.	−
Alvåsen et al., 2012 (Sweden)	Mortality	4,252 (NA)	Tiestall vs. freestall with automatic or conventional milking system	Herds with tiestalls had the lowest numerical MR[7] but it was not statistically different. There was an interaction between housing type and milk yield on MR, with milk yield affecting MR in freestalls but not in tiestalls.	=
McConnel et al., 2008 (US)	Mortality	953 (NA)	Tiestall vs. "other" (survey questions included use of tiestall and freestall, as well as use of pasture, drylot, or no outside area)	In univariable analysis, tiestall housing associated with lower mortality rates. No multivariable effect of housing.	+/=
Bielfeldt et al., 2006 (Switzerland)	Culling risk	1,674 (71,469)	Tiestalls vs. loose housing; 517 herds transitioned from tiestall to loose housing during the study; data limited to those herds that did not use alpine summer pasturing	Loose-housed cattle had lower relative culling rate vs. tied cattle. Highest relative culling rate was during the change from tiestall to loose housing.	−/+
Dechow et al., 2011 (US)	Mortality, early culling	314 (NA)	Freestall + no outdoor access; freestall + outdoor access; tiestall + no outdoor access; tiestall + outdoor access with TMR feeding; tiestall + outdoor access (but no TMR)	Tiestalls had more aged cows than freestalls when these were the exclusive housing types used, and a lower percentage of the herd culled by 60 DIM. The mortality rate was lower in tie stalls compared with freestalls. Tiestalls with outdoor access (but no TMR) also performed better than tiestalls and freestalls with complete confinement.	+/−
Popescu et al., 2013 (Romania)	Mortality	80 (3,192)	Tiestalls (160–250 cm × 85–190 cm) with straw or sawdust (≤1.5kg /head per d) with regular outdoor exercise (paddock, pasture or both) vs. no exercise.	Mortality higher in cows not permitted exercise. The percentage of down cows was also higher.	−
	Respiratory disorders			No difference in percentage of cows with nasal or ocular discharge, percentage of cows with increased respiratory rate, or in coughing frequency.	=
Popescu et al., 2014 (Romania)	Respiratory disorders	60 (2,624)	Tiestalls (160–250cm x 85–190cm; most used straw or sawdust bedding (≤1.5kg/d); some had access to pasture or paddocks); cubicles (sawdust bedding); straw yards	The percentage of cattle with ocular discharge and increased respiratory rate higher in tiestalls. No difference in frequency of coughing or percentage of cows with nasal discharge.	−/=
	Diarrhea			Percentage of cattle with diarrhea higher in tiestalls.	−
	Integument alterations			Percentage of cattle with at least 1 hairless patch higher in tiestalls. No difference in percentage of cows with at least one lesion.	−/=
	Mortality			Mortality higher in tiestall cattle. Percentage of downer cows higher in loose housing.	−/+

Continued

Table 5 (Continued). Articles comparing other diseases or conditions in tiestalls versus less-restrictive systems [listed for each study are the disease or condition, the country, number of herds and total number of cows, the comparison of housing systems being made, dimensions and feeding regimens of the tiestall herds and the other housing types, results (with statements referencing "no difference" representing $P \geq 0.05$), and direction of these results]

Study (country)	Condition	No. of herds (no. of cows)	System comparison[1]	Results	Effect[2]
Corazzin et al., 2010 (Italy)	Respiratory disorders	24 (NA)	Tiestalls [mean (min, max) stall width = 1.1 m (0.8, 1.8); length = 1.7m (1.5, 2.0)] with vs. without summer grazing on mountain pasture (for a mean ± SD of 93 ± 6 d)	No difference in percentage of cows with nasal discharge or cough between tiestall systems with vs. without grazing; however, the percentage of cows with a cough decreased during the grazing phase.	=/−
	Enteric health			No difference in percentage of cows with soft feces between tiestall systems with vs. without grazing; however, percentage of cows with soft feces increased during grazing.	=/+
	Injury			The percentage of cows with injuries decreased during the grazing phase. The percentage of cows with injuries also decreased after grazing compared with cows not permitted grazing.	−
Busato et al., 2000 (Switzerland)	Traumatic injury	152 (1,856)	Tiestalls vs. free housing	Tiestalls associated with increased odds of joint injuries vs. free housing. No difference in soft tissue and claw injuries between housing types.	−/=
Corazzin et al., 2009 (Italy)	Nose, eye discharge	24 (NA)	Tiestalls [mean (min, max) stall width = 1.1m (0.8, 1.8); length = 1.7m (1.1, 2.0)] with vs. without summer grazing on mountain pasture	No difference in the percentage of cows with nasal or ocular discharge.	=
Smith et al., 1998 (US)	Winter dysentery	36 (NA)	Tiestall, freestall, stanchion, or stanchion + freestall	Housing in tiestalls or stanchions increased herd-level risk of outbreaks compared with freestalls.	−

[1]Housing types being compared in each study. Stall dimensions and other characteristics are specified for all housing types if this information is provided in the article.

[2]Where + indicates a beneficial effect of tiestall housing, − indicates a negative effect, and = indicates no statistical different at $P \geq 0.05$ unless otherwise specified.

[3]Tendency not significant at $P < 0.05$.

[4]Information is either not applicable or has not been provided.

[5]MAP = *Mycobacterium avium* ssp. *paratuberculosis* (the etiologic agent of Johne's disease).

[6]Numbers reflect the first year of the project. In the second year, records from 80,691 cows were obtained.

[7]MR = mortality rate.

pregnancy rate, fertility indices, calving-to-conception intervals, incidence of anestrus, prevalence of anovulation, incidence of cystic ovaries, and general reproductive performance. The exception (Hackett et al., 1984), reported increased days to first estrus and days to first service in freestall versus tiestall housing.

Milk Yield. As milk production is an indirect welfare metric, the results are provided in Supplemental Table S2 (http://dx.doi.org/10.6084/m9.figshare.14769567; Beaver et al., 2021). Fifteen studies were included in this section. Moving cattle from tiestalls to freestalls or other types of loose housing typically resulted in decreased milk production, although production recovered or exceeded the tiestall baseline in timespans ranging from 1 d to 1 yr after the move. Variable results for milk yield were found in studies comparing tiestalls to loose housing.

Natural Behavior

Studies evaluating the effect of tiestall housing on the behavior of dairy cattle (n = 19) are shown in Table 6. Eight of these studies compared tiestall to freestall or loose housing, 5 compared tiestall with different levels of outdoor access, and 5 addressed both of these aspects. One study evaluated the effect of moving cows from pasture to tiestalls and back.

Lying behavior was most frequently reported in studies comparing tiestalls to loose housing. All included studies found at least some negative effects of tiestalls on lying patterns, including increased time standing idle and longer standing bouts (Haley et al., 2000), greater frequency of lying interruptions (Jensen, 1999), reduced synchronization of lying behavior (Krohn et al., 1992), more interruptions of the lying down movement (Krohn and Munksgaard, 1993), abnormal lying patterns (Shepley et al., 2019) more collisions lying down (Plesch et al., 2010; Popescu et al., 2014; Shepley et al., 2019), and a greater percentage of cows lying at least partially outside the lying area (Mattiello et al., 2009; Plesch et al., 2010; Ostojić-Andrić et al., 2011). In one study, however, (Müller et al., 1989), the reported benefits of loose housing could not be differentiated from the presence or absence of bedding. Housing cattle in tiestalls also had negative effects on other behavior patterns, including increases in the frequency of licking the ground or equipment, self grooming, bar biting, and leaning against equipment (Krohn, 1994; although these differences were not always tested statistically). Two studies also investigated feeding behavior (Colenbrander et al., 1991; Haley et al., 2000;), but the results were neutral. Only one study (Popescu et al., 2014) found behavioral benefits in tiestalls, in the form of reduced agonistic interactions.

The studies evaluating the effect of outdoor access for tied cattle reported mixed results for lying behavior (Krohn and Munksgaard, 1993; Gustafson and Lund-Magnussen, 1995; Loberg et al., 2004; Corazzin et al., 2009, 2010), and the results for agonistic and social interactions were similarly mixed (Loberg et al., 2004; Popescu et al., 2013). There was a reduction in stereotypies and other abnormal behaviors when cattle were permitted regular outdoor access, including a reduction in self grooming (Loberg et al., 2004), tongue playing (Corazzin et al., 2010), rubbing against equipment, and bar biting (Krohn, 1994). Cattle in tiestalls without daily exercise opportunities also spent more time licking and sniffing the ground or other objects (Krohn, 1994; Loberg et al., 2004) and less time ruminating (Loberg et al., 2004). When released, tied cattle without regular outdoor access spent more time engaged in play behavior and trotting (Loberg et al., 2004), which was judged to be compensatory.

Affective State

Few studies attempted to evaluate affective state as an outcome measure; those that did (n = 14) are included in Table 7. Several of the affective states addressed were derived from the WQA protocol including "absence of prolonged hunger" (evaluated by means of BCS; Ostojić-Andrić et al., 2011; Popescu et al., 2013, 2014), and good "human–animal relationship" (evaluated via avoidance distance; Mattiello et al., 2009; Popescu et al., 2013, 2014). The theme of "comfort" [expressed as "cow comfort" (Haley et al., 2000), "comfort situation" (Tarantola et al., 2016), and "comfort around resting" (Plesch et al., 2010; Ostojić-Andrić et al., 2011; Popescu et al., 2013, 2014)] was addressed in 6 of the 14 studies. Stress, as measured by physiological parameters such as cortisol, was addressed in 7 studies (Varner et al., 1983; Redbo, 1992, 1993; Higashiyama et al., 2007; Veissier et al. 2008; Tarantola et al., 2016; Peric et al., 2017).

When cattle were loose housed, or when tied cattle were let outdoors, affective state was generally improved. Specifically, studies reported reduced levels of comfort (Haley et al., 2000; Plesch et al., 2010; Ostojić-Andrić et al., 2011; Popescu et al., 2013, 2014), increased physiological stress measures (Redbo, 1992, 1993; Higashiyama et al., 2007; Tarantola et al., 2016), and a more negative emotional state (Popescu et al., 2013, 2014) for cows kept in tiestalls. However, 3 studies reported positive aspects of tiestalls: Popescu et al. (2014) and Mattiello et al. (2009) reported lower avoidance distances in tied cattle (indicative of a good "human–animal relationship"), and Ostojić-Andrić et

Table 6. Articles comparing natural behaviors in tiestalls versus less-restrictive systems [listed for each study, where specified, are the behavior(s) under study, country, number of herds and total number of cows, comparison of housing systems being made, dimensions of the tiestall herds and the other housing type(s), the results (with the statement "no difference" representing $P \geq 0.05$), and the direction of these results]

Study (country)	Measure	No. of herds (no. of cows)	System comparison[1]	Results	Effect[2]
Krohn, 1994 (Denmark)	Abnormal behavior	1 (48)	Cattle housed in either (1) L: Loose housing + access to feeding table, deep bedding, yard and pasture, 2 time/d milking; (2) TN1: tiestall (1.25 × 1.8 m with neckbar tie), no exercise, concrete floor + 1 kg straw, 2 times/d milking; (3) TN2: tiestall, rubber mats + 2 kg straw, 4 times/d milking, no exercise; (4) TE: same as Group 3 but + 1 h daily exercise in the yard.	Across all housing groups: frequency of bar biting was lowest in loose housing and duration of bar biting lowest in TE.[3] Frequency and duration of sniffing and licking ground or equipment higher in tiestalls vs. loose housing.[3] Frequency of leaning against equipment was higher in tiestalls.[3] Statistical comparisons were made between the tiestall groups only: frequency and duration of bar biting lower in TE vs. TN2. Frequency and duration of sniffing and licking ground or equipment (when all these behaviors were considered collectively) was lower and less frequent in TE.	−
	Grooming			Frequency of self-grooming and sniffing and licking other cows lower in loose housing vs. the 3 tiestall groups.[3] Compared with TE, cattle in TN1 rubbed against equipment with increased frequency and increased duration.	−
Popescu et al., 2013 (Romania)	Agonistic interactions	80 (3,192)	Tiestalls (160–250 cm × 85–190 cm) with straw or sawdust (≤1.5 kg/head per d) with regular outdoor exercise (paddock, pasture or both) vs. no exercise.	Higher frequency of butts/cow/h in cows permitted exercise. Frequency of displacements/cow/h higher without exercise.	+/−
Colenbrander et al., 1991 (NA[4])	Feeding behavior	1 (31)	Primiparous cows in tiestalls + individual feed boxes. Multiparous cows in freestalls + individual feeding facility. Tied cows housed within 2 steps of feed; freestall cows within ~15m.	In the first observation period, cattle in tiestalls (compared with freestalls) spent more time eating and ruminating, but bout length of these behaviors was shorter. No difference in time spent eating and ruminating in the second observation period. Bout length of ruminating continued to be shorter in tiestalls.	=
	Lying and standing behavior		Tiestall + restricted feeding vs. freestall + freely fed	No difference in lying and standing time between tiestall and freestall cattle.	=
Veissier, 2008 (France)	Locomotion motivation	1(30)	Phase 1: Freestall, or tiestall for durations from 1 d to 1 mo	After 1 d of tethering, cows spent more time and covered longer distance. Differences less clear after intermediate periods of tethering. However, when cows tethered for 1 mo, they spent more time walking and for a longer distance. No difference in walking speed or time spent trotting.	−/=
			Phase 2: Freestall, or tiestall for 1 mo. Some tied cows had daily access to exercise. All cows evaluated in an exercise arena at the end of the experiment	No difference in time spent trotting and distance covered between freestalls and tiestalls with 1 h/d of exercise. However, cattle that had been continuously tethered for 1 mo covered more distance and spent more time trotting after they were released. No difference in time spent walking.	−/=

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Table 6 (Continued). Articles comparing natural behaviors in tiestalls versus less-restrictive systems [listed for each study, where specified, are the behavior(s) under study, country, number of herds and total number of cows, comparison of housing systems being made, dimensions of the tiestall herds and the other housing type(s), the results (with the statement "no difference" representing $P \geq 0.05$), and the direction of these results]

Study (country)	Measure	No. of herds (no. of cows)	System comparison[1]	Results	Effect[2]
Loberg et al., 2004 (Sweden)	Lying behavior	1 (52)	Cattle in tiestalls (1.2 × 2.75 m; rubber mats + chopped straw) with either: exercise for 1 h/d on outdoor paddocks (either 3,220 or 2,040 m^2) (E7); exercise 2 times/wk (E2), exercise 1 time/wk (E1), or no exercise (E0)	No difference in duration of lying down between treatments.	=
	Aggressive interactions			Cows in E7 had fewer aggressive interactions than cows in E2 or E1. (E0 was not included in this analysis.)	=
	Social interactions			No difference in social interactions among the treatments. (E0 was not included in this analysis).	–
	Eating time			Cows in E7 were observed eating less often than cows in E2 or E1. (E0 was not included in this analysis.)	=
	Rumination			Cows in E7 ruminated more than cows in E2, which in turn ruminated more than cows in E1. (E0 was not included in this analysis).	?[4]
	Exploratory and play behavior			Cattle in E1 and E2 showed more exploratory behavior (sniffing and licking objects or the ground) than those in E7. More play behavior was seen with decreasing amounts of exercise (15% of observations for E7; 17% for E2; 27.5% for E1). (E0 was not included in this analysis.)	–
	Self-grooming			Cows in E1 performed more self-grooming than cows in other groups (E2 and E7). (E0 was not included in this analysis.)	–
	Locomotion			Mean percentage of walking and trotting increased with decreasing access to exercise. (E0 was not included in this analysis.)	–
Enriquez-Hidalgo et al., 2018 (Ireland)	Lying behavior	1 (48)	Moved from pasture to tiestall (1.35 × 1.2 m, 3 cm deep rubber mats for 12 d) then back to pasture.	Less time lying in early confinement (d 3) compared with the 2d before confinement, late confinement (d 10), and after confinement (d 13 and 14). When confined (vs. on pasture), lying bouts were shorter and more numerous.	–
Gustafson and Lund-Magnussen, 1995 (Sweden)	Lying behavior	1 (65)	Cows either permitted outdoor access (2–3 km/d from May to Oct.; 400–800 m/d for rest of year) or remained in tiestalls (1.2 × 2.15 m with a 50–60 cm neck chain, rubber mats + 2 kg of sawdust and straw per day). For behavioral recording, cattle in both groups were moved to an individual stall.	Tied cows without exercise had a longer phase 1 for lying down.[5] Cattle without exercise had more interruptions of pendulum movement. No difference in phase 2. Also, no difference in number of lying bouts/24 h between groups, or in time required to stand	–
Haley et al., 2000 (Canada)	Lying behavior	1(8)	Cows spent 3 wk in 2 housing types: (1) loose housing individually in box stalls (4.2 × 3.9 m) with mattress and 2 cm chopped straw and (2) tiestalls (1.8 × 1.3 m) with a neck chain and concrete floor with 2 cm chopped straw.	Loose-housed cows lay down longer than tied cows. Tied cows stood idle for longer. Frequency of lying was higher in loose housing vs. tiestalls as was frequency of standing. Standing bouts were longer in tiestalls. Changes in body position from lying to standing (and vice versa) were less frequent in tiestalls. Few differences in body, head, and leg positions during lying. No difference in lying-bout duration.	–/=
	Feeding behavior			No difference in time spent feeding between groups	=

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Table 6 (Continued). Articles comparing natural behaviors in tiestalls versus less-restrictive systems [listed for each study, where specified, are the behavior(s) under study, country, number of herds and total number of cows, comparison of housing systems being made, dimensions of the tiestall herds and the other housing type(s), the results (with the statement "no difference" representing $P \geq 0.05$), and the direction of these results]

Study (country)	Measure	No. of herds (no. of cows)	System comparison[1]	Results	Effect[2]
Jensen, 1999 (NA)	Lying behavior	1 (48)	Heifers brought in from pasture and housed individually on straw before study. In the experimental period (24 d), heifers were tethered in either (1) stalls + concrete floor for 24 d, (2) for the final 10 d, (3) for the final 3 d, or (4) controls (stayed in pens without tethering).	Number of lying bouts/24 h lower in heifers tethered for 3 d vs. all other groups. Mean duration of lying down and latency to lie were longer. Number of intentions to lie down (per lying time) was higher. Number of lying interruptions (per lying time) higher in heifers tethered for 3 or 10 d vs. controls. No difference in time spent lying down between treatments.	−/=
Popescu et al., 2014 (Romania)	Lying behavior	60 (2,624)	Tiestalls (160–250 cm × 85–190 cm; most used straw or sawdust bedding (≤1.5k g/d); some had access to pasture or paddocks); cubicles (sawdust bedding); straw yards	Duration of lying down movements was longer in tiestalls and percentage of lying down movements with collisions was also higher. No difference in percentage of cows lying partly outside the lying area.	−/=
	Agonistic interactions			Frequency of butts/cow per hour and displacements/cow per hour higher in loose housing.	+
Krohn et al., 1992 (NA)	Lying behavior	1 (48)	Cows housed in either: (1) a dairy cow park [deep-bedded stall (7 m^2/cow), feeding table, milking parlor (2 times/d milking), yard (35 m^2/cow) and pasture (0.4 ha/cow)]; (2) tiestalls, 2 times/d milking, no exercise; (3) tiestalls, 4 times/d milking, no exercise; (4) tiestalls, 4 times/d milking, daily exercise.	Lying behavior more synchronized on pasture than in tiestalls. No difference between the 3 tiestall groups. Synchronization on deep bedding was intermediate.	−
Krohn and Munksgaard, 1993 (Denmark)	Lying behavior	1 (48)	Cattle housed in either: (1) loose housing + access to feeding table, deep bedding (7 m^2/cow), yard (35 m^2/cow) and pasture (0.4 ha/cow), with milking 2 times/d; (2) Tiestalls (1.25 × 1.8 m with neckbar tie), no exercise, concrete floor + 1 kg straw, 2 times/d milking; (3) tiestalls, rubber mats + 2 kg straw, 4 times/d milking, no exercise; (4) same as Group 3 but with 1 h daily exercise in the yard.	Duration of the "lying-down pattern," which included time spent searching for a lying place, longer in tiestalls vs. loose housing. Cows in tiestalls took more time to examine the lying place, and interruptions in lying down movement were more frequent. Duration of lying down movement was longer in tiestalls with concrete compared with loose housing. Cattle in loose housing (vs. tiestalls) had shorter total lying times. Exercise had no effect on lying time, but kneeling duration shorter in the exercise groups. Kneeling duration also shorter in loose housing vs. tiestalls without exercise. Cows in loose housing spent more time lying with their head back or on the ground than cows in tiestalls. Cows loose housed on pasture spent more time lying flat on their sides and performed this behavior with greater frequency vs. tied cattle.	−
Mattiello et al., 2009 (Italy)	Lying behavior	14 (NA)	Cubicles vs. tiestalls (with and without access to mountain pasture in summer)	Lying down and rising were more abnormal in tiestalls. In freestalls, only 1 cow was observed to perform an abnormal movement	−
Müller et al. 1989 (Germany)	Lying behavior	1 (16)	Loose-housed (10 × 6 m pens with deep straw) vs. tiestalls (tethered in a nearby barn. Stanchions with a 40 cm chain attached to the 60-cm-high feeding trough. Concrete and partially slatted floor, no straw)	Tied cattle without straw had a lower frequency of lying down, changed position less often, investigated the lying area more often before lying down, and had a longer latency between first lying intention and the act of lying down. These differences were more pronounced after 12 wk vs. 1 wk of tethering.	−

Continued

Table 6 (Continued). Articles comparing natural behaviors in tiestalls versus less-restrictive systems [listed for each study, where specified, are the behavior(s) under study, country, number of herds and total number of cows, comparison of housing systems being made, dimensions of the tiestall herds and the other housing type(s), the results (with the statement "no difference" representing $P \geq 0.05$), and the direction of these results]

Study (country)	Measure	No. of herds (no. of cows)	System comparison[1]	Results	Effect[2]
Ostojić-Andrić et al., 2011 (Serbia)	Lying behavior	6 (400)	Tied without exercise vs. loose housed with and without grazing	Tied cattle took longer to lie down, had a higher percentage of lying down movements with collisions, and a higher percentage of lying outside the lying area.	−
Plesch et al., 2010 (Austria and Germany)	Lying behavior	35	Tiestall; cubicle; deep litter (sloped floor with straw bedding)	Compared with straw yards, cattle in tiestalls (and cubicles) had longer durations of lying down, more collisions lying down, and a greater percentage of cows lying at least partially outside the lying area.	−
Shepley et al. 2019 (Canada)	Lying behavior	1 (17)	Tiestall (1.41 m × 1.87 m, wood shavings, 4.4 cm pasture mats) vs. deep-bedded loose pen (3.35 m × 4.88 m, straw bedding, concrete floor + 1.9 cm-thick rubber mats)	No difference in total lying time between tied and loose cattle. Tied cattle more often made contact with housing equipment when attempting to lie down. Abnormal lying patterns were observed more frequently in tiestalls; cows in loose housing spent more time with their hind legs extended and their heads resting toward the back.	−
Corazzin et al., 2010 (Italy)	Tongue playing	24 (NA)	Tiestalls [mean (min, max) stall width = 1.1 m (0.8, 1.8); length = 1.7 m (1.5, 2.0)] with vs. without summer grazing on mountain pasture (for a mean ± SD of 93 ± 6 d)	Percentage of cows exhibiting tongue playing stereotypy tended[6] to be lower during grazing compared with before grazing and after grazing. No other differences between phases or systems.	=/−
	Standing behavior			Percentage of cows rising incorrectly tended[6] to be higher after grazing vs. in herds without grazing. Rising duration was longer before vs. after grazing. No other differences between phases or systems.	=/+
Corazzin et al., 2009 (Italy)	Standing behavior	24 (NA)	Tiestalls [mean (min, max) stall width = 1.1 m (0.8, 1.8); length = 1.7 m (1.1, 2.0)] with vs. without summer grazing on mountain pasture	Percentage of incorrect rising was higher with summer grazing. There was no difference in rising time, lying time, or % of incorrect lying down.	=/+

[1]Lists housing types being compared in each study. Stall dimensions and other characteristics are specified for all housing types if this information is provided in the article.

[2]Where + indicates a beneficial effect of tiestall housing, − indicates a negative effect, and = indicates no statistical different at $P \geq 0.05$ unless otherwise specified.

[3]No statistical test performed.

[4]NA indicates information is either not applicable or has not been provided. ? signifies that the effect is unclear.

[5]Phase 1 of the lying down pattern = time from when the cow began to move her head close to the ground "in a pendulum movement" (Gustafson and Lund-Magnussen, 1995, p. 27) until she was recumbent.

[6]Tendency not significant at $P < 0.05$.

al. (2011) observed a lower percentage of very lean cows (indicative of "absence of prolonged hunger").

DISCUSSION

Basic Health and Biological Functioning

The reviewed literature suggests that tiestalls are associated with reduced prevalence of various infectious and noninfectious foot lesions, most notably white line disease and DD, and a decreased prevalence of *E. coli* IMI. In contrast, loose housing was associated with reduced knee and hock lesions, injuries, and a lower prevalence of IMI caused by streptococci and staphylococci.

The differences in bacterial agents of IMI may be influenced by factors categorically associated with housing type, such as the milking process, or by factors largely independent of housing system (e.g., facility age, water sources, or other management practices; Bartlett et al., 1992; Sampimon et al., 2009). The majority of studies in the systematic review were cross-sectional, and these management factors were rarely described or adjusted for. The age of facilities, for example, was seldom referenced but was likely to be variable. Taponen et al. (2017) noted that IMI risk was highest in older freestall barns compared with newer tiestall or freestall facilities. It thus becomes difficult to identify the extent to which tethering itself influences the prevalence of these bacterial populations. In turn, differences in SCC between herd types (e.g., Hultgren, 2002; Dechow et al., 2011; Sabbioni et al., 2012) could partially be explained by these disparate bacterial communities; SCC patterns are known to vary according to the nature of the infection, with different lengths and peaks of high SCC attributed to specific bacterial agents (de Haas et al., 2004). Despite differences in causative agents of IMI between the housing types, mastitis prevalence was similar.

Freestall versus tiestall farms are more likely to have larger herd sizes and to make use of a milking parlor. Congruently, the odds of lameness may increase when cattle spend longer in the holding area before milking (Jewell et al., 2019) and with increasing herd size (see Oehm et al., 2019), although this effect is not always reported (Chapinal et al., 2013; Chapinal et al., 2014). The reviewed studies show no consistent relationship between lameness and housing type (e.g., Sogstad et al., 2005; Mattiello et al., 2009; Kara et al., 2011; Popescu et al., 2014). It should be noted that the majority of studies employed the same gait scoring systems for loose and tied cattle and assessed tied cattle during temporary release. Corazzin et al. (2010), however, used separate lameness scoring systems for tethered and loose cattle. Similarly, studies scoring cattle according to the WQA Protocol (e.g., in Popescu et al., 2014) were provided the option to score cattle when standing or walking; thus, different criteria may have been applied to different housing types. In-stall lameness assessment has been shown to result in a 27% underestimation of herd prevalence (Leach et al., 2009); conversely, gait scoring tied cattle that are unaccustomed to walking may conceivably lead to overestimation of lameness prevalence.

The higher prevalence of hoof lesions in loose housing may be partially attributed to herd-level management factors (e.g., bedding depth, alley scraping frequency, and hoof trimming routines; Cramer et al., 2009) as well as structural properties such as uneven surfaces and concrete flooring (Solano et al., 2015). Interestingly, Solano et al. (2016) found that odds of white line disease and sole ulcers were more than twice as high in freestalls versus deep-bedded packs. In the present review, freestalls and bedded packs were both classed as loose for purposes of comparison to tiestalls. Thus, the increased prevalence of white line disease in loose housing may be a property of specific freestall systems. More research directly comparing tiestalls to other forms of loose housing would help tease apart these relationships.

With respect to hoof lesions, the influence of management may carry more weight in freestalls compared with tiestalls due to increased contact with different flooring types, surfaces, and barn areas (such as cubicles, alleyways, and holding pens). Conversely, the increased prevalence of injuries in tethered compared with loose-housed cattle, such as neck lesions (Mattiello et al., 2009), integument alterations (Ostojić-Andrić et al., 2011; Popescu et al., 2014) and traumatic injuries (Busato et al., 2000; Corazzin et al., 2010) may be attributed, in part, to a tied cow's long-term exposure to the stall.

Hoof lesions are associated with a damp and soiled flooring substrate (Somers et al., 2005), and the provision of multiple walking areas may make it more difficult to maintain cleanliness. According to Taponen et al. (2017), "tiestalls are usually fairly dry, whereas the floors of the walking areas of freestalls are often wet, depending on the design of the alleys and the effectiveness of the manure removal system" (p. 500). Thus, although it is difficult to disentangle freestall housing from aspects of its management, freestall systems seem more likely to implement management practices that contribute to the increased prevalence of certain hoof disorders, such as DD.

This difficulty in separating the system from its management holds for other metrics as well. With respect to infectious diseases, there is a potential advantage

Table 7. Articles comparing affective state in tiestalls versus less-restrictive systems [listed for each study, where specified, are the measure of affect used, country, number of herds and total number of cows, the comparison of housing systems being made, the dimensions of the tiestall herds and the other housing type(s), the results (with the statement "no difference" representing $P \geq 0.05$), and the direction of these results]

Study (country)	Measure (operational definition)	No. of herds (no. of cows)	System comparison[1]	Results	Effect[2]
Ostojić-Andrić et al., 2011 (Serbia)[3]	"Absence of prolonged hunger" (BCS)	6 (400)	Tied without exercise vs. loose housed with and without grazing	Percentage of very lean cows higher in loose housing.	+
	"Comfort around resting" (time required to lie down, collisions with housing equipment during lying, lying at least partially outside the lying area)			Overall "comfort around resting" score higher in loose-housed cattle due to shorter durations of lying down movements, lying down with collisions, and lying outside the lying area	−
Plesch et al., 2010 (Austria and Germany)[3]	"Comfort around resting" (duration of lying down and rising, collisions while lying, lying at least partially outside the lying area)	35 (NA[4])	Tiestall; cubicle; deep litter (sloped floor with straw bedding)	There was an effect of housing on "resting comfort." Compared with straw yards, cattle in tiestalls and cubicles had longer durations of lying down, more collisions lying down, and a greater percentage of cows lying outside the lying area.	−
Popescu et al., 2013 (Romania)[3]	"Absence of prolonged hunger" (BCS)	80	Tiestalls (160–250 cm × 85–190 cm) with straw or sawdust (≤1.5 kg/head per day) with regular outdoor exercise (paddock, pasture or both) vs. no exercise.	Percentage of very lean cows not different between the groups.	=
	"Comfort around resting" (Duration of lying down movements, collisions while lying down, lying outside the lying area)			"Comfort around resting" was higher in herds that permitted exercise, due to reduced percentages of cows lying down with collisions and lying outside the lying area.	−
	"Good human–animal relationship" (Avoidance distance)			Higher mean percentages of cows with exercise could be touched, and a higher median percentage of cows without exercise could not be approached.	−
	"Positive emotional state" (QBA[5] using 20 terms[6])			Scores for QBA were higher for the cows permitted exercise (indicating better emotional state). However, in both systems, "the negative welfare measures prevailed."	−
Popescu et al., 2014 (Romania)[3]	"Absence of prolonged hunger" (BCS)	60 (2,624)	Tiestalls (160–250 cm × 85–190 cm; most used straw or sawdust bedding (≤1.5kg/d); some had access to pasture or paddocks); cubicles (sawdust bedding); straw yards	No difference between the housing types.	=
	"Absence of disease"			Loose-housed cows had improved scores.	−
	"Absence of injury"			No difference between the housing types.	=
	"Positive emotional state" (QBA[4] using 20 terms[5])			Scores for QBA were higher for the loose-housed cows (indicating better emotional state).	−
	"Comfort around resting" (Duration of lying down movements, collisions while lying down, lying outside the lying area)			Comfort around resting was improved in loose housing.	−
	"Good human–animal relationship" (Avoidance distance)			The human–animal relationship was improved in tiestalls, with a higher percentage of cattle that could be touched and a lower percentage of cattle that could not be approached.	+
Müller et al., 1989 (Germany)	"Aversiveness" of stimuli and "emotional reaction" (heart rate)	1 (16)	Loose-housed (10 × 6 m pens with deep straw) vs. tiestalls (tethered in a nearby barn. Stanchions with a 40 cm chain attached to a 60 cm high feeding trough. Concrete and partially slatted floor, no straw)		−/=

Continued

Table 7 (Continued). Articles comparing affective state in tiestalls versus less-restrictive systems [listed for each study, where specified, are the measure of affect used, country, number of herds and total number of cows, the comparison of housing systems being made, the dimensions of the tiestall herds and the other housing type(s), the results (with the statement "no difference" representing $P \geq 0.05$), and the direction of these results]

Study (country)	Measure (operational definition)	No. of herds (no. of cows)	System comparison[1]	Results	Effect[2]
Haley et al., 2000 (Canada)	"Cow comfort"	1 (8)	Cows spent 3 wk in 2 housing types: (1) loose housing individually in stalls (4.2 × 3.9 m) with mattress and 2 cm chopped straw and 2) tiestalls (1.8 × 3 m) with neck chain and concrete floor with 2 cm chopped straw.	Higher percentage of cows standing idle in tiestalls compared with large pens. Authors suggest that time standing idle is an indicator of poor cow comfort. However, few other differences were found between the housing types.	−/=
Varner et al., 1983 (NA)	Stress (serum corticosteroid concentration)	2 (86)	Two herds of cattle moved from tiestalls to freestalls (including a change in diet). Half the cattle from herd 1 remained in tiestalls and half were moved 100 m across a deep flush gutter. Cattle from herd 2 transported 7 km.	Serum corticosteroids increased in relocated cows for only 2 d (for herd 1) and 3 d (for herd 2) after relocation. The authors suggest that stress-related effects of relocation to freestalls were minor. On d 5, corticosteroid concentrations were higher in control (tied) cattle.	=
Veissier et al., 2008 (France)	Frustration (locomotion motivation); stress (cortisol responses to ACTH)	1 (30)	Phase 1: Freestall (1.24 m × 1.86 m, 0.5 kg/d wood shavings), or tiestall (1.35 m × 2.20 m, 3 cm rubber mats, 0.5 kg/d wood shavings) for durations of 1 d to 1 mo	Tethering thwarts the motivation to walk, which the authors concluded leads to frustration; however, this frustration does not result in a physiological stress response (as measured by cortisol responses to ACTH).	−/=
Mattiello et al., 2009 (Italy)	"Human–animal bond" (avoidance distance)	14 (NA)	Phase 2: Freestall, or tiestall for 1 mo. Some tied cows had daily access to exercise.	Mean avoidance distance at the feeding rack was lower in tie stalls, suggesting a better human–animal bond	+
Peric et al., 2017 (Italy)	Stress [changes in cortisol and dehydroepiandrosterone (DHEA) concentrations in hair]	1 (45)	Cows housed year-round in tiestalls vs. in tiestalls with summer housing on mountain pastures (June–Sept).	Cows kept in tiestalls year-round had increased hair cortisol from Aug-Oct (when the trial ended). Cows kept on pasture had increased hair cortisol during the first month of grazing. Hair DHEA remained constant among cows kept in tiestalls, and increased in grazing cows during the last month of grazing.	?
Higashiyama et al., 2007 (Japan)	Stress (changes in cortisol levels and frequency of lying down while ruminating)	1 (7)	Cattle were transferred from pasture to tiestalls, then back to pasture.	Cortisol increased 3.4-fold 1 d after transfer to tiestalls. Cortisol levels remained elevated for the first wk, then declined, and basal levels were maintained during the last 3 wk. No change in cortisol levels after the cows returned to pasture. Ratio of lying down while ruminating decreased when cows were in tiestalls, and this ratio returned to pretethering levels when the cows returned to pasture.	−

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Table 7 (Continued). Articles comparing affective state in tiestalls versus less-restrictive systems [listed for each study, where specified, are the measure of affect used, country, number of herds and total number of cows, the comparison of housing systems being made, the dimensions of the tiestall herds and the other housing type(s), the results (with the statement "no difference" representing $P \geq 0.05$), and the direction of these results]

Study (country)	Measure (operational definition)	No. of herds (no. of cows)	System comparison[1]	Results	Effect[2]
Redbo, 1992 (Sweden)	Stress (stereotypies)	1 (16)	Cows were (1) tethered in stalls after a 4 mo grazing period, (2) tethered in stalls during the normal grazing period, or (3) tethered for 8 mo and then transferred to loose housing.	Group 1 stereotypy levels were the highest during the first 3 wk of tethering, and decreased afterward. Group 1 and 2 cows had different stereotypy levels 2–6 wk after tethering. Group 3 cows stopped performing stereotypies after transfer to loose housing.	−
Redbo, 1993 (Sweden)	Stress (stereotypies and cortisol levels)	1 (14)	Heifers were transferred from pasture to indoor tiestalls.	All 3 groups showed similar stereotypy and cortisol patterns during the 8 wk of tethering; stereotypy levels increased during the first 4 wk, and levels decreased afterward. Cortisol concentrations were high during the first wk of tethering, and concentrations decreased afterward.	−
Tarantola et al., 2016 (Italy)	"Stress conditions of cattle"; "comfort situation"; "fear and anxiety stress measures" [locomotion scoring system, salivary cortisol, blood parameters, serum acute phase proteins (albumin, haptoglobin, serum amyloid A, lysozyme)]	1 (15)	The same group of cattle compared before and after stable renovation from tiestall (concrete floor + straw bedding) to freestall housing (2.6 m × 1.2 m, concrete floor + straw bedding)	Salivary cortisol, which the authors identify as one of the best stress indicators, was higher in tied cattle. Lysozyme concentration, also identified as a stress indicator, was higher in tied cattle. Most blood parameters were not influenced by time of sampling, despite a change in housing creating a "stressful situation." However, greater basophil concentrations were observed during restructuring, and greater monocytes were observed when cows were tied. The authors state that monocytosis is associated with inflammation, necrosis of tissue, and sometimes in stress leukograms.	−

[1]Housing types being compared in each study. Stall dimensions and other characteristics are specified for all housing types if this information is provided in the article.

[2]Where + indicates a beneficial effect of tiestall housing, − indicates a negative effect, and = indicates no statistical different at $P \geq 0.05$ unless otherwise specified.

[3]Assessments based upon Welfare Quality (2009).

[4]NA indicates information is either not applicable or has not been provided.

[5]QBA = qualitative behavior assessment (Wemelsfelder and Lawrence, 2001).

[6]Terms used in the QBA were active, relaxed, fearful, agitated, calm, content, indifferent, frustrated, friendly, bored, playful, positively occupied, lively, inquisitive, irritable, uneasy, sociable, apathetic, happy, distressed.

for tied animals if the herd manager begins by milking disease-free animals first. However, although this management practice may be facilitated by tiestall housing, its implementation in tiestall herds is not guaranteed, and loose-housed cows can also be grouped and managed by disease status and risk. Other managerial and demographic elements associated with housing type may influence specific disease outcomes. For instance, Corbett et al. (2018a) found a lower prevalence of *Mycobacterium avium* ssp. *paratuberculosis* (**MAP**; the etiological agent of Johne's disease) in tiestalls compared with freestalls. The environmental prevalence of MAP may indeed be lower in tiestalls due to different contact structures between animals in the 2 housing types; however, the authors acknowledge that specific elements of tiestall management (e.g., the common use of gutter scrapers) may decrease *detection* of MAP, rather than its prevalence. Furthermore, farms with smaller herd sizes often have a decreased likelihood of testing MAP-positive (Wells and Wagner, 2000; Wolf et al., 2015; Beaver et al., 2016); the prevalence of MAP in tiestalls could therefore also be lower based on herd size. Indeed, Wolf et al. (2014) found no difference in MAP prevalence between tiestall and freestall environments with small herd sizes (<100 cows/herd). With respect to other diseases, effects of housing were neutral overall, although an insufficient number of studies were available in each category to reach an informed conclusion about specific conditions.

Indirect Measures of Basic Health and Biological Functioning. As widely discussed in the literature, a decline in production or reproduction can sometimes indicate a welfare issue; however, good production and reproduction do not automatically signal good welfare (Oltenacu et al., 2005; Coignard et al., 2014). We found no consistent evidence of higher milk yield in either loose or tethered cattle (Supplemental Table S2; 10.6084/m9.figshare.14769567; Beaver et al., 2021). The numerous studies attempting to compare tiestalls and freestalls by moving cattle between systems can only truly measure parameters associated with relocation itself (unless crossover or other more sophisticated designs are used, for example). Many of these studies focused on relocation from tiestall to loose housing, typically reporting an initial decrease in milk yield followed by an eventual increase or return to baseline (Norell and Appleman, 1981; Varner et al., 1983; Broucek et al., 2015).

With regard to fertility, cattle in tiestalls typically showed impaired (or at best equivalent) performance compared with cattle in loose housing, including pregnancy risk, pregnancy rate, insemination rate, and incidence of anestrus. These differences may partially reflect traits of the tiestall system itself; cattle in tiestalls cannot display normal estrus behaviors (Felton et al., 2012), and producers may thus rely more heavily upon timed AI programs to boost reproductive performance.

Several studies assessed hygiene in tiestalls versus freestalls and found that freestalls were associated with improved stall cleanliness (Herlin et al., 1994) and udder hygiene (Neja et al., 2016). However, certain studies (e.g., Kara et al., 2011) found no difference in udder and leg hygiene between the housing types, and others found improved lower-leg hygiene scores in tiestalls (Ostojić-Andrić et al., 2011). Several authors (e.g., Kivaria et al., 2007; Popescu et al., 2013) referred to hygiene as a welfare measure, perhaps because of its perceived effect on infectious diseases such as mastitis and DD. Because these conditions themselves were directly assessed in this review, cleanliness was not formally evaluated.

Natural Behavior

There is ample evidence that the expression of highly motivated behavioral patterns is impaired in tiestalls. Of the 13 studies in the current review measuring some aspect of lying behavior across different housing types, none found advantages to tethering, and 9 found at least some impairments when cattle were tied compared with loose-housed. These impairments included increases in collisions while lying down, lying outside the lying area, duration to reach recumbency, time spent kneeling, unfulfilled intentions to lie down, abnormal lying postures, and lying interruptions (Krohn et al., 1992; Krohn and Munksgaard, 1993; Plesch et al., 2010; Ostojić-Andrić et al., 2011; Popescu et al., 2014; Shepley et al., 2019).

It has long been known that lying down comprises a substantial portion of the time budget for dairy cattle; as such, even short deprivations can result in welfare impairments (Metz, 1985; Munksgaard and Simonsen, 1996). More recent research has examined subtleties of this issue and have found cattle to be highly motivated to access a desirable lying area (Tucker at al., 2018). Other research has shown that heifers express inelastic demand for resting (Jensen et al., 2005) and that physiological indicators of stress (e.g., cortisol and ACTH) are elevated in response to restricted lying times (Fisher et al., 2002). Collectively, this evidence indicates that welfare is impaired when lying down movements are restricted.

It bears mentioning that certain behaviors cannot be studied in tiestalls, because certain behaviors cannot occur in tiestalls; the implications of this statement extend beyond the tautologous. For example, social behaviors are largely prevented in tethered cattle. Cattle are highly social animals, and under naturalistic conditions, form lasting bonds with conspecifics (Reinhardt and Reinhardt, 1981; Murphey, 1990). Moreover,

social deprivation can impair coping ability (Færevik et al., 2006) and cognition (Meagher et al., 2015). It is difficult to determine how welfare is influenced by restricted levels of tactile contact between tethered cattle. To empirically investigate this question, cattle could be moved between loose and tied systems in a counterbalanced manner. However, the ability to cope with social deprivation may differ between permanently tethered cattle and those given some level of social interaction (as necessitated by experimental design), making it difficult to answer questions related to social restriction.

Other thwarted natural behaviors may provoke stereotypies, such as tongue rolling (Gustafson et al., 1993; Corazzin et al., 2010), which is associated with an inability to graze (Krohn, 1994). The use of stereotypies to assess welfare is also problematic, as the absence of stereotypies does not guarantee good welfare (Mason and Latham, 2004). In addition, tied cattle are not entirely disadvantaged by the lack of social contact, which can reduce the risk of agonistic interactions (Proudfoot and Habing, 2015). Indeed, Popescu et al. (2014) noted that tied cattle showed reduced frequencies of agnostic behaviors.

Affective State

Affective state was the least researched of the 3 welfare spheres. Conditions such as mastitis and lameness are known to be painful, and several articles included in the present review (e.g., Alban et al., 1995; Cook, 2003; Levison et al., 2016) alluded to affective state by referencing the pain associated with these conditions. Few studies, however, attempted to directly measure affect, and it was rarely considered a primary outcome measure. Studies that did attempt to measure affect predominantly assessed cow comfort and physiological indicators (commonly cortisol), with reference to "stress."

Cow Comfort. The topic of cow comfort is of importance to dairy producers (Bewley et al., 2001, 2017) and both regional and international animal welfare organizations (RSPCA, 2017; BCSPCA, 2018). Despite the importance of the concept, there is no agreed-upon operational definition of cow comfort. Interestingly, 32 included studies referenced "comfort," but only 6 attempted to measure it. Several studies have defined cow comfort by a single metric, such as time spent standing idle (Haley et al., 2000) or cortisol (Tarantola et al., 2016). Others took a more multifaceted approach and amalgamated a variety of animal-based measures (Plesch et al., 2010; Ostojić-Andrić et al., 2011; Popescu et al., 2013, 2014). The consensus (albeit based on a limited number of studies) was that comfort is improved when housing is less restrictive.

Physiological Indicators. In 4 studies (Redbo, 1992, 1993; Higashiyama et al., 2007; Tarantola et al., 2016) cortisol was higher in tied vs. loose-housed or exercised cattle, suggesting higher levels of stress. However, cortisol levels fluctuate throughout the day (Mason and Mendl, 1993) and are not consistently associated with negative affect (Hewson, 2003). Several studies address additional explanations for changes in cortisol levels, such as heat stress, novelty, age, and differences in metabolic rates (Redbo, 1993; Higashiyama et al., 2007; Veissier et al., 2008; Peric et al., 2017).

Given the variety of measures available for assessing affective state in cattle (as reviewed by Ede et al., 2019), there is room for further research into the affective state of tied cattle beyond hormone concentrations and the elusive concept of cow comfort. The studies included in the present review have only scratched the surface of this topic, because many methods to measure affective state in cattle are new or are still in development. Two included articles (Popescu et al., 2013, 2014) evaluated positive emotional state using qualitative behavior assessment (Wemelsfelder and Lawrence, 2001); researchers have increasingly suggested that assessment of positive affect for farm animals is warranted (Mellor and Beausoleil, 2015; Mellor, 2016; Lawrence et al., 2018).

Several studies attempted to compare human–animal relationships between tied and loose-housed cattle. Both Popescu et al. (2014) and Mattiello et al. (2009) found that tethered cattle were easier to approach. Although this may be indicative of a better human–animal bond (perhaps due to increased individual attention), it is also possible that fear may be expressed differently in cattle when they cannot effectively move away from the experimenter. If, for example, cattle are chained to their stalls, passive avoidance (e.g., immobilization) may supplant active avoidance (e.g., flight; see Forkman et al., 2007).

Effects of Movement Opportunity for Tied Cattle

The term "exercise" for tied dairy cattle is widely used in the literature. As discussed by Shepley et al. (2020), the designation is imprecise, as it often does not adequately address all facets of exercise, including provision of adequate space (and the properties of this space), plus the individual cow's decision to use this space for physical exertion and locomotor activity. Thus, housing type cannot simply be equated with levels of exercise. Shepley et al. (2020) propose "movement opportunity" as a more comprehensive term to account for these subtleties.

As part of the current review, we investigated the movement opportunity associated with providing tied

cattle partial access to a loose housing type (including, e.g., freestall, pasture, yard, or bedded pack). With the exception of Veissier et al. (2008), all studies considering this research question provided tied cattle with access to outdoor areas, predominantly pasture. In addition to, or in place of pasture, a small number of studies provided access to outdoor "yards" (n = 4), "paddocks" (n = 2), "lots" (n = 1), or "runs" (n = 1).

According to the majority of studies we reviewed, outdoor access for tied cattle is beneficial for leg and claw health. These benefits were typically proportional to the amount of access provisioned, although research investigating the optimal frequency and duration of outdoor access remains to be undertaken. It should be noted that although outdoor access, on balance, led to improved leg health, it was sometimes associated with a higher prevalence of foot lesions. However, locomotion scores were universally better among cattle given outdoor access. We conclude that when cattle are housed in tiestalls, permitting movement opportunities (at least via outdoor access) improves gait.

Outdoor access for tied cattle was also typically associated with fewer teat injuries. There was insufficient evidence to ascertain the effect of outdoor access on other conditions or diseases because few articles addressed the same health parameters. Conditions included ketosis, mastitis, respiratory disorders, and mortality rates. Taken together, the balance of studies indicates a positive effect of outdoor access, but further research is required for in-depth conclusions regarding specific diseases. We also found no consistent effect of outdoor access on milk yield or fertility.

Few studies addressed the effect of outdoor access on natural behavior; those that did uncovered positive or neutral effects on lying behavior (Krohn and Munksgaard, 1993; Gustafson and Lund-Magnussen, 1995; Loberg et al., 2004; Popescu et al., 2013). These mixed-positive results suggest that partial access to pasture mitigates issues with lying down in tiestalls but is perhaps not fully restorative. There was, however, a reduction in stereotypies and other abnormal behaviors when tied cattle were allowed outdoors (Krohn, 1994; Loberg et al., 2004; Corazzin et al., 2010).

Denis-Robichaud et al. (2016) found that a larger proportion of tiestall compared with freestall herds permitted outdoor access, but the extent to which outdoor access mitigates movement restriction has not been widely studied. Veissier et al. (2008) reported lower milk cortisol levels for cattle housed in tiestalls with access to an exercise area compared with cattle permanently housed in freestalls. Similarly, according to Seo et al. (2007), tiestalls with outside areas typically received better scores on the Animal Needs Index compared with freestalls with no outside access. There is little information on how the duration of access and the type of area (e.g., pasture compared with indoor dry lots) compare with various types of zero-grazing, loose-housing systems. Studies that examine the interaction between housing type and all other elements of movement opportunity are required, as are studies that disentangle any benefits of outdoor access and access to grass (Charlton and Rutter, 2017).

Limitations and Final Thoughts

A fundamental limitation of comparing rearing systems is the considerable variation within systems, and the likelihood of this variation confounding inferences associated with system per se. For example, a variety of welfare outcomes vary with farm size (Robbins et al., 2016). Farm size varies greatly within and among rearing systems, but in the United States at least, tiestall herds tend to be smaller (USDA, 2016).

Farms also vary in their standard of management and the degree to which, within a system, they follow recommended practices. For example, Bouffard et al. (2017) found that the majority of Canadian tiestalls (of a sample of 100 in Quebec and Ontario) were not compliant with industry standards; for instance, only 22% of herds in Quebec met recommendations for stall width. In evaluating 3,485 cattle from these farms, the researchers uncovered an association between noncompliance and animal-based health measures such as increased risk of lameness, knee lesions, and neck injuries. The authors suggest that the renovation of dairy barns has not kept pace with increases in dairy cow size. Of course, the design argument can apply across systems, with poor freestall design contributing to increases in lesions and injuries (see Chapinal et al., 2013; 2014). Indeed, Vasseur et al. (2015) found that only 35% of cows on average would fit in freestalls with average bed length and width (according to the DFC-NFACC, 2009). However, it may be argued that the consequences of a poorly designed stall are likely magnified if the animal is physically unable to leave. Permitting animals choice and agency in their environments is largely associated with welfare improvement (Špinka, 2019).

Thus, we caution readers that the results of the studies we have reviewed are likely due in part to factors that may vary both within and between systems (such as the quality of walking and lying surfaces). Much work remains to be done in identifying and implementing improved management practices within both tiestall and loose housing systems. If these refinements are implemented, some of the system differences we have identified above will potentially change. However, we also note that some factors are inherent to the system, most notably the inability to move freely in tiestalls; no

change in management will be able to resolve this issue short of allowing cows out of the stalls.

CONCLUSIONS

Some measures of basic health and biological functioning are improved in loose housing and some in tiestall systems; providing outdoor access improved these measures for tied cows. The expression of natural behavior, particularly lying behavior, is inhibited in tiestalls. Most included studies showed benefits of loose housing on affective state, but this aspect of welfare has not been widely researched.

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REFERENCES

Alban, L. 1995. Lameness in Danish dairy cows: Frequency and possible risk factors. Prev. Vet. Med. 22:213–225. https://doi.org/10.1016/0167-5877(94)00411-B.

Alban, L., L. G. Lawson, and J. F. Agger. 1995. Foul in the foot (interdigital necrobacillosis) in Danish dairy cows—frequency and possible risk factors. Prev. Vet. Med. 24:73–82. https://doi.org/10.1016/0167-5877(95)00473-A.

Alvåsen, K., M. Jansson Mörk, C. Hallén Sandgren, P. T. Thomsen, and U. Emanuelson. 2012. Herd-level risk factors associated with cow mortality in Swedish dairy herds. J. Dairy Sci. 95:4352–4362. https://doi.org/10.3168/jds.2011-5085.

Bakken, G. 1981. Environment and bovine udder diseases in the loose housing system for dairy cows with reference to relevant data from the cowhouse system. Acta Agric. Scand. 31:445–451. https://doi.org/10.1080/00015128109435726.

Barkema, H. W., M. A. G. von Keyserlingk, J. P. Kastelic, T. J. G. M. Lam, C. Luby, J. P. Roy, S. J. LeBlanc, G. P. Keefe, and D. F. Kelton. 2015. Invited review: Changes in the dairy industry affecting dairy cattle health and welfare. J. Dairy Sci. 98:7426–7445. https://doi.org/10.3168/jds.2015-9377.

Barnouin, J., S. Bord, S. Bazin, and M. Chassagne. 2005. Dairy management practices associated with incidence rate of clinical mastitis in low somatic cell score herds in France. J. Dairy Sci. 88:3700–3709. https://doi.org/10.3168/jds.S0022-0302(05)73056-3.

Bartlett, P. C., G. Y. Miller, S. E. Lance, and L. E. Heider. 1992. Managerial determinants of intramammary coliform and environmental streptococci infections in Ohio dairy herds. J. Dairy Sci. 75:1241–1252. https://doi.org/10.3168/jds.S0022-0302(92)77873-4.

BCSPCA (The British Columbia Society for the Prevention of Cruelty to Animals). 2018. Standards for the Raising and Handling of Dairy Cattle. BCSPCA. https://spca.bc.ca/wp-content/uploads/SPCA-Certified-Dairy-Standards-2012-v.4.pdf.

Beaver, A., C. L. Cazer, P. L. Ruegg, Y. T. Gröhn, and Y. H. Schukken. 2016. Implications of PCR and ELISA results on the routes of bulk-tank contamination with *Mycobacterium avium* ssp. *paratuberculosis*. J. Dairy Sci. 99:1391–1405. https://doi.org/10.3168/jds.2015-9855.

Beaver, A., D. Weary, and M. von Keyserlingk. 2021. Supplemental Files: Beaver et al. Invited review: The welfare of dairy cattle housed in tiestalls compared to less-restrictive housing types: A systematic review. figshare. Journal contribution. https://doi.org/https://doi.org/10.6084/m9.figshare.14769567.v2.

Bendixen, P. H., B. Vilson, I. Ekesbo, and D. B. Åstrand. 1986. Disease frequencies of tied zero-grazing dairy cows and of dairy cows on pasture during summer and tied during winter. Prev. Vet. Med. 4:291–306. https://doi.org/10.1016/0167-5877(86)90011-5.

Bendixen, P. H., B. Vilson, I. Ekesbo, and D. B. Åstrand. 1988a. Disease frequencies in dairy cows in Sweden. VI. Tramped teat. Prev. Vet. Med. 6:17–25. https://doi.org/10.1016/0167-5877(88)90022-0.

Bendixen, P. H., B. Vilson, I. Ekesbo, and D. B. Åstrand. 1988b. Disease frequencies in dairy cows in Sweden. V. Mastisis. Prev. Vet. Med. 5:263–274. https://doi.org/10.1016/0167-5877(88)90012-8.

Bergsten, C., and A. H. Herlin. 1996. Sole haemorrhages and heel horn erosion in dairy cows: The influence of housing system on their prevalence and severity. Acta Vet. Scand. 37:395–408.

Bernhard, J. K., B. Vidondo, R. L. Achermann, R. Rediger, K. E. Müller, and A. Steiner. 2020. Carpal, tarsal, and stifle skin lesion prevalence and potential risk factors in Swiss dairy cows kept in tie stalls: A cross-sectional study. PLoS One 15:e0228808. https://doi.org/10.1371/journal.pone.0228808.

Bewley, J., R. W. Palmer, and D. B. Jackson-Smith. 2001. A comparison of free-stall barns used by modernized Wisconsin dairies. J. Dairy Sci. 84:528–541. https://doi.org/10.3168/jds.S0022-0302(01)74504-3.

Bewley, J. M., L. M. Robertson, and E. A. Eckelkamp. 2017. A 100-Year Review: Lactating dairy cattle housing management. J. Dairy Sci. 100:10418–10431.

Bielfeldt, J.C., R. Badertscher, K.H. Tölle, and J. Krieter. 2004. Factors influencing somatic cell score in Swiss dairy production systems. Schweiz. Arch. Tierheilk. 146:555–560. https://doi.org/10.1024/0036-7281.146.12.555.

Bielfeldt, J. C., R. Badertscher, K. H. Tölle, and J. Krieter. 2005. Risk factors influencing lameness and claw disorders in dairy cows. Livest. Prod. Sci. 95:265–271. https://doi.org/10.1016/j.livprodsci.2004.12.005.

Bielfeldt, J. C., K. H. Tölle, R. Badertscher, and J. Krieter. 2006. Longevity of Swiss Brown cattle in different housing systems in Switzerland. Livest. Sci. 101:134–141. https://doi.org/10.1016/j.livprodsci.2005.10.023.

Bouffard, V., A. M. de Passillé, J. Rushen, E. Vasseur, C. G. R. Nash, D. B. Haley, and D. Pellerin. 2017. Effect of following recommendations for tiestall configuration on neck and leg lesions, lameness, cleanliness, and lying time in dairy cows. J. Dairy Sci. 100:2935–2943. https://doi.org/10.3168/jds.2016-11842.

Brambell, F. W. R. 1965. Report of the Technical Committee to Enquire into the Welfare of Animals Kept Under Intensive Livestock Husbandry Systems. Her Majesty's Stationary Office.

Breuer, K., P. H. Hemsworth, J. L. Barnett, L. R. Matthews, and G. J. Coleman. 2000. Behavioural response to humans and the productivity of commercial dairy cows. Appl. Anim. Behav. Sci. 66:273–288.

Broucek, J., S. Mihina, M. Uhrincat, J. Lendelova, and A. Hanus. 2015. Impact of gestation and lactation stage on the dairy cow response following removal to unfamiliar housing and milking system. Ital. J. Anim. Sci. 14:233–237.

Broucek, J., M. Uhrincat, Z. Palkovicova, V. Tancin, and A. Hanus. 2013. Effect of relocation and sire lineage on behaviour and milk yield of dairy cows. Arch. Anim. Breed. 56:208–215. https://doi.org/10.7482/0003-9438-56-020.

Bruun, J., A. K. Ersbøll, and L. Alban. 2002. Risk factors for metritis in Danish dairy cows. Prev. Vet. Med. 54:179–190. https://doi.org/10.1016/S0167-5877(02)00026-0.

Busato, A., P. Trachsel, and J. W. Blum. 2000. Frequency of traumatic cow injuries in relation to housing systems in Swiss organic dairy herds. J. Vet. Med. A Physiol. Pathol. Clin. Med. 47:221–229. https://doi.org/10.1046/j.1439-0442.2000.00283.x.

CDIC (Canadian Dairy Information Centre). 2019. Dairy barns by type in Canada. Accessed Jun. 24, 2020. https://www.dairyinfo.gc.ca/resources/prod/dairy/pdf/barn_types_e.pdf.

Chapinal, N., A. K. Barrientos, M. A. G. von Keyserlingk, E. Galo, and D. M. Weary. 2013. Herd-level risk factors for lameness in freestall farms in the northeastern United States and California. J. Dairy Sci. 96:318–328. https://doi.org/10.3168/jds.2012-5940.

Chapinal, N., Y. Liang, D. M. Weary, Y. Wang, and M. A. G. von Keyserlingk. 2014. Risk factors for lameness and hock injuries in Holstein herds in China. J. Dairy Sci. 97:4309–4316. https://doi.org/10.3168/jds.2014-8089.

Charlton, G. L., and S. M. Rutter. 2017. The behaviour of housed dairy cattle with and without pasture access: A review. Appl. Anim. Behav. Sci. 192:2–9. https://doi.org/10.1016/j.applanim.2017.05.015.

Coignard, M., R. Guatteo, I. Veissier, A. Lehébel, C. Hoogveld, L. Mounier, and N. Bareille. 2014. Does milk yield reflect the level of welfare in dairy herds? Vet. J. 199:184–187.

Colenbrander, V. F., C. H. Noller, and R. J. Grant. 1991. Effect of fiber content and particle size of alfalfa silage on performance and chewing behavior. J. Dairy Sci. 74:2681–2690. https://doi.org/10.3168/jds.S0022-0302(91)78446-4.

Condas, L. A. Z., J. De Buck, D. B. Nobrega, D. A. Carson, S. Naushad, S. De Vliegher, R. N. Zadoks, J. R. Middleton, S. Dufour, J. P. Kastelic, and H. W. Barkema. 2017. Prevalence of non-*aureus* staphylococci species causing intramammary infections in Canadian dairy herds. J. Dairy Sci. 100:5592–5612. https://doi.org/10.3168/jds.2016-12478.

Cook, N. B. 2003. Prevalence of lameness among dairy cattle in Wisconsin as a function of housing type and stall surface. J. Am. Vet. Med. Assoc. 223:1324–1328. https://doi.org/10.2460/javma.2003.223.1324.

Corazzin, M., S. Dovier, E. Bianco, and S. Bovolenta. 2009. Survey on welfare of dairy cow in tie-stalls in mountain area. Ital. J. Anim. Sci. 8(Suppl 2):610–612. https://doi.org/10.4081/ijas.2009.s2.610.

Corazzin, M., E. Piasentier, S. Dovier, and S. Bovolenta. 2010. Effect of summer grazing on welfare of dairy cows reared in mountain tie-stall barns. Ital. J. Anim. Sci. 9:e59. https://doi.org/10.4081/ijas.2010.e59.

Corbett, C. S., S. A. Naqvi, C. A. Bauman, J. De Buck, K. Orsel, F. Uehlinger, D. F. Kelton, and H. W. Barkema. 2018a. Prevalence of Mycobacterium avium ssp. paratuberculosis infections in Canadian dairy herds. J. Dairy Sci. 101:11218–11228. https://doi.org/10.3168/jds.2018-14854.

Corbett, C. S., S. A. Naqvi, J. De Buck, U. Kanevets, J. P. Kastelic, and H. W. Barkema. 2018b. Environmental sample characteristics and herd size associated with decreased herd-level prevalence of *Mycobacterium avium* ssp. *paratuberculosis*. J. Dairy Sci. 101:8092–8099. https://doi.org/10.3168/jds.2018-14661.

Cramer, G., K. D. Lissemore, C. L. Guard, K. E. Leslie, and D. F. Kelton. 2008. Herd- and cow-level prevalence of foot lesions in ontario dairy cattle. J. Dairy Sci. 91:3888–3895. https://doi.org/10.3168/jds.2008-1135.

Cramer, G., K. D. Lissemore, C. L. Guard, K. E. Leslie, and D. F. Kelton. 2009. Herd-level risk factors for seven different foot lesions in Ontario Holstein cattle housed in tie stalls or free stalls. J. Dairy Sci. 92:1404–1411. https://doi.org/10.3168/jds.2008-1134.

Dairy Farmers of Canada and National Farm Animal Care Council (DFC-NFACC). 2009. Code of practice for the care and handling of dairy cattle. Accessed Jul. 2, 2020. http://www.nfacc.ca/pdfs/codes/dairy_code_of_practice.pdf.

de Haas, Y., R. F. Veerkamp, H. W. Barkema, Y. T. Gröhn, and Y. H. Schukken. 2004. Associations between pathogen-specific cases of clinical mastitis and somatic cell count patterns. J. Dairy Sci. 87:95–105. https://doi.org/10.3168/jds.S0022-0302(04)73146-X.

Dechow, C. D., E. A. Smith, and R. C. Goodling. 2011. The effect of management system on mortality and other welfare indicators in Pennsylvania dairy herds. Anim. Welf. 20:145–158.

Denis-Robichaud, J., R. L. A. Cerri, A. Jones-Bitton, and S. J. LeBlanc. 2016. Survey of reproduction management on Canadian dairy farms. J. Dairy Sci. 99:9339–9351. https://doi.org/10.3168/jds.2016-11445.

Directorate-General for Health and Food Safety. 2017. Welfare of Cattle on Dairy Farms. Publications Office of the European Union. Accessed Jun. 24, 2020. https://ec.europa.eu/food/audits-analysis/overview_reports/act_getPDF.cfm?PDF_ID=1139.

Dohoo, I. R., S. W. Martin, and A. H. Meek. 1984. Disease, production and culling in Holstein-Friesian cows VI. Effects of management on disease rates. Prev. Vet. Med. 3:15–28. https://doi.org/10.1016/0167-5877(84)90021-7.

Eckelkamp, E. A., J. L. Taraba, K. A. Akers, R. J. Harmon, and J. M. Bewley. 2016. Sand bedded freestall and compost bedded pack effects on cow hygiene, locomotion, and mastitis indicators. Livest. Sci. 190:48–57. https://doi.org/10.1016/j.livsci.2016.06.004.

Ede, T., B. Lecorps, M. A. G. von Keyserlingk, and D. M. Weary. 2019. Symposium review: Scientific assessment of affective states in dairy cattle. J. Dairy Sci. 102:10677–10694. https://doi.org/10.3168/jds.2019-16325.

Enriquez-Hidalgo, D., D. L. Teixeira, E. Lewis, F. Buckley, L. Boyle, and K. O'Driscoll. 2018. Behavioural responses of pasture based dairy cows to short term management in tie-stalls. Appl. Anim. Behav. Sci. 198:19–26. https://doi.org/10.1016/j.applanim.2017.09.012.

Ericsson Unnerstad, H., A. Lindberg, K. Persson Waller, T. Ekman, K. Artursson, M. Nilsson-Öst, and B. Bengtsson. 2009. Microbial aetiology of acute clinical mastitis and agent-specific risk factors. Vet. Microbiol. 137:90–97. https://doi.org/10.1016/j.vetmic.2008.12.005.

Færevik, G., M. B. Jensen, and K. E. Bøe. 2006. Dairy calves social preferences and the significance of a companion animal during separation from the group. Appl. Anim. Behav. Sci. 99:205–221. https://doi.org/10.1016/j.applanim.2005.10.012.

Faye, B., and F. Lescourret. 1989. Environmental factors associated with lameness in dairy cattle. Prev. Vet. Med. 7:267–287. https://doi.org/10.1016/0167-5877(89)90011-1.

Felton, C. A., M. G. Colazo, P. Ponce-Barajas, C. J. Bench, and D. J. Ambrose. 2012. Dairy cows continuously-housed in tie-stalls failed to manifest activity changes during estrus. Can. J. Anim. Sci. 92:189–196. https://doi.org/10.4141/cjas2011-134.

Ferguson, J. D., G. Azzaro, M. Gambina, and G. Licitra. 2007. Prevalence of mastitis pathogens in ragusa, sicily, from 2000 to 2006. J. Dairy Sci. 90:5798–5813. https://doi.org/10.3168/jds.2006-903.

Fisher, A. D., G. A. Verkerk, C. J. Morrow, and L. R. Matthews. 2002. The effects of feed restriction and lying deprivation on pituitary-adrenal axis regulation in lactating cows. Livest. Prod. Sci. 73:255–263. https://doi.org/10.1016/S0301-6226(01)00246-9.

Forkman, B., A. Boissy, M. C. Meunier-Salaün, E. Canali, and R. B. Jones. 2007. A critical review of fear tests used on cattle, pigs, sheep, poultry and horses. Physiol. Behav. 92:340–374. https://doi.org/10.1016/j.physbeh.2007.03.016.

Fraser, D., D. Weary, E. Pajor, and B. Milligan. 1997. A scientific conception of animal welfare that reflects ethical concerns. Anim. Welf. 6:187–205.

Geden, C. J., D. A. Rutz, and D. R. Bishop. 1990. Cattle lice (Anoplura, Mallophaga) in New York: seasonal population changes, effects of housing type on infestations of calves, and sampling efficiency. J. Econ. Entomol. 83:1435–1438. https://doi.org/10.1093/jee/83.4.1435.

Gustafson, G. M. 1993. Effects of daily exercise on the health of tied dairy cows. Prev. Vet. Med. 17:209–223. https://doi.org/10.1016/0167-5877(93)90030-W.

Gustafson, G. M., J. Luthman, E. , and Bursted.. 1993. Effect of daily exercise on performance, feed efficiency and energy balance of tied dairy cows. Acta Agric. Scand. A Anim. Sci. 43:219–227. https://doi.org/10.1080/09064709309410170.

Gustafson, G. M., and E. Lund-Magnussen. 1995. Effect of daily exercise on the getting up and lying down behaviour of tied dairy cows. Prev. Vet. Med. 25:27–36. https://doi.org/10.1016/0167-5877(95)00496-3.

Hackett, A. J., T. R. Batra, and A. J. McAllister. 1984. Estrus detection and subsequent reproduction in dairy cows continuously housed indoors. J. Dairy Sci. 67:2446–2451. https://doi.org/10.3168/jds.S0022-0302(84)81594-5.

Haley, D. B., J. Rushen, and A. M. de Passillé. 2000. Behavioural indicators of cow comfort: Activity and resting behaviour of dairy cows in two types of housing. Can. J. Anim. Sci. 80:257–263. https://doi.org/10.4141/A99-084.

Herlin, A. H., M. Magnusson, and P. Michanek. 1994. Faecal contamination of the lying area for dairy cows in different housing systems. Swed. J. Agric. Res. 24:171–176.

Hewson, C. J. 2003. What is animal welfare? Common definitions and their practical consequences. Can. Vet. J. 44:496–499.

Higashiyama, Y., M. Nashiki, H. Narita, and M. Kawasaki. 2007. A brief report on effects of transfer from outdoor grazing to indoor tethering and back on urinary cortisol and behaviour in dairy cattle. Appl. Anim. Behav. Sci. 102:119–123. https://doi.org/10.1016/j.applanim.2006.03.007.

Hovinen, M., M. D. Rasmussen, and S. P. Pyörälä. 2009. Udder health of cows changing from tie stalls or free stalls with conventional milking to free stalls with either conventional or automatic milking. J. Dairy Sci. 92:3696–3703. https://doi.org/10.3168/jds.2008-1962.

Hultgren, J. 2002. Foot/leg and udder health in relation to housing changes in Swedish dairy herds. Prev. Vet. Med. 53:167–189. https://doi.org/10.1016/S0167-5877(01)00279-3.

Jensen, M. B. 1999. Adaptation to tethering in yearling dairy heifers assessed by the use of lying down behaviour. Appl. Anim. Behav. Sci. 62:115–123. https://doi.org/10.1016/S0168-1591(98)00227-5.

Jensen, M. B., L. J. Pedersen, and L. Munksgaard. 2005. The effect of reward duration on demand functions for rest in dairy heifers and lying requirements as measured by demand functions. Appl. Anim. Behav. Sci. 90:207–217. https://doi.org/10.1016/j.applanim.2004.08.006.

Jewell, M. T., M. Cameron, J. Spears, S. L. McKenna, M. S. Cockram, J. Sanchez, and G. P. Keefe. 2019. Prevalence of lameness and associated risk factors on dairy farms in the Maritime Provinces of Canada. J. Dairy Sci. 102:3392–3405. https://doi.org/10.3168/jds.2018-15349.

Kalmus, P., A. Viltrop, B. Aasmäe, and K. Kask. 2006. Occurrence of clinical mastitis in primiparous Estonian dairy cows in different housing conditions. Acta Vet. Scand. 48:21. https://doi.org/10.1186/1751-0147-48-21.

Kara, N. K., A. Galic, and M. Koyuncu. 2011. Effects of stall type and bedding materials on lameness and hygiene score and effect of lameness on some reproductive problems in dairy cattle. J. Appl. Anim. Res. 39:334–338. https://doi.org/10.1080/09712119.2011.607890.

Keil, N. M., T. U. Wiederkehr, K. Friedli, and B. Wechsler. 2006. Effects of frequency and duration of outdoor exercise on the prevalence of hock lesions in tied Swiss dairy cows. Prev. Vet. Med. 74:142–153. https://doi.org/10.1016/j.prevetmed.2005.11.005.

Kivaria, F. M., J. P. T. M. Noordhuizen, and H. M. Msami. 2007. Risk factors associated with the incidence rate of clinical mastitis in smallholder dairy cows in the Dar es Salaam region of Tanzania. Vet. J. 173:623–629. https://doi.org/10.1016/j.tvjl.2006.01.009.

Krohn, C. C. 1994. Behaviour of dairy cows kept in extensive (loose housing/pasture) or intensive (tie stall) environments. III. Grooming, exploration and abnormal behaviour. Appl. Anim. Behav. Sci. 42:73–86. https://doi.org/10.1016/0168-1591(94)90148-1.

Krohn, C. C., and L. Munksgaard. 1993. Behaviour of dairy cows kept in extensive (loose housing/pasture) or intensive (tie stall) environments II. Lying and lying-down behaviour. Appl. Anim. Behav. Sci. 37:1–16. https://doi.org/10.1016/0168-1591(93)90066-X.

Krohn, C. C., L. Munksgaard, and B. Jonasen. 1992. Behaviour of dairy cows kept in extensive (loose housing/pasture) or intensive (tie stall) environments I. Experimental procedure, facilities, time budgets – diurnal and seasonal conditions. Appl. Anim. Behav. Sci. 34:37–47. https://doi.org/10.1016/S0168-1591(05)80055-3.

Landbruks- og matdepartementet. 2004. Forskrift om hold av storfe. FOR-2017-05-24-643. Accessed Sep. 8, 2020. https://lovdata.no/dokument/SF/forskrift/2004-04-22-665.

Lawrence, A. B., R. C. Newberry, and M. Špinka. 2018. Positive welfare: What does it add to the debate over pig welfare? Pages 415–444 in Advances in Pig Welfare. Woodhead Publishing.

Leach, K. A., S. Dippel, J. Huber, S. March, C. Winckler, and H. R. Whay. 2009. Assessing lameness in cows kept in tie-stalls. J. Dairy Sci. 92:1567–1574. https://doi.org/10.3168/jds.2008-1648.

Levison, L. J., E. K. Miller-Cushon, A. L. Tucker, R. Bergeron, K. E. Leslie, H. W. Barkema, and T. J. DeVries. 2016. Incidence rate of pathogen-specific clinical mastitis on conventional and organic Canadian dairy farms. J. Dairy Sci. 99:1341–1350. https://doi.org/10.3168/jds.2015-9809.

Lischer, C. J., M. Wehrle, H. Geyer, B. Lutz, and P. Ossent. 2000. Heilungsverlauf von Klauenläsionen bei Milchkühen unter Alpbedingungen. Dtsch. Tierarztl. Wochenschr. 107:255–261.

Loberg, J., E. Telezhenko, C. Bergsten, and L. Lidfors. 2004. Behaviour and claw health in tied dairy cows with varying access to exercise in an outdoor paddock. Appl. Anim. Behav. Sci. 89:1–16. https://doi.org/10.1016/j.applanim.2004.04.009.

Lundmark Hedman, F., J. Hultgren, H. Röcklinsberg, B. Wahlberg, and C. Berg. 2018. Non-compliance and follow-up in Swedish official and private animal welfare control of dairy cows. Animals (Basel) 8:72. https://doi.org/10.3390/ani8050072.

Manson, F. J., and J. D. Leaver. 1988. The influence of concentrate amount on locomotion and clinical lameness in dairy cattle. Anim. Sci. 47:185–190. https://doi.org/10.1017/S0003356100003251.

Mason, G., and M. Mendl. 1993. Why is there no simple way of measuring animal welfare? Anim. Welf. 2:301–319.

Mason, G. J., and N. R. Latham. 2004. Can't stop, won't stop: Is stereotypy a reliable animal welfare indicator? Anim. Welf. 13:S57–S69.

Mattiello, S., D. Arduino, M. V. Tosi, and C. Carenzi. 2005. Survey on housing, management and welfare of dairy cattle in tie-stalls in western Italian Alps. Acta Agric. Scand. A Anim. Sci. 55:31–39. https://doi.org/10.1080/09064700510009270.

Mattiello, S., C. Klotz, D. Baroli, M. Minero, V. Ferrante, and E. Canali. 2009. Welfare problems in alpine dairy cattle farms in Alto Adige (Eastern Italian Alps). Ital. J. Anim. Sci. 8(sup2):628–630. https://doi.org/10.4081/ijas.2009.s2.628.

McConnel, C. S., J. E. Lombard, B. A. Wagner, and F. B. Garry. 2008. Evaluation of factors associated with increased dairy cow mortality on united states dairy operations. J. Dairy Sci. 91:1423–1432. https://doi.org/10.3168/jds.2007-0440.

Meagher, R. K., R. R. Daros, J. H. C. Costa, M. A. G. von Keyserlingk, M. J. Hötzel, and D. M. Weary. 2015. Effects of degree and timing of social housing on reversal learning and response to novel objects in dairy calves. PLoS One 10:e0132828. https://doi.org/10.1371/journal.pone.0132828.

Mellor, D. J. 2016. Updating animal welfare thinking: Moving beyond the "five freedoms" towards "a life worth living". Animals (Basel) 6:21. https://doi.org/10.3390/ani6030021.

Mellor, D. J., and N. J. Beausoleil. 2015. Extending the "Five Domains" model for animal welfare assessment to incorporate positive welfare states. Anim. Welf. 24:241–253. https://doi.org/10.7120/09627286.24.3.241.

Metz, J. H. M. 1985. The reaction of cows to a short-term deprivation of lying. Appl. Anim. Behav. Sci. 13:301–307. https://doi.org/10.1016/0168-1591(85)90010-3.

Miljø- og Fødevareministeriet. 2017. Bekendtgørelse af lov om hold af malkekvæg og afkom af malkekvæg. Fødevarestyrelsen, j. nr. 2017–32–30–00072. Accessed Sep. 8, 2020. https://www.retsinformation.dk/eli/lta/2017/58.

Müller, C., J. Ladewig, H. H. Thielscher, and D. Smidt. 1989. Behavior and heart rate of heifers housed in tether stanchions without straw. Physiol. Behav. 46:751–754. https://doi.org/10.1016/0031-9384(89)90362-4.

Munksgaard, L., and H. B. Simonsen. 1996. Behavioral and pituitary adrenal-axis responses of dairy cows to social isolation and deprivation of lying down. J. Anim. Sci. 74:769–778. https://doi.org/10.2527/1996.744769x.

Murphey, R. M. 1990. Social aggregations in cattle. I. Segregation by breed in free-ranging herds. Behav. Genet. 20:341–354. https://doi.org/10.1007/BF01065562.

Neja, W., M. Bogucki, M. Jankowska, and A. Sawa. 2016. Effect of cow cleanliness in different housing systems on somatic cell count in milk. Acta Vet. Brno 85:55–61. https://doi.org/10.2754/avb201685010055.

Norell, R. J., and R. D. Appleman. 1981. Change of milk production with housing system and herd expansion. J. Dairy Sci. 64:1749–1755. https://doi.org/10.3168/jds.S0022-0302(81)82759-2.

Nyman, A. K., U. Emanuelson, A. H. Gustafsson, and K. Persson Waller. 2009. Management practices associated with udder health of first-parity dairy cows in early lactation. Prev. Vet. Med. 88:138–149. https://doi.org/10.1016/j.prevetmed.2008.08.005.

O'Driscoll, K., D. Gleeson, B. O'Brien, and L. Boyle. 2010. Effect of milking frequency and nutritional level on hoof health, locomotion score and lying behaviour of dairy cows. Livest. Sci. 127:248–256.

Oehm, A. W., G. Knubben-Schweizer, A. Rieger, A. Stoll, and S. Hartnack. 2019. A systematic review and meta-analyses of risk factors associated with lameness in dairy cows. BMC Vet. Res. 15:346. https://doi.org/10.1186/s12917-019-2095-2.

Olde Riekerink, R. G. M., H. W. Barkema, D. F. Kelton, and D. T. Scholl. 2008. Incidence rate of clinical mastitis on Canadian dairy farms. J. Dairy Sci. 91:1366–1377. https://doi.org/10.3168/jds.2007-0757.

Olechnowicz, J., J. M. Jaśkowski, and W. Nowak. 2010. Effect of hind limb conformation on claw disorders in dairy primiparous cows. Bull. Vet. Inst. Pulawy 54:437–439.

Oltenacu, P. A., and B. Algers. 2005. Selection for increased production and the welfare of dairy cows: Are new breeding goals needed? Ambio 34:311–315.

Ostojić-Andrić, D., S. Hristov, Z. Novakovic, V. Pantelic, M. M. Petrovic, Z. Zlatanovic, and D. Niksic. 2011. Dairy cows welfare quality in loose vs tie housing system. Biotechnol. Anim. Husb. 27:975–984. https://doi.org/10.2298/BAH1103975O.

Peric, T., M. Corazzin, A. Romanzin, S. Bovolenta, A. Prandi, M. Montillo, and A. Comin. 2017. Cortisol and DHEA concentrations in the hair of dairy cows managed indoor or on pasture. Livest. Sci. 202:39–43. https://doi.org/10.1016/j.livsci.2017.05.020.

Plesch, G., N. Broerkens, S. Laister, C. Winckler, and U. Knierim. 2010. Reliability and feasibility of selected measures concerning resting behaviour for the on-farm welfare assessment in dairy cows. Appl. Anim. Behav. Sci. 126:19–26. https://doi.org/10.1016/j.applanim.2010.05.003.

Popescu, S., C. Borda, E. A. Diugan, M. Niculae, R. Stefan, and C. D. Sandru. 2014. The effect of the housing system on the welfare quality of dairy cow. Ital. J. Anim. Sci. 13:2940. https://doi.org/10.4081/ijas.2014.2940.

Popescu, S., C. Borda, E. A. Diugan, M. Spinu, I. S. Groza, and C. D. Sandru. 2013. Dairy cows welfare quality in tie-stall housing system with or without access to exercise. Acta Vet. Scand. 55:43. https://doi.org/10.1186/1751-0147-55-43.

Proudfoot, K., and G. Habing. 2015. Social stress as a cause of diseases in farm animals: Current knowledge and future directions. Vet. J. 206:15–21. https://doi.org/10.1016/j.tvjl.2015.05.024.

Redbo, I. 1992. The influence of restraint on the occurrence of oral stereotypies in dairy cows. Appl. Anim. Behav. Sci. 35:115–123. https://doi.org/10.1016/0168-1591(92)90002-S.

Redbo, I. 1993. Stereotypies and cortisol secretion in heifers subjected to tethering. Appl. Anim. Behav. Sci. 38:213–225. https://doi.org/10.1016/0168-1591(93)90020-P.

Regula, G., J. Danuser, B. Spycher, and B. Wechsler. 2004. Health and welfare of dairy cows in different husbandry systems in Switzerland. Prev. Vet. Med. 66:247–264. https://doi.org/10.1016/j.prevetmed.2004.09.004.

Reimus, K., K. Alvåsen, U. Emanuelson, A. Viltrop, and K. Mõtus. 2020. Herd-level risk factors for cow and calf on-farm mortality in Estonian dairy herds. Acta Vet. Scand. 62:15. https://doi.org/10.1186/s13028-020-0513-x.

Reinhardt, V., and A. Reinhardt. 1981. Cohesive relationships in a cattle herd (*Bos indicus*). Behaviour 77:121–150. https://doi.org/10.1163/156853981X00194.

Robbins, J. A., C. Roberts, D. M. Weary, B. Franks, and M. A. G. von Keyserlingk. 2019. Factors influencing public support for dairy tie stall housing in the U.S. PLoS One 14:e0216544. https://doi.org/10.1371/journal.pone.0216544.

Robbins, J. A., M. A. G. von Keyserlingk, D. Fraser, and D. M. Weary. 2016. Invited review: Farm size and animal welfare. J. Anim. Sci. 94:5439–5455. https://doi.org/10.2527/jas.2016-0805.

RSPCA (Royal Society for the Prevention of Cruelty to Animals). 2017. RSPCA welfare standards for dairy cattle. Accessed Oct. 28, 2020. https://science.rspca.org.uk/documents/1494935/9042554/RSPCA+welfare+standards+for+dairy+cattle+%28PDF+7.76MB%29.pdf/41638530-20de-c6cc-5e9c-7b73f9c8f4b7?t=1557731468543.

Sabbioni, A., V. Beretti, L. Tardini, S. Vezzali, V. Paini, and P. Superchi. 2012. Milk production and lactation curves of Bianca Val Padana and Italian Friesian dairy cows in relation to the management system. Ital. J. Anim. Sci. 11:e26. https://doi.org/10.4081/ijas.2012.e26.

Sampimon, O. C., H. W. Barkema, I. M. Berends, J. Sol, and T. J. Lam. 2009. Prevalence and herd-level risk factors for intramammary infection with coagulase-negative staphylococci in Dutch dairy herds. Vet. Microbiol. 134:37–44.

Seo, T., K. Date, T. Daigo, F. Kashiwamura, and S. Sato. 2007. Welfare assessment of Japanese dairy farms using the Animal Need Index. Anim. Welf. 16:221–223.

Shepley, E., J. Lensink, and E. Vasseur. 2020. Cow in motion: A review of the impact of housing systems on movement opportunity of dairy cows and implications on locomotor activity. Appl. Anim. Behav. Sci. 230:105026. https://doi.org/10.1016/j.applanim.2020.105026.

Shepley, E., G. Obinu, T. Bruneau, and E. Vasseur. 2019. Housing tiestall dairy cows in deep-bedded pens during an 8-week dry period: Effects on lying time, lying postures, and rising and lying-down behaviors. J. Dairy Sci. 102:6508–6517. https://doi.org/10.3168/jds.2018-15859.

Simensen, E., O. Østerås, K. E. Bøe, C. Kielland, L. E. Ruud, and G. Næss. 2010. Housing system and herd size interactions in Norwegian dairy herds; associations with performance and disease incidence. Acta Vet. Scand. 52:14. https://doi.org/10.1186/1751-0147-52-14.

Smith, D. R., P. J. Fedorka-Cray, R. Mohan, K. V. Brock, T. E. Wittum, P. S. Morley, K. H. Hoblet, and L. J. Saif. 1998. Epidemiologic herd-level assessment of causative agents and risk factors for winter dysentery in dairy cattle. Am. J. Vet. Res. 59:14.

Sogstad, Å. M., T. Fjeldaas, O. Østerås, and K. P. Forshell. 2005. Prevalence of claw lesions in Norwegian dairy cattle housed in tie stalls and free stalls. Prev. Vet. Med. 70:191–209. https://doi.org/10.1016/j.prevetmed.2005.03.005.

Solano, L., H. W. Barkema, S. Mason, E. A. Pajor, S. J. LeBlanc, and K. Orsel. 2016. Prevalence and distribution of foot lesions in dairy

cattle in Alberta, Canada. J. Dairy Sci. 99:6828–6841. https://doi.org/10.3168/jds.2016-10941.

Solano, L., H. W. Barkema, E. A. Pajor, S. Mason, S. J. LeBlanc, J. C. Zaffino Heyerhoff, C. G. R. Nash, D. B. Haley, E. Vasseur, D. Pellerin, J. Rushen, A. M. de Passillé, and K. Orsel. 2015. Prevalence of lameness and associated risk factors in Canadian Holstein-Friesian cows housed in freestall barns. J. Dairy Sci. 98:6978–6991. https://doi.org/10.3168/jds.2015-9652.

Somers, J. G. C. J., K. Frankena, E. N. Noordhuizen-Stassen, and J. H. M. Metz. 2005. Risk factors for interdigital dermatitis and heel erosion in dairy cows kept in cubicle houses in the Netherlands. Prev. Vet. Med. 71:23–34. https://doi.org/10.1016/j.prevetmed.2005.05.001.

Špinka, M. 2019. Animal agency, animal awareness and animal welfare. Anim. Welf. 28:11–20.

Sprecher, D. J., D. E. Hostetler, and J. B. Kaneene. 1997. A lameness scoring system that uses posture and gait to predict dairy cattle reproductive performance. Theriogenology 47:1179–1187. https://doi.org/10.1016/S0093-691X(97)00098-8.

Svensson, C., A. K. Nyman, K. P. Waller, and U. Emanuelson. 2006. Effects of housing, management, and health of dairy heifers on first-lactation udder health in southwest Sweden. J. Dairy Sci. 89:1990–1999. https://doi.org/10.3168/jds.S0022-0302(06)72266-4.

Taponen, S., E. Liski, A. M. Heikkilä, and S. Pyörälä. 2017. Factors associated with intramammary infection in dairy cows caused by coagulase-negative staphylococci, *Staphylococcus aureus*, *Streptococcus uberis*, *Streptococcus dysgalactiae*, *Corynebacterium bovis*, or *Escherichia coli*. J. Dairy Sci. 100:493–503. https://doi.org/10.3168/jds.2016-11465.

Tarantola, M., E. Valle, M. De Marco, S. Bergagna, D. Dezzutto, M. S. Gennero, D. Bergero, A. Schiavone, and L. Prola. 2016. Effects of abrupt housing changes on the welfare of Piedmontese cows. Ital. J. Anim. Sci. 15:103–109. https://doi.org/10.1080/1828051X.2015.1128691.

Thomsen, P. T., A. M. Kjeldsen, J. T. Sørensen, H. Houe, and A. K. Ersbøll. 2006. Herd-level risk factors for the mortality of cows in Danish dairy herds. Vet. Rec. 158:622–626. https://doi.org/10.1136/vr.158.18.622.

Tucker, C. B., L. Munksgaard, E. M. Mintline, and M. B. Jensen. 2018. Use of a pneumatic push gate to measure dairy cattle motivation to lie down in a deep-bedded area. Appl. Anim. Behav. Sci. 201:15–24. https://doi.org/10.1016/j.applanim.2017.12.018.

Uehlinger, F. D., S. J. Greenwood, R. O'Handley, J. T. McClure, T. Coklin, B. R. Dixon, M. De Boer, H. Zwiers, and H. W. Barkema. 2011. Prevalence and genotypes of Giardia duodenalis in dairy and beef cattle in farms around Charlottetown, Prince Edward Island, Canada. Can. Vet. J. 52:967–972.

USDA. 2016. Dairy 2014: Dairy Cattle Management Practices in the United States. USDA.

Vaarst, M., J. Hindhede, and C. Enevoldsen. 1998. Sole disorders in conventionally managed and organic dairy herds using different housing systems. J. Dairy Res. 65:175–186. https://doi.org/10.1017/S0022029997002823.

Valde, J. P., D. W. Hird, M. C. Thurmond, and O. Østerås. 1997. Comparison of ketosis, clinical mastitis, somatic cell count, and reproductive performance between free stall and tie stall barns in Norwegian dairy herds with automatic feeding. Acta Vet. Scand. 38:181–192.

Varner, M. A., B. H. Johnson, J. H. Britt, B. T. McDaniel, and R. D. Mochrie. 1983. Influence of herd relocation upon production and endocrine traits of dairy cows. J. Dairy Sci. 66:466–474. https://doi.org/10.3168/jds.S0022-0302(83)81815-3.

Vasseur, E., J. Gibbons, J. Rushen, D. Pellerin, E. Pajor, D. Lefebvre, and A. M. de Passillé. 2015. An assessment tool to help producers improve cow comfort on their farms. J. Dairy Sci. 98:698–708. https://doi.org/10.3168/jds.2014-8224.

Veissier, I., S. Andanson, H. Dubroeucq, and D. Pomiès. 2008. The motivation of cows to walk as thwarted by tethering. J. Anim. Sci. 86:2723–2729. https://doi.org/10.2527/jas.2008-1020.

von Keyserlingk, M. A. G., and M. J. Hötzel. 2015. The ticking clock: Addressing farm animal welfare in emerging countries. J. Agric. Environ. Ethics 28:179–195. https://doi.org/10.1007/s10806-014-9518-7.

Wade, S. E., H. O. Mohammed, and S. L. Schaaf. 2000. Epidemiologic study of *Giardia* sp. infection in dairy cattle in southeastern New York State. Vet. Parasitol. 89:11–21. https://doi.org/10.1016/S0304-4017(99)00228-9.

Welfare Quality. 2009. Welfare Quality® assessment protocol for cattle. Welfare Quality® Consortium, Lelystad, Netherlands. Accessed Jun. 20, 2020. http://www.welfarequalitynetwork.net/media/1088/cattle_protocol_without_veal_calves.pdf.

Wells, S. J., A. M. Trent, W. E. Marsh, and R. A. Robinson. 1993. Prevalence and severity of lameness in lactating dairy cows in a sample of Minnesota and Wisconsin herds. J. Am. Vet. Med. Assoc. 202:78–82.

Wells, S. J., and B. A. Wagner. 2000. Herd-level risk factors for infection with *Mycobacterium paratuberculosis* in US dairies and association between familiarity of the herd manager with the disease or prior diagnosis of the disease in that herd and use of preventive measures. J. Am. Vet. Med. Assoc. 216:1450–1457. https://doi.org/10.2460/javma.2000.216.1450.

Wemelsfelder, F., and A. B. Lawrence. 2001. Qualitative assessment of animal behaviour as an On-Farm Welfare-monitoring tool. Acta Agric. Scand. A Anim. Sci. 51(sup030):21–25. https://doi.org/10.1080/090647001300004763.

Whist, A. C., O. Østerås, and L. Sølverød. 2006. Clinical mastitis in Norwegian herds after a combined selective dry-cow therapy and teat-dipping trial. J. Dairy Sci. 89:4649–4659. https://doi.org/10.3168/jds.S0022-0302(06)72515-2.

Wolf, R., H. W. Barkema, J. De Buck, and K. Orsel. 2015. Sampling location, herd size, and season influence *Mycobacterium avium* ssp. *paratuberculosis* environmental culture results. J. Dairy Sci. 98:275–287. https://doi.org/10.3168/jds.2014-8676.

Wolf, R., H. W. Barkema, J. De Buck, M. Slomp, J. Flaig, D. Haupstein, C. Pickel, and K. Orsel. 2014. High herd-level prevalence of *Mycobacterium avium* subspecies *paratuberculosis* in Western Canadian dairy farms, based on environmental sampling. J. Dairy Sci. 97:6250–6259. https://doi.org/10.3168/jds.2014-8101.

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