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Short confinement of sows after farrowing, but not pen type affects live-born piglet mortality

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A B S T R A C T

Over the last decades, permanent crating of farrowing and lactating sows has led to serious public concerns with regard to sow welfare. As one alternative, it has been suggested to restrict crating to the period when suckling piglets are at the highest risk to die. Therefore, the aim of this study was to investigate live-born piglet mortality with regard to different confinement periods (**CFP**) as well as farrowing pen types. On three research farms (A, B and C), four confinement periods were compared: In **CFP 0** (control), sows were not confined at all, sows in **CFP 3** were crated after the end of farrowing for three days. In **CFP 4**, sows were confined one day before the due date of farrowing until three days after parturition and sows in **CFP 6** were crated one day before expected farrowing until five days after parturition. Furthermore, five different pen types designed for temporary crating (**PT**; 5.5–7.3 m^2) were compared. In total, production data from 638 litters were analysed. For each piglet found dead (n = 1 580), the cause of death was determined by the farm personnel and verified by necropsy (all three farms) and additional video analysis (farms A and B only). Data were analysed using logistic mixed models with CFP 0 and pen type Fluegel as reference categories (CFP 0 was control and this pen type was present on all three farms and the largest number of litters was born in this pen type). Live-born piglet mortality was lower in temporarily crated sows than in sows without confinement (CFP 0; $P < 0.015$). Pairwise posthoc tests did not reveal differences between CFP 3, CFP 4 and CFP 6 (odds ratios 0.75, 0.59 and 0.69), nor between pen types. Additional factors associated with increasing live-born piglet mortality were larger litter size, higher sow parity as well as the administration of hormones around farrowing. Factors influencing mortality due to crushing were similar to those for total live-born mortality with the exception of CFP 3 not differing significantly from CFP 0. It can be concluded, that confinement of the sow for three days after farrowing is an effective measure to reduce live-born piglet mortality in the pen types tested. An extension of the confinement period to five days after parturition does not result in a further reduction of live-born mortality rate.

Implications

Permanent crating of farrowing and lactating sows is a worldwide practice to keep piglet mortality at acceptable levels. However, from the sows' welfare point of view, there are serious concerns. In the pen types examined, the sows were able to move around to a limited extent in the prepartal phase and after opening of the crate. Highest piglet losses occurred when the sows were not confined at all. Thus, confinement of the sow until day 3 after parturition is recommended in the pen types tested. Systems for temporary crating have the potential to ensure basic behavioural needs of sows and contribute to improvement of sow welfare.

Introduction

Since its introduction in the 1960s, the farrowing crate has become the predominant housing system in commercial farrowing units worldwide (Pedersen et al., 2013). It was designed to restrict sow movement and thereby reduce piglet losses due to crushing. Furthermore, this housing system provides economic advantages

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due to lower space requirements, improved piglet management and decreased labour, e.g. removal of faeces and urine through slatted flooring (Edwards and Fraser, 1997; Marchant et al., 2001). However, confinement has undoubtedly negative impacts on sow welfare: Confined sows can neither perform nest-building behaviour adequately nor separate lying from excretion or feeding areas (Ahaw, 2007; Baxter et al., 2011). Confined animals show more posture changes antepartum (Cronin et al., 1994; Jarvis et al., 2001), which could be interpreted as nervousness and reduced well-being. Also, crated sows show more stereotypies than loose sows (Damm et al., 2003) and reduced mother-piglet interactions (Chidgey et al., 2016). Furthermore, there is also physiological evidence of the negative consequences of this system, such as increased plasma ACTH and blood cortisol levels in confined compared to loose gilts (Lawrence et al., 1994; Jarvis et al., 1997) and sows (Jarvis et al., 2001).

Due to the reasons mentioned above, confinement of the sow should be avoided or at least be restricted to the period, when piglets are at the highest risk to be crushed (“critical phase of life of suckling piglets”, 1. Tierhaltungsverordnung (BMGF, 2004), amendment BGBl. II Nr. 61/2012 (BMG, 2012)). This period lies somewhere within the first few days, or even hours of life (Marchant et al., 2000; Andersen et al., 2005), independent of the type of farrowing accommodation.

Temporary confinement of sows (for 4–7 days after parturition, total pen size between 4.7 m^2 and 6.3 m^2) results in lower piglet mortality compared to zero confinement in the same pens (Moustsen et al., 2013; Hales et al., 2015a and 2015b). Additionally, Lambertz et al. (2015) and Condous et al. (2016) reported similar piglet mortality in temporary confinement systems (pen size 4.6–6.0 m^2) compared to permanent crating of sows. Systems with permanent crating require less space (average total pen size of 3.5 m^2) compared to loose farrowing pens (total average pen size of 7.1 m^2 in “designed pens” and 10.5 m^2 in pens with “uniform space”, i.e. without separation between excretion and lying area) and therefore entail lower investment (Vosough Ahmadi et al., 2011), while temporary crating systems represent an intermediary solution regarding space. Hence, taking sow and piglet welfare as well as economic considerations into account, temporary crating might be a feasible option, when space is limited and/or modifications in existing barns have to be made (i.e. reconstruction or expansion difficult). Systems for temporary crating might also be of interest, if farmers are not yet willing or able to work with loose farrowing systems.

Therefore, in this study, five farrowing systems (all with a pen size of $\geq$5.5 m^2) allowing temporary confinement of the sow were investigated. Our first aim was to compare different confinement strategies and secondly, different pen types with regard to live-born piglet mortality and mortality due to piglet crushing, respectively. We hypothesised that confining the sow in the farrowing crate for three or five days after farrowing would reduce piglet mortality compared to not confining the sow at all and that a longer confinement period (**CFP**) would be more effective. Furthermore, we assumed that the starting point of confinement (one day before expected farrowing day or directly after farrowing) would not have an effect on live-born piglet mortality. Regarding pen types, we assumed that no effect on piglet mortality would be observed.

Material and methods

Animals and management

The study was conducted on three research farms (A, B and C) in Austria: Farm A housed 600 crossbred sows (“PIC” (Pig Improvement Company) and Landrace × Large White), farm B kept 55 Large White sows and farm C kept 120 Large White and Landrace × Large White sows. All farms applied batch farrowing and standard operating procedures regarding sow and piglet management were carried out according to best practice procedures defined in a project handbook (Heidinger et al., 2017). Sow groups were moved into the farrowing pens approximately five days before the calculated farrowing date. Sows on farms A and B were used to permanent crating in the farrowing pen before the start of the experiment, while sows on farm C were already used to zero confinement in pen type Pro Dromi® (see below). Sows on all farms were fed commercial feed restrictively according to their nutritional demands. Sows were provided with at least 0.5 kg of straw or hay per day from one day before the calculated farrowing date until the actual farrowing day. Hormonal induction of farrowing was permitted after the 116th day of pregnancy and cross-fostering was carried out only within 12–36 h postpartum. On farm A, piglets were weaned after a suckling period of three weeks (due to a 4-week production rhythm), on farms B and C, weaning took place at four weeks of age (due to a 3-week production rhythm). Therefore, the mean weaning age in days was 22.7 ± 3.9 (farm A: 19.6 ± 1.4, farm B: 26.9 ± 2.4, farm C: 26.9 ± 1.5). Mean parity of the sows was 3.1 ± 1.8 (farm A: 2.9 ± 1.6, farm B: 3.9 ± 2.1, farm C: 3.1 ± 1.8). The average proportion of gilts accounted for 37.4% (farm A: 47.9%, farm B: 22.4%, farm C: 29.5%).

Experimental design

Four different confinement periods were applied: In **CFP 0** (control), sows were not confined at all. Sows in **CFP 3** were crated as soon as possible after farrowing (end of farrowing indicated by expulsion of placenta or manual control to check for piglets) until three days after parturition. In **CFP 4** and **CFP 6**, sows were confined one day before the calculated farrowing date until three and five days after parturition, respectively.

On all farms, sows were assigned to groups and moved into the test pens repeatedly. Except for gilts on farms A and C, sows were randomly assigned to the different pen types regardless of previous experience. On farm A, 25% of gilts per batch were allocated to each of the four pen types. On farm C, gilts were allocated to the four pen types in a balanced way. Each batch underwent the same treatment with regard to confinement period. In order to rule out seasonal effects, confinement periods were balanced across the four seasons (March to May, June to August, September to November, and December to February).

Sample size for the study was predetermined in order to detect a two-percent difference in live-born mortality with 70% power by a two-factorial analysis of variance. The effect of two percent was based on a previous study conducted by Baumgartner et al. (2009). Furthermore, we assumed a SD of 5% and α = 0.05.

On each farm, at least three out of five pen types were tested: Three pen types with a total area of 5.5 m^2: Fluegel (**PT F**), Knick (**PT K**), Trapez (**PT T**), two with a larger area: SWAP (**PT S**; 6.0 m^2) and Pro Dromi® (**PT P**; 7.3 m^2). PT F and T were present on all three farms, whereas PT K only on farms A and B, PT S only on farms A and C and PT P, only on farm C (already existing system there). The piglet creep areas in all pen types had warm water heated solid concrete or plastic flooring and were covered.

Pen type Fluegel

The pen size was 5.5 m^2 (2.10 m × 2.62 m), and the crate was arranged straight with the trough directed to the service corridor. The side elements of the crate were telescopic and could be pivoted wing-like to release the sow. Details about the dimensions are given in Fig. 1. Farrowing rails were attached to the rear and both sidewalls of the pen. Flooring consisted of minimally slatted (max.

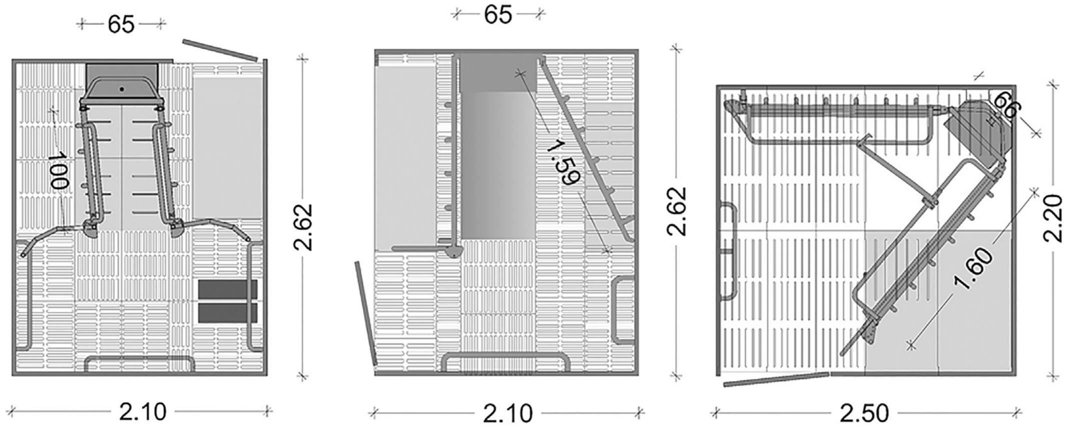

Fig. 1. Draft of three farrowing pens for sows with total pen size of 5.5 m^2 each and open crates: Fluegel pen (F) on the left (dimensions of the closed crate excluding trough: 1.57–2.02 m × 0.49–0.67 m, i.e. minimum and maximum values for adjustable crate length × width), Knick pen (K) in the middle (dimensions of the closed crate excluding trough: 1.25–1.85 m × 0.71–0.81 m, i.e. minimum and maximum values for adjustable crate length × width) and Trapez pen (T) on the right (dimensions of the closed crate excluding trough: 1.70–1.90 m × 0.63–0.72 m, i.e. minimum and maximum values for adjustable crate length × width). Crate width measured at rear end.

5% perforation) concrete floor in front of the trough (lying area of the sow when the crate was closed), cast iron slatted floor at the rear end of the closed crate, as well as plastic slatted floor and solid plastic floor in the remaining areas of the pen.

Pen type Knick

The pen measured 5.5 m^2 (2.10 m × 2.62 m, see Fig. 1). One side element of the crate could be swung to the side and was fixed to the sidewall of the pen. The other crate element next to the creep area was fixed to the floor. Both side elements were telescopic. Farrowing rails were attached to the rear and one sidewall of the pen. The pen was equipped with solid concrete floor in front of the trough (front area of the closed crate), cast iron slatted floor in the rear area of the closed crate and plastic slatted floor as well as plastic partially slatted floor in the remaining areas of the pen.

Pen type Trapez

The pen provided a total space of 5.5 m^2 (2.20 m × 2.50 m, see Fig. 1). In this pen, the crate was arranged diagonally with the rear side facing the corridor and one side element was equipped with a wheel in the rear and could be opened using a lever attached to the top of the crate. The other side element remained fixed in front of the piglet creep area. A farrowing rail was mounted to one sidewall of the pen. The pen was equipped with solid concrete floor in front of the trough (lying area of the sow during confinement), cast iron slatted floor in the rear area of the pen (rear area of the closed crate) and plastic slatted floor in the remaining area of the pen.

Pen type SWAP

The total size of the pen was 6.0 m^2 (2.00 m × 3.00 m, see Fig. 2). The crate consisted of a foldable metal barrier on one side and a sloped wall attached to the sidewall of the pen functioning as a side element of the crate. To release the sow, the metal barrier had to be folded and attached to the creep area, the rear crate door was removed from the pen. Two feeding troughs were available: one in the front to feed and water the sow during crating, one on the sidewall for the time after crating. The lying area was solid concrete floor (60%) with a gradient of 2% towards the slatted iron cast in the back. The rear wall and one sidewall were equipped with farrowing rails.

Pen type Pro Dromi®

The Pro Dromi® pen was the largest of the tested pen types (7.3 m^2, 2.17 m × 3.36 m, see Fig. 3). The crate could be opened by attaching one crate element to the sidewall, whereas the other side element remained fixed to the trough. The rear crate door remained attached to the side elements forming the crate into a V-shaped barrier. A sloped wall was mounted on one sidewall of the pen. Flooring consisted of metal slatted floor in front of the

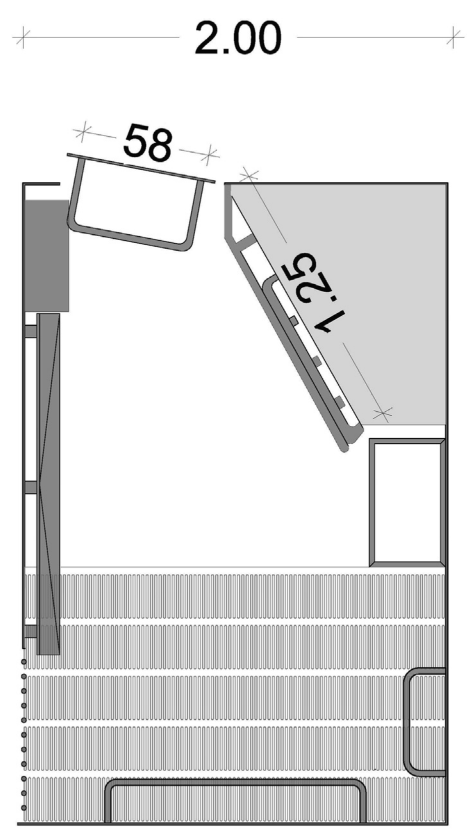

Fig. 2. Draft of farrowing pen SWAP (S) for sows with open crate; one side element folded and attached to the creep area. Width of the closed crate adjustable (0.55–0.99 m; measured at rear end); crate length (1.86 m, measured from the front end of the crate to the straight part of the rear carte door excluding the trough).

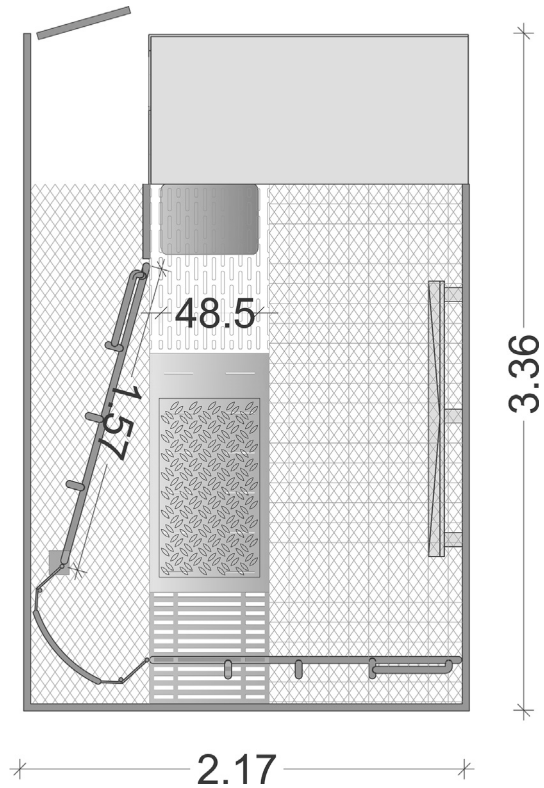

Fig. 3. Draft of farrowing pen Pro Dromi® (P) for sows with open crate. Dimensions of the closed crate excluding trough, not adjustable: 1.92 m × 0.62 m. Crate width measured at rear end.

trough (see Fig. 3), minimally slatted solid concrete floor (in the middle of the soẃs lying area when the crate was closed) and slatted iron cast in the rear area of the closed crate. The remaining pen area was equipped with solid plastic floor (on the right side of the trough and next to the creep area, see Fig. 3) and with plastic slatted floor.

Performance and health-related parameters

Stockpersons documented birth date, number of stillborn and live-born piglets, piglet losses (date and assumed cause of death), cross-fostering and date of confinement and release of sows. Furthermore, interventions (e.g. manual delivery of piglets), medical treatments of sows (e.g. MMA, lameness) and of piglets (e.g. diarrhoea, injuries) were recorded. In total, data from 638 litters were analysed (farm A: 370, farm B: 119, farm C: 149). For each combination of pen type and confinement period, 9 to 50 litters were observed (Supplementary Table S1).

To determine the cause of death, all dead piglets were subjected to postmortem examination. If the cause of death documented by the farm staff was not in agreement with the result of necropsy or in case of an inconclusive necropsy result, video material was used to confirm the cause of death (for farms A and B). All performance data were collected in the software program "Online Sauenplaner®" (Co. Intelicon).

Statistical analysis

For statistical analyses, a uniform trial period covering the period from farrowing until at least the 17th day of piglets' lives was defined. Live-born litter size was determined as number of live-born piglets plus/minus the number of piglets cross-fostered.

Logistic mixed models (Zuur et al., 2009) were applied to determine factors affecting overall live-born piglet mortality and mortality due to crushing (for specification of the model, see Supplementary Material S1). Mixed effect models enable random effects to account for complex data structures such as clustered data (outcomes were obtained from animals of different farms). Confinement period, pen type, litter size, sow parity, season, as well as treatments of litter and sow were considered as fixed effects, whereas sow identification number and farm were included as nested random effects. Litter size and sow parity were used as numerical variables in our models. As we wanted to draw conclusions for practical use of the farrowing pens and confinement periods, we did not include interaction effects of pen type and confinement period. Relevant influencing factors were identified by stepwise forward selection using the Bayesian Information Criterion. Based on the significant regression coefficients, the odds ratios were determined as the exponent of the estimated model coefficients. The odds ratios represented the odds of live-born piglet mortality and mortality due to crushing associated with the significant model factors. Tukey posthoc tests were used to distinguish pairwise differences at the significance level of 0.05. For the analysis of categorical variables, it is necessary to define reference categories due to the model structure. We chose pen type F as reference category for the variable pen type because it was present on all three farms and had the largest number of litters. CFP 0 served as control and was therefore chosen as reference category for the variable confinement period.

As litter size after cross-fostering ranged between 6 and 20 piglets, it was centred around the mean value of 12.9 piglets to allow for an easier comparison of the estimated regression coefficients. All statistical analyses were conducted with the statistic software R version 3.3.2 and the R packages "lme4" and "ggplot2".

Results

Across all farms, 8 228 piglets (farm A: 4 577, farm B: 1 632, farm C: 2 019) were born alive, while stillborn piglets accounted for 6.5% (575/8 803, farm A: 4.8% [231/4 808], farm B: 10.6% [193/1 825], farm C: 7.0% [151/2 170]) of total born piglets (for details about stillbirths in relation to CFP and PT, see Supplementary Table S2). The litter size after cross-fostering ranged between 6 and 20 piglets with a mean value of 12.9 (±2.1) piglets (farm A: 12.4 ± 1.7, farm B: 13.7 ± 2.4, farm C: 13.6 ± 2.5).

Across all farms and CFPs, total preweaning mortality of live-born piglets after cross-fostering (n = 1 580) was 19.2% (1 580/8 228; 14.9% on farm A, 19.2% on farm B and 22.6% on farm C). With 67.8% (1 072/1 580) of all losses among live-born piglets, crushing was the most prevalent mortality reason after cross-fostering, followed by "euthanasia" (11.6%, 183/1 580), "perished" (8.0%, 126/1 580), "runt" (5.6%, 88/1 580), "other" (4.9%, 77/1 580) and "not viable" (2.2%, 34/1 580).

One or more piglets died in 78.2% (499/638) of all observed litters, with at least one piglet lost due to crushing in 65.8% (420/638) of all litters. Average age of piglets at death across all causes was 3.2 ± 4.5 days, ranging from 2.6d (±3.6) for crushing, 3.0d ± 4.6 for euthanasia, 5.1d ± 5.4 for other reasons, 5.7d ± 6.7 for perished piglets to 6.9d ± 6.3 for runts (Supplementary Table S3).

The most common treatment in sows was administration of hormones (oxytocin or prostaglandin F2α) due to dystocia, (prevention of) retained placenta and metritis, agalactia or induction of labour (56.3%, 359/638). Other reasons for medicinal treatments were injuries/inflammations of the legs and lameness (15.5%, 99/638) and PDS/MMA (14.9%, 95/638). Manual assistance during farrowing was provided to 9.2% (59/638) of sows, while 2.0% (13/638) were treated with azaperone due to aggression towards piglets. In piglets, common reasons for treatment included diarrhoea (12.4%; 79/638 of litters with at least one treatment) and locomotory problems (10.8%; 69/638) followed by other reasons such as traumatic injuries and abscesses (2.7%, 17/638).

Estimated odds ratios (**OR**) of significant fixed effects on total live-born piglet mortality are presented in Fig. 4. The higher the OR is, the higher were the odds of an increase in total piglet mortality. For the coefficient estimators, SE and *P*-values of the significant fixed effects, see Table 1. All pairwise comparisons of confinement periods with effect sizes, SE and *P*-values can be found in Table 2. Odds ratios for CFP 3, CFP 4 and CFP 6 were below 1, which means that the mortality risk was significantly higher in CFP 0 than in all other CFPs. There was no significant difference between CFP 3, CFP 4 and CFP 6. Additionally, hormone administration was associated with a higher likelihood of piglet losses compared to no hormones applied. Every one-unit increase of sow parity and litter size increased the odds of piglet losses by a factor of 1.29 and 1.16, respectively. Accordingly, assuming a litter size of 13 piglets (corresponds to the mean), sow parity 3 (corresponds to the mean) and no hormone administration, the highest expected piglet mortality rate was calculated for CFP 0, see Fig. 5.

Factors influencing mortality due to crushing were similar to those for total mortality: Confinement period ($P < 0.001$), litter size ($P < 0.001$) and sow parity ($P < 0.001$) were identified as significant effects, while hormone administration did not improve model performance (Fig. 6, Table 1). In contrast to total live-born mortality, mortality due to crushing in CFP 3 did not differ significantly from that in CFP 0 ($P = 0.079$; OR CFP 3: 0.77 [0.62; 0.95]; Table 2, Fig. 6). However, odds ratios for piglet losses due to crushing did not differ between CFP 3 and CFP 4 and CFP 6 either, while a difference was found between CFP 0 and both CFP 4 and CFP 6. Accordingly, expected piglet mortality due to crushing was again highest in CFP 0 (see Fig. 7).

The pen types had no effect on live-born mortality or piglet crushing rates (all *P*-values > 0.05).

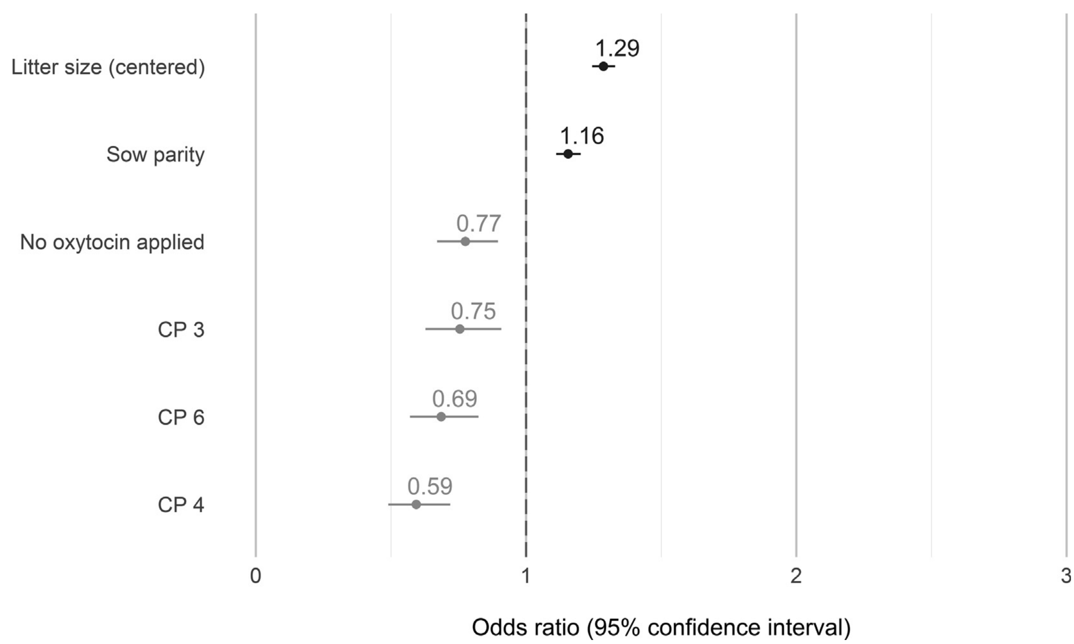

Fig. 4. Estimated odds ratios (95% confidence interval) of significant effects for live-born mortality (piglet losses in live-born piglets after cross-fostering): the dashed line indicates the reference level of the categorical variables (hormone administration = yes; CFP = 0, no confinement), the horizontal lines indicate ranges of confidence intervals, whereas the dots on the lines indicate odds ratios; the numerical variables litter size and sow parity show higher odds of live-born mortality for every one-unit increase. Abbreviations: CFP 3 = confinement after farrowing until three days after parturition; CFP 4 and 6 = confinement one day before the calculated farrowing date until three (CFP 4) and five days (CFP 6) after parturition.

Table 1
Coefficient estimates, SE and *P*-values of only the significant fixed effects using logistic mixed models for total live-born piglet mortality and separately for mortality due to crushing.

	Total live-born piglet mortality			Mortality due to crushing		
Variable	Coefficient Estimate	SE	*P*-value	Coefficient Estimate	SE	*P*-value
Intercept	−1.739	0.101	<0.001	−2.413	0.166	<0.001
Litter size[1]	0.252	0.017	<0.001	0.243	0.021	<0.001
Sow parity	0.145	0.020	<0.001	0.143	0.024	<0.001
No hormones applied[2]	−0.255	0.074	0.001	–	–	–
CFP 3	−0.281	0.094	0.003	−0.259	0.109	0.017
CFP 4	−0.521	0.098	<0.001	−0.527	0.113	<0.001
CFP 6	−0.378	0.094	<0.001	−0.507	0.111	<0.001

Abbreviations: CFP 3 = confinement after farrowing until three days after parturition; CFP 4 and 6 = confinement one day before the calculated farrowing date until three (CFP 4) and five days (CFP 6) after parturition.
[1] Litter size was scaled for modelling purposes and centred around the mean value 12.9 (e.g. litter size 13 had a scaled value of 0.1).
[2] "No hormones applied" did not have a significant effect on mortality due to crushing.

Table 2
Results of pairwise comparisons between confinement periods (CFPs) for live-born piglet mortality (piglet losses in live-born piglets after cross-fostering) and for mortality due to crushing.

	Total live-born piglet mortality			Mortality due to crushing		
Compared CFP	Effect (link)	SE	*P*-value	Effect (link)	SE	*P*-value
3–0	−0.281	0.094	0.015	−0.259	0.109	0.079
4–0	−0.521	0.098	<0.001	−0.527	0.113	<0.001
6–0	−0.378	0.094	<0.001	−0.507	0.111	<0.001
4–3	−0.240	0.099	0.071	−0.268	0.113	0.082
6–3	−0.096	0.094	0.737	−0.248	0.110	0.110
6–4	0.144	0.101	0.481	0.020	0.118	0.998

Abbreviations: CFP 0 = no confinement at all; CFP 3 = confinement after farrowing until three days after parturition; CFP 4 and CFP 6 = confinement one day before the calculated farrowing date until three (CFP 4) and five days (CFP 6) after parturition.

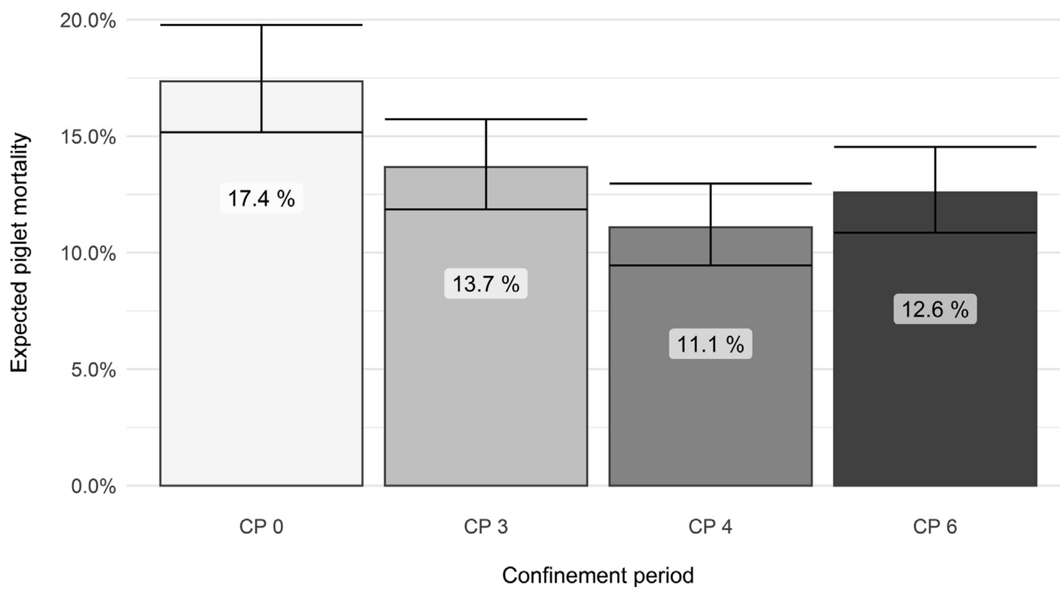

Fig. 5. Expected live-born piglet mortality (in live-born piglets after cross-fostering) with 95% confidence interval (indicated by whiskers) based on model results with the assumed mean values (litter size of 13 piglets, sow parity 3 and no hormone administration). Abbreviations: CFP 0 = no confinement at all; CFP 3 = confinement after farrowing until three days after parturition; CFP 4 and 6 = confinement one day before the calculated farrowing date until three (CFP 4) and five days (CFP 6) after parturition.

Discussion

Our study is one of the first to investigate both, the effects of different durations of temporary crating and pen type on live-born piglet mortality. It was designed as a multicentre study to improve external validity of results, as three different, farm individual situations are reflected. As study design and assessment procedures were largely standardised, it was possible to analyse data from all three farms in one model. The study design aimed at a balanced number of litters per confinement period and pen type, which was achieved with regard to the confinement period (150 to 169 litters per confinement period), but due to limited resources, pen type P was underrepresented with only 47 litters (all on farm C).

As mentioned, we conducted a power analysis beforehand, which aimed at two factors with four categories each. Nevertheless, in our final statistical model, further factors such as litter size, sow parity and farm were considered. This was necessary to detect and sort out confounders, although actual power could have been reduced. For the power analysis, we considered a two-percent difference in live-born mortality as relevant and, based on previous studies, determined a SD of 5% and $\alpha = 0.05$. For detection of smaller differences in live-born mortality at the power of 70%, a larger dataset would have been required. However, considering all mentioned factors, we were able to show substantial effects of the different confinement periods applied.

In this study, total live-born preweaning piglet mortality across all farms and confinement periods was 19.2%, which is at the upper limit of the range (10–20%) that is considered as "normal" for commercial pig herds using conventional farrowing crates (Muns et al., 2016). Expected live-born piglet mortality rates in confinement periods with confinement of the sow varied between 11.1 and 13.7% (Fig. 5) which is comparable to live-born mortality rates in conventional farrowing crates on Austrian farms (average of 12.7% over the years from 2001 to 2020; (Doppelreiter et al., 2021)). In 67.8% of all cases, piglet losses occurred due to crushing by the sow, which is in accordance with former studies, reporting crushing rates varying from 55 to 75% (Marchant et al., 2001; KilBride et al., 2012).

Effect of confinement period on live-born piglet mortality and crushing

In the investigated housing systems, live-born mortality and mortality due to crushing were higher in non-confined sows (CFP 0) than in sows that were crated, regardless of the duration of confinement. Our results confirm previous studies, which showed that short confinement of the sow (until day 4 postpartum, regardless of starting time of confinement) is effective to reduce piglet mortality compared to not confining the sow at all in systems with restricted space allowance (Moustsen et al., 2013; Hales et al., 2015a). However, contrary to findings from Hales et al. (2015a) and Condous et al. (2016), in our study, confinement before

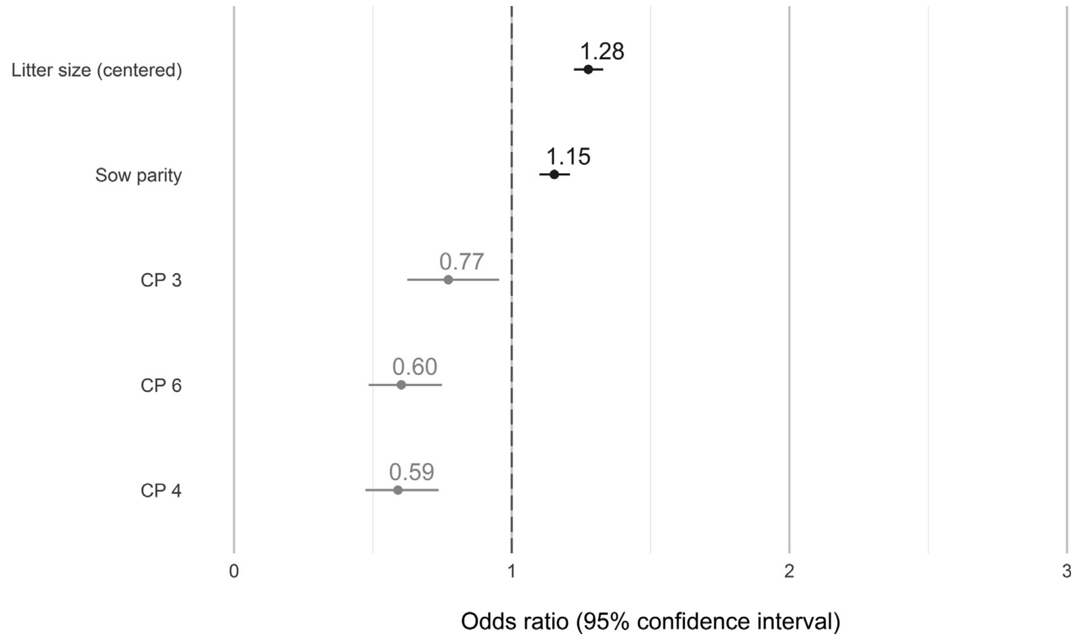

Fig. 6. Estimated odds ratios (95% confidence interval) of significant effects for piglet mortality due to crushing (piglet losses after cross-fostering): the dashed line indicates the reference level of the categorical variable (CFP = 0, no confinement), the horizontal lines indicate ranges of confidence intervals, whereas the dots on the lines indicate odds ratios; the numerical variables litter size and sow parity show higher odds of live-born mortality for every one-unit increase. Abbreviations: CFP 3 = confinement after farrowing until three days after parturition; CFP 4 and 6 = confinement one day before the calculated farrowing date until three (CFP 4) and five days (CFP 6) after parturition.

expected farrowing (CFP 4 and CFP 6) did not result in lower piglet mortality or crushing rates compared to crating the sow after farrowing (CFP 3). From a sow welfare point of view, confinement before farrowing should be avoided allowing unrestricted nest building. As the majority of crushing events have been reported to occur during the first 24 h of piglets' lives (Marchant et al., 2001), confining the sow at the end of the nest-building phase, i.e. shortly before the first piglet is born, might be recommendable. However, careful management and supervision are crucial, as sudden confinement at parturition might result in additional stress for the sow and impair the farrowing process (Yun et al., 2015). In the near future, precision livestock technologies might facilitate close monitoring of farrowing, which could aid the decision process of when to confine (Traulsen et al., 2018; Oczak et al., 2020). Confinement of the sow for more than three days after farrowing (in CFP 6) did not result in a further reduction of mortality or crushing rates, thus confirming Moustsen et al. (2013) who investigated a confinement period of up to day 7 postpartum. Therefore, it can be concluded that in the pen types tested, the "critical phase of life of suckling piglets" ended at day 3 postpartum and that piglet mortality may not justify further confinement. For future studies, it might be interesting to further improve the crate opening management as there is evidence that piglet mortality increases immediately after opening and is dependent on the time of day at which the crate is opened (King et al., 2019).

Effect of pen type on piglet mortality and crushing

Pen type did not affect total live-born piglet mortality or crushing rate. Assuming that specific risks of piglet losses which relate to the pen type apply mainly to the postconfinement period, each pen type seemed to provide conditions (i.e. protection rails, creep area) equally suited to result in similar mortality and crushing rates after the sows had been released. However, the significantly higher live-born mortality and crushing rate in CFP 0 suggest that using the tested pen types for free farrowing (sow loose during farrowing and lactation) would result in higher piglet losses. It could be argued that a pen size of 5.5 m^2 as provided in pen types F, K and T was too small for free farrowing. Nevertheless, both larger pen types (SWAP, 6.0 m^2 and Pro Dromi®, 7.3 m^2) did not outperform with regard to live-born piglet mortality or mortality due to crushing. Therefore, it can be concluded that not only pen size but also other design criteria (i.e. flooring, arrangement of resources, geometry of space for movement etc.) are of importance for piglet protection as well as sow and piglet behaviour and their interaction, as previously described by Baxter et al. (2011).

Other effects on piglet mortality and crushing

Apart from confinement period, increasing litter size and sow parity led to a significant increase in piglet mortality. Increasing litter size has been associated with prolonged duration of farrowing (Hales et al., 2015b), higher stillbirth rate (Oliviero et al., 2008), reduced piglet vitality and increased preweaning piglet mortality (for a review, see Rutherford et al. (2013), with the latter also being confirmed in our study. Hermesch (2000) mentioned 13 piglets as a critical threshold of litter size regarding piglet mortality. Litter size can also be seen as a critical factor for increased crushing mortality, as there are more piglets "*available to be crushed*" (Weary et al., 1998).

The result, that higher live-born piglet mortality and crushing were associated with increased age of sows, confirms previous studies (Hellbrügge et al., 2008; Hales et al., 2015b). This might be explained by the increased litter size of older sows that are heavier, maybe "more clumsy" (Weary et al., 1998), and at the same time have relatively little space to move around. Higher weight and larger physical size of older sows may affect their agility and ability to perform standing up and lying down behaviour in a controlled way (D'Eath and Jarvis, 2002; Hales et al., 2015a) and they may even suffer from impaired physical constitution including lameness and less intact teats or mammary glands. Using treatment incidence, the health status of sows (and piglets) did not have a significant effect on live-born piglet mortality or crushing in this study. An explanation for this might be, that the incidence of treatments was relatively rare and other factors were more important.

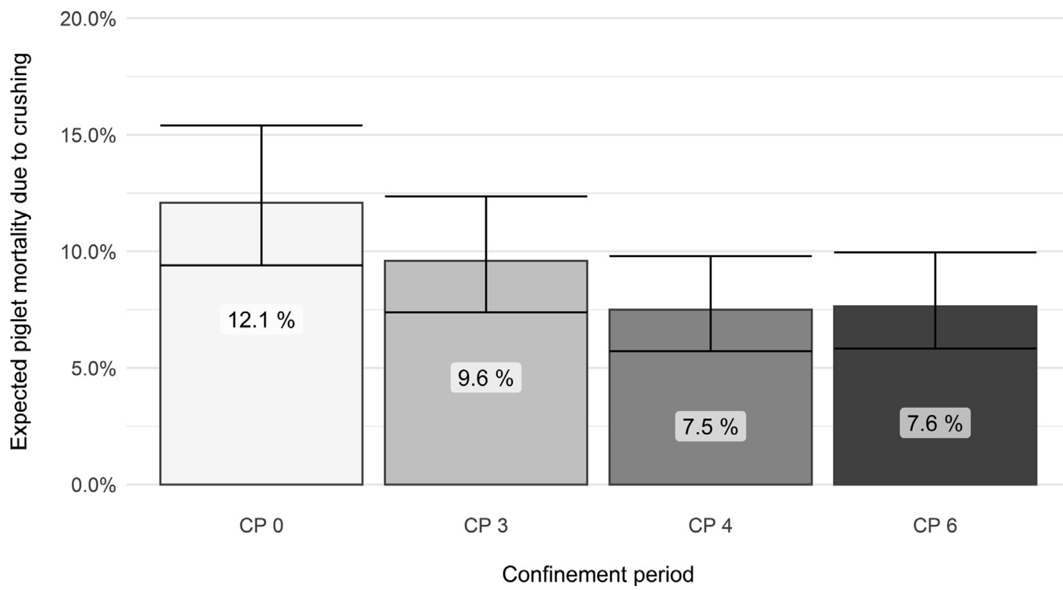

Fig. 7. Expected piglet mortality due to crushing (after cross-fostering) with 95% confidence interval (indicated by whiskers) based on model results with the assumed mean values (litter size of 13 piglets and sow parity 3). Abbreviations: CFP 0 = no confinement at all; CFP 3 = confinement after farrowing until three days after parturition; CFP 4 and 6 = confinement one day before the calculated farrowing date until three (CFP 4) and five days (CFP 6) after parturition.

Administration of hormones was associated with increased liveborn piglet mortality but not mortality due to crushing. However, as this indicator combines different reasons for treatment (induction of labour, dystocia, (prevention of) retained placenta, agalactia), it is difficult to interpret: Sows without administration of hormones were presumably those, that experienced less complications and stress around the time of parturition and therefore maybe had better preconditions for survival of their piglets. In future studies, the indication for hormone administration should be recorded to be able to determine cause and effect.

Conclusion

Confinement of the sow is considered as an effective way to reduce piglet mortality in farrowing systems with restricted space allowance. In the investigated five farrowing pens designed for temporary crating (with a total size of 5.5–7.3 m^2), confining the sow for three days after parturition was sufficient to reduce liveborn piglet mortality and crushing, respectively, compared to not confining the sow at all. Based on our results, we recommend that sows should not be crated for longer than three days after farrowing and from a sow welfare point of view not before onset of farrowing.

No difference was found regarding pen type so that more research is needed to consider different design criteria of farrowing pens in a more systematic approach: for example, controlled experiments in one pen type regarding piglet mortality by means of varying type of flooring or positioning and specific design of pen equipment (rails, sloped walls etc.) or piglet creep design while keeping other design elements constant.

Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.animal.2021.100446.

Ethics approval

Project "Pro-SAU" was authorised by the Committee of Animal Experimentation of the Austrian Federal Ministry of Science, Research and Economy (GZ: BMWFV-68.205/0082-WF/II/3 b/2014) according to the Austrian Tierversuchsgesetz 2012, BGBl. I Nr. 114/2012 (BMWF, 2012) and by the Ethical Committee of the University of Veterinary Medicine Vienna.

Data and model availability statement

None of the data were deposited in an official repository. Data are available on request.

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Declaration of interest

The authors have no conflict of interest to declare.

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