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Impact of supplemental liquid feed pre-weaning and piglet weaning age on feed intake post-weaning

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HIGHLIGHTS

- Intake dropped when milk replacer was changed to liquid feed during lactation.
- Liquid feed pre-weaning shortened the latency to the first feed intake post-weaning.
- Liquid feed pre-weaning did not increase feed and water intake post-weaning.
- Weaning at 35 vs 24 days shortened the latency to first feed intake post-weaning.
- Weaning at 35 vs 24 days increased eating bouts post-weaning.

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ABSTRACT

The impact of weaning age and/or supplemental liquid feed in the farrowing pen on pre- and post-weaning feed intake was investigated. The supplemental feed systems consisted of a milk replacer from day 2, changed to a cereal-based liquid feed 12 days after birth. By continuing with the same feed post-weaning, but in dry form, we hypothesised that the feed change would be less abrupt and would increase feed intake post-weaning. The study consisted of 24 sows and their litters in a 2 × 2 factorial design. The design factors were weaning age (WeaningAge) at either 24 days (D24) or 35 days (D35) and with or without access to supplementary liquid milk replacer/feed (+SupFeed/-SupFeed). Individual eating behaviour pre- and post-weaning was observed on video recordings. Results of this study showed that the transition from milk replacer to liquid feed during lactation (on day 12) caused a drop in number of bouts observed per piglet of ingesting supplemental feed (day 11 compared to days 12 and 13) ($p < 0.05$). Independent of WeaningAge, more bouts of ingesting supplemental feed per piglet were seen the day before weaning in piglets with lower suckling success ($p < 0.05$). WeaningAge D35 compared to D24 shortened the latency to the first observation of solid feed consumption and drinking water, and litters weaned at D35 had more eating and drinking bouts per piglet the first 12 h post-weaning ($p < 0.05$). WeaningAge D35 also increased eating bouts the day after weaning (24 to 36 h post-weaning) ($p < 0.05$), 6 days after weaning ($p < 0.05$) and the daily amount of feed consumed per pen the first week post-weaning. Access to supplemental feed shortened the latency to the first feed consumption but increased the latency to water consumption within 12 h of weaning ($p < 0.05$). Access to supplemental feed and the mean frequency of feed intake pre-weaning (days 11-13) did not affect the frequency of feed or water consumption per piglet post-weaning ($p > 0.1$). Nor did access to supplemental feed affect the daily amount of feed consumed per pen from weaning to 6 days after ($p > 0.1$). The results of the present study show that later weaning, to a greater extent than supplemental feed pre-weaning, could increase feed intake post-weaning. However, the effect on gut health and diarrhoea needs to be investigated to evaluate whether it is an effective alternative to antibiotics and medical zinc.

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1. Introduction

Piglets are subjected to an abrupt feed change at weaning from milk to solid feed. This frequently results in a reduced feed intake, reduced growth and diarrhoea (Spreeuwenberg et al., 2001; Bruininx et al., 2002). To treat diarrhoea, antibiotics or medical zinc is widely used. High use of antibiotics is in turn associated with high risk of developing antimicrobial resistance (Gresse et al., 2017), and since use of medical zinc has been banned by the European Union (EU) Commission beginning in 2022 (Directive 2001/82/EC 2017), alternatives to prevent/reduce post-weaning diarrhoea (PWD) are sought. The common weaning practice is to remove piglets from the sow between 18 and 35 days of age, depending on the country (Edwards et al., 2020). Within the EU, the minimum age is 28 days while 21 days is allowed in cases where piglets are weaned in batches into cleaned and sectioned pens (COUNCIL DIRECTIVE 2008/120/EC, 2008). With increasing litter size, the weaning age tends to be driven towards lower age due to the use of nurse sows and space limitations in the farrowing unit (Baxter et al., 2020). For example, the mean weaning age in Denmark is reported to be 25 days of age in average (Udesen and Christiansen, 2017). Due to variation in farrowing day and to the oldest born litters determining the weaning time for the entire batch, it means that the youngest litters may be several days younger. The immunological state of piglets at this age is characterised by a gap in the protective immune system due to lack of maternal immunity and an immature immune system (Moeser et al., 2017). Piglets' active immunity is developed from about 4-5 weeks of age (McCracken and Kelly, 1993), and thus weaning after this point is assumed to increase piglets' resilience to diarrhoea. Weaning at a later age will also give piglets more time to start eating as well as increase body weight and gut maturity and thus start adapting their gastrointestinal tract to plant-based solid feed gradually (Dong and Pluske, 2007). Previous studies have shown that later weaning increases feed intake post-weaning (Davis et al., 2006; van der Meulen et al., 2010). As such, increasing weaning age is a potential strategy to mitigate the abrupt feed change at weaning. The abrupt feed change may also be mitigated if the piglets start eating pre-weaning. Previous results have shown that eaters of solid feed pre-weaning start eating earlier post-weaning than non-eaters (Bruininx et al., 2002). However, getting piglets to eat solid feed before week 4 after birth has largely been unsuccessful, and only in average around 50% of piglets within a litter eat pre-weaning (Bruininx et al., 2002; Heo et al., 2018). An alternative to providing solid feed pre-weaning is to provide milk replacer/liquid feed. There is an increasing interest in providing sow-reared piglets with milk replacer (mainly due to the large litter size of modern hyper-prolific sows), which due to greater resemblance to sow milk may hold more interest for piglets than solid feed. What is more, in many farms using commercial milk replacer systems, it is standard to change the supplemental milk replacer to a cereal-based feed resembling liquid feed at around day 12. By continuing the same supplemental feed into the first week post-weaning (in liquid or dry form), the feed change will become less abrupt and help initiate and promote the gut and digestive enzyme development that may help piglets to utilise other feed sources once milk is removed (De Passillé et al., 1989). However, as seen with solid feed pre-weaning, piglets may have minimal motivation to consume milk replacer when they can suckle the sow (Kobek-Kjeldager et al., 2020a). Further, piglets' interest in supplemental feed pre-weaning may be reduced by a shift from milk replacer to liquid feed. It may also be that the largest and most mature piglets start to eat pre-weaning (Pajor et al., 1991; Kobek-Kjeldager et al., 2020a) leaving the smaller piglets as vulnerable to weaning stress and diarrhoea as without access to supplemental feed. Therefore, the aim of the current study was to investigate the eating behaviour of piglets in the transition from milk replacer to liquid feed in an automatic system pre-weaning and the effect of supplemental milk/feed and weaning age on eating behaviour on the day of weaning, the day after weaning and 6 days after. We hypothesised that A) the transition from milk replacer to liquid feed during lactation at day 12 of age would decrease the bouts of ingesting supplemental feed per piglet, B) more bouts of ingesting supplemental feed pre-weaning would be associated with 1) larger piglets 2) later weaning and 3) less successful suckling events the day before weaning. In turn, we hypothesised that C) later weaning and supplemental feed would reduce the latency to the first feed and water intake on the day of weaning and result in higher feed intake on the day of weaning as well as 1 and 6 days after.

2. Materials and Methods

This study was conducted at Department of Animal Science, AU-Foulum, Aarhus University, Denmark, from February to April 2019. Housing and rearing were in compliance with Danish legislation and regulations for the humane care and use of animals in research (The Danish Ministry of Justice, 1995). The experiment was conducted according to the Danish Animal Experimental Inspectorate.

2.1. Study design

The study consisted of 24 sows and their litters ($N = 360$ piglets) in a 2×2 factorial design. The design factors were weaning age (WeaningAge) at either 24 days post partum (*pp)* (D24) or 35 days *pp* (D35). The second factor was with or without access to supplementary liquid feed (SupFeed) from day 2 *pp* to weaning (+SupFeed/-SupFeed). The piglets' eating behaviour was recorded for 12 h on days 11 to 13 *pp* (D11, D12, D13), 24 to 12 h before weaning (DayBeforeWeaning), 0 to 12 h after weaning (WeaningDay), 24 to 36 h after weaning (WeanD1) and 6 days after weaning (WeanD6). The animals were also part of a dose-response sow gestation feeding trial looking at piglet survival (Feyera et al., 2021). Further, during lactation, all sows and their litters were used in a study looking at effect of weaning age and supplemental feed during suckling on piglet performance, gut health and diarrhoea pre- and post-weaning.

2.2. Animals and housing

2.2.1. Farrowing facility

The 24 second parity sows were cross-bred Landrace × Yorkshire, and their litters were Landrace × Yorkshire × Duroc piglets (Danbred, Axelborg, Denmark). Sows were moved from the gestation facility into the farrowing pen 7 days prior to expected farrowing. The farrowing facility consisted of two rooms with ten farrowing pens with crates for sows (Fig. 1) and a third room with four pens also with crates (2.7×1.8 m). The floor area of each pen consisted of 50% slatted floor and 50% concrete floor. All sows were provided a rope in every pen before farrowing, and

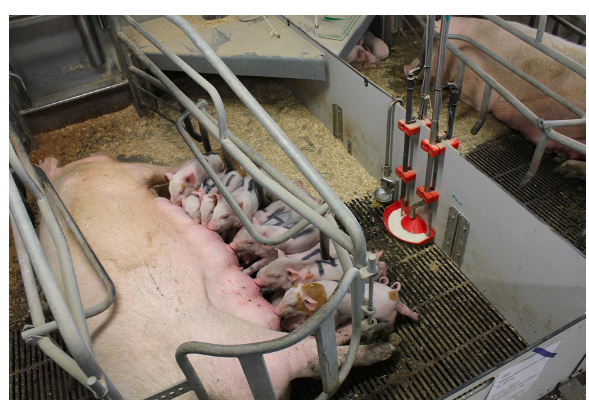

Fig. 1. The liquid supplemental feeder for piglets automatically supplied milk replacer from days 2 to 12 after birth and liquid feed from day 12 to weaning (either at day 24 or at day 35). The system needed no activation from the piglets. It was set to feed ad libitum.

wood shavings were provided during the nest-building phase. Because the animals were part of a dose-response feeding trial during the last 7 days of gestation, sows were not given straw for nest building. All farrowings were monitored, and piglets underwent the following procedure (see details in Feyera et al. (2021)): blood sampling, drying/wiping, ear tagging, shortening of umbilical cord and weighing before being returned to the udder. Farrowing assistance was performed when the interval between two consecutive births exceeded 1 h. At farrowing, room temperature was kept at 20°C until day 5 after birth and thereafter reduced by 0.1°C each day until reaching 16°C on day 28. The creep area was covered and heated with an infrared lamp. Water was available at *ad libitum* for both sows and their pigletss in nipple and trough drinkers, respectively. The intake was not recorded. On day 2, the litters were standardised to 15 piglets without taking into account the number of functional teats of the sow. The mean number of functional teats per sow was 14 (range: 12 to 16). If the sow had more than 15 live piglets on day 2, the smallest piglets were excluded (median 1.1 kg, range 649 g to 1.9 kg). The mean weight of the piglets on day 2 was 1.6 ± 0.3 kg.

2.3. Supplemental piglet feed: milk replacer and liquid feed

From day 2 to day 12, litters in the +SupFeed treatment were supplemented with milk replacer (Pigipro 1 Milk Care, 3S, Schills, Sittard, The Netherlands) in an automatic system (Babydos Bopil, Sønderborg, Danmark). On day 12 at 08.00 h, the milk replacer was automatically changed to liquid feed by using a Danish standard starter meal diet (Vestjyllands Stjerne Care, Ringkøbing, Denmark) mixed with water immediately before automatic feeding. The liquid feed was then supplied until weaning (D24/D35). The milk replacer/liquid feed was supplied in a trough (semicircle with radius of 10 cm) automatically and needed no activation from the piglets (Fig. 1). The system was set to supply supplemental feed with the highest frequency, so that the supplemental milk/feed would in theory be accessible *ad libitum*. In practice, this was not always the case. Furthermore, when the supplemental milk/feed was supplied, the feeder made a distinct sound. These two characteristics will be discussed later as they are relevant for the interpretation of the results. The nutritional content of the milk replacer and liquid feed is shown in Table 1. After weaning, the pigs were provided with the same feed (Vestjyllands Stjerne Care, Ringkøbing, Denmark) as given from day 12 until weaning but in dry, meal form until the end of the study (6 days after weaning).

2.4. Chemical analysis of supplemental piglet feed

The supplemental piglet feed was analysed for their nutritional content (Table 1). The DM was determined by drying the samples at 105°C to a constant weight. Dietary ash was analysed according to the AOAC method 942.05, and dietary nitrogen was analysed by the Dumas method (Hansen, 1989). Dietary gross energy was determined in an adiabatic bomb calorimeter (IKAC 400; IKA Werke, Staufen, Germany). Content of starch in the diet was analysed as described by Knudsen (1997). Dietary fat was extracted with diethyl ether after hydrochloric acid hydrolysis (Stoldt, 1952). Lactose was analysed using high-performance anion exchange chromatography with pulsed amperometric detection (Corradini et al., 2012).

Table 1
The nutritional content of the piglet supplemental feed.

	Pigipro 1 Start[1]	Vestjyllands Stjerne Care[2]
DM (%)	95.5	91.9
CP (% of DM)	23.4	21.4
Ash (% of DM)	6.9	6.9
Fat (% of DM)	16.3	NA
Starch (% of DM)	5.6	39.8
Lactose (% of DM)	43.6	NA
Gross energy (MJ/kg DM)	20.9	19.0

[1] provided from day 2 to day 12 after birth.
[2] provided as liquid feed from day 12 to weaning and solid feed from weaning to day 6 after weaning.

2.5. Sow feed

During gestation and the last 7 days before farrowing, sows were part of a dose-response feeding trial. The aim of that study was to increase piglet survival by feeding the sows increasing amounts of feed in turn improving the sows' energy status (Feyera et al., 2021). The sows were stratified for body weight and randomly assigned to one of six dietary treatments. During lactation, the sows were fed according to the Danish recommendations (Tybirk et al., 2018).

2.5.1. Weaning facility

On the weaning day (D24/D35), two litters from the same group of WeaningAge and SupFeed were individually marked and moved to the weaning facility, placed in the same building and housed in one pen. Two piglets from each litter were slaughtered in order to investigate gut health (not part of this study). The mean number of pigs per weaner pen was 23 (range 19-26). The weaner pen (5 × 2.5 m) had 2/3 of slatted floor and 1/3 of covered concrete floor with heating to create a two-climate pen environment. The pens had two feed troughs (TR4, Rotecna, Agramunt, Spain, 2 × 70 cm feeding space), a drinking nipple and a water trough that was automatically refilled. Wood shavings (20 kg, Finspån, Agroline, Vestjyllands Andel, Ringkøbing, Denmark) were provided in the weaner pens from the day of weaning. An extra 10 kg of wood shavings was provided within the first 6 days after weaning. Due to minimal feed intake the first day after weaning in the first two weaner pens (weaning took place on different days due to variation in farrowing dates), it was found necessary to place a long trough (200 × 22 cm) in the pens to stimulate eating. To keep uniformity in the design, a long feed trough was also installed in the remaining weaner pens on day 2 post-weaning independent of the piglets' eating behaviour. The long troughs were removed after WeanD6.

2.6. Data sampling

Piglets were weighed at birth (BiW), on day 2 and at weaning (D24/D35). The individual eating behaviour of all piglets was recorded. Piglets were marked individually with a number on their back using a black pen in the morning from 08.30 to 11.00 h on all observation days. On days 11-13 (the milk replacer was changed to liquid feed on day 12 at 08.00 h), each bout of ingesting supplemental feed was recorded according to the description in the ethogram (Table 2). The actual amount of feed ingested was not known. On the DayBeforeWeaning, observations of missed milk letdown (approx. 10 events of milk letdown per litter were observed) were also included (Table 2). On the WeaningDay, from the time piglets were moved to the weaning pen at 11.00 h, individual drinking and eating behaviour was recorded continuously until 23.00 h (Table 2). On WeanD1 and WeanD6, drinking and eating behaviour was recorded by instantaneous scan sampling every 5 min for a 3 × 2-h period (11.00-13.00, 15.00-17.00, 20.00-22.00). Scanning every 5 min was chosen as Bruininx et al. (2001) found that the average eating bout lasted about 5 min the first 8 days after weaning. Scanning every 5 min should therefore enable recording most eating bouts. However, this scanning interval could not record the shorter drinking bouts properly, and therefore data on drinking on WeanD1 and WeanD6 will not be presented. Due to technical problems with the video recordings, variations appeared in the number of litters observed each day, which will be considered in the interpretation of the results. The amount of supplemental feed supplied to each pen pre-weaning was automatically recorded. Post-weaning, the amount of dry feed eaten per weaner pen was recorded by manually weighing feed residues daily the first week after weaning.

Table 2
Ethogram of piglet behaviour observed in the farrowing pen on days 11-13, the day before weaning, and in the weaner pen on the day of weaning, the day after weaning and 6 days after.

Behaviour	Definition	Observation day	Time period
Pre-weaning			
Bout of ingesting supplemental feed	A piglet has its head in the trough for at least 2 s when milk replacer/liquid feed is visible in the trough.	D11, D12, D13, DayBeforeWeaning	11.00-23.00
Milk letdown	After a period of intensive massaging of the udder by more than 50% of the litter, piglets suck simultaneously and persistently on a teat for approx. 15 s	DayBeforeWeaning	11.00-23.00
Missing milk letdown	A piglet visibly not having a teat in its mouth at milk letdown		
Post-weaning			
Drinking water	A piglet has its head above the drinking trough or inside the drinking nipple for at least 5 s. The piglet's head must be away from the water for at least 5 s to count as a new drinking bout.	WeaningDay	11.00-23.00, continuously
Eating dry feed	A piglet has its head in the feeding trough for at least 5 s. The piglet's head must be away from the feed trough for at least 5 s to count as a new eating bout.		
Eating dry feed	A piglet has its head in the feeding trough.	WeanD1, WeanD6	Instantaneous scan sampling every 5 min, 11.00-13.00, 15.00-17.00, 20.00-22.00
Drinking water	A piglet has its head above the drinking trough or inside the drinking nipple.		

D11, D12 and D13 refer to days 11, 12 or 13 after birth.
DayBeforeWeaning refers to 24 to 12 h before weaning on either day 23 or 34 after birth, depending on treatment.
WeaningDay refers to 0 to 12 h after the piglets were moved from the farrowing facility into a weaner pen on either day 24 or 35 after birth.
WeanD1 refers to the day after weaning (24 to 36 h after moving to weaner pen) on either day 25 or 36 after birth.
WeanD6 refers to 6 days after weaning on either day 30 or 41 after birth.

2.7. Data processing

2.7.1. Variables

The number of bouts per piglet per day of ingesting supplemental feed on D11, D12 and D13 and the DayBeforeWeaning (24 to 12 h pre-weaning) as well as eating and drinking water on the WeaningDay (0 to 12 h post-weaning) was calculated. For each piglet, the mean number of bouts of ingesting supplemental feed per piglet/12 h was calculated across days 11, 12 and 13. In case video observations were missing on one of the days, the mean was calculated for the two remaining days. From the video observations on day DayBeforeWeaning, the events of milk letdown in which each piglet successfully suckled the sow in the 12-h period were also recorded. On WeaningDay, the latency to the first observation of eating and of drinking during the first 12 h was calculated for each piglet. The eating bouts on WeanD1 (24 to 36 h post-weaning) and WeanD6 were recorded as instantaneous scan sampling, and, from this, the proportion of scans each pig was observed eating was calculated.

2.7.2. Statistical analysis

The bouts per piglet per day of ingesting supplemental feed pre-weaning and eating and drinking post-weaning were analysed in four negative binomial generalised linear mixed models (due to being non-normally distributed count data with a greater variance than mean – i.e. not Poisson distributed). The latency to the first eating and drinking bout was investigated using a survival analysis and the daily amount of feed consumed the first week after weaning in a linear mixed model. Below, each model is described in detail.

2.7.2.1. Supplemental feed pre-weaning (D11, D12, D13 and DayBeforeWeaning). In the first model (**M1**), the response variable was the bouts per piglet of ingesting supplemental feed on days 11, 12 and 13 ($N = 126$ pigs $\times$ 3 days).

$$log(\mu) = \log[12h] + \beta_0 + \beta_1 BiW + \beta_2 LitterSize + \sum_{i=1}^{2} \alpha_i DAY_i \qquad \text{(M1)}$$

Where log[12 h] is the log-offset of the 12-h observation period. μ refers to the probability parameter in the negative binomial distribution. β_0 refers to the intercept for day 13, β_1 refers to the continuous covariate piglet birth weight, β_2 refers to the continuous effect of LitterSize on the given DAY. α_{1-3} are the parameters describing the effect of the observation days 11 and 12 in relation to the reference (day 13; index *i*). DAY_i is indicator functions (implying that these sum to 0 (if DAY is 13).

In the second model (**M2a**), consisting only of piglets in the treatment +SupFeed, it was investigated whether the number of bouts of ingesting supplemental feed per piglet on the DayBeforeWeaning was affected by the number of events of milk letdown each piglet successfully suckled the sow in the 12-h period ($N = 78$ pigs). As WeaningWeight was highly correlated with WeaningAge, the former was not included in **M2a** but instead substituted for WeaningAge in a similar model within D24 and D35, respectively (**M2b**).

$$log(\mu) = \log[12h] + \beta_0 + \beta_3 No.Suckling + \beta_4 WeaningLitterSize + \beta_5 WeaningAge \qquad \text{(M2a)}$$

Where log[12 h] is the log-offset of the 12-h observation period. μ refers to the probability parameter in the negative binomial distribution. β_0 refers to the intercept, and β_3 refers to the number of milk letdown that each piglet successfully suckled, β_4 refers to the continuous effect of litter size on the day of weaning, and β_5 refers to the binary effect of WeaningAge.

2.7.2.2. Eating and drinking bouts the day of weaning (WeanD0). The latency for a pig to eat and drink during the first 12 h (720 min) after weaning was analysed separately using the 'survival' package with the 'coxph' function in R (**S1**) with censoring at 12 h ($N = 168$ pigs). In the survival analysis, the WeaningAge and SupFeed were included as fixed effects and the number of pigs in the weaner pen (PigsWeanerPen) as covariate. The effect of WeaningWeight was analysed within subsets of each WeaningAge (as WeaningWeight was correlated with WeaningAge). Furthermore, within +SupFeed, the continuous effect of mean number of bouts of ingesting supplemental feed per piglet/12 h across days 11, 12 and 13 was substituted by SupFeed ($N = 85$ pigs). Next, the number of bouts of ingesting supplemental feed on DayBeforeWeaning was substituted for SupFeed on number of eating bouts per piglet/12 h ($N = 47$ pigs).

In the third negative binomial generalised linear mixed model (**M3a**), the bouts per piglet of eating and drinking water the day of weaning were analysed as response variables for an effect of the two treatments ($N = 168$ pigs).

$$log(\mu) = \log[12h] + \beta_0 + \beta_4 PigsWeanerPen + \beta_5 WeaningAge + \beta_6 SupFeed \qquad \text{(M3a)}$$

Where log[12 h] is the log-offset of the 12-h observation period. μ refers to the probability parameter in the negative binomial distribution. β_0 refers to the intercept for WeaningAge35 and +SupFeed. β_4 refers to the continuous effect of the number of pigs in the weaner pen (PigsWeanerPen), β_5 refers to the binary effect of WeaningAge, β_6 refers to binary effect of SupFeed. A similar model (**M3b**) only included piglets in +SupFeed and tested the effect of the mean number of bouts of ingesting supplemental feed per piglet across days 11, 12 and 13 ($N = 85$). In **M3c**, the effect of the number of bouts of ingesting supplemental feed on the DayBeforeWeaning on the number of eating bouts per piglet/12 h ($N = 47$ piglets) was investigated.

2.7.2.3. Eating bouts on days 1 and 6 after weaning. A fourth negative binomial generalised linear mixed model (**M4a**) was used to analyse the percentage of scans a piglet was observed eating on WeanD1 and WeanD6. This variable was tested for normality and homogeneity of variance and analysed as a response variable in a linear mixed model. The percentage on WeanD1 was log-transformed in order to achieve normality. The percentage of scans was analysed for an effect of the two treatments in **M4a** ($N = 146$ pigs) and then in +SupFeed for an effect of mean number of bouts of ingesting supplemental feed across days 11, 12 and 13 *pp* in **M4b** ($N = 78$ pigs).

$$\%Eating\big/Scans_{ijn} = \mu + WeaningAge_j + SupFeed_n + \vartheta_m + \varepsilon_{ijnm} \quad \text{(M4a)}$$

where %Eating/Scans is the percentage of scans each piglet was observed eating out of the total scans on either WeanD1 or WeanD6 (index *ijn*). μ is the overall mean of the observations, WeaningAge (index *j*) describes the binary effect of weaning on D24 or D35. In **M4a**, SupFeed (index *n*) describes the binary effect of access to supplemental feed pre-weaning or not. ϑ is a normal distributed random effect to account for the repeated measures within weaner pen (index *m*), and ε (index ijnm) refers to the normal distributed residual error. In **M4b**, the mean number of bouts of ingesting supplemental feed on days 11, 12 and 13 per piglet was included instead of SubFeed and as continuous effect (index *n*).

2.7.2.4. Feed intake the first week after weaning. The last model (**M5**) was a linear mixed model analysing the daily amount of feed (kg) consumed the first week after weaning ($N = 96$, 12 weaner pens × 8 days).

$$Feed_{ijn} = \mu + \sum_{i=1}^{7} \alpha_i DAY_i + WeaningAge_j + SupFeed_n + PigsWeanerPen_m + \vartheta_o + \varepsilon_{ijnmo} \quad \text{(M5)}$$

Feed is the daily amount (kg) of feed consumed per pen the first week after weaning (index *ijn*). μ is the overall mean of the observations. α_{1-3} are the parameters describing the effect of the observation days WeaningDay and WeanD1 in relation to the reference (WeanD6; index *i*). DAY_i is indicator functions (implying that these sum to 0 (if DAY is WeanD6). *WeaningAge* (index *j*) describes the binary effect of weaning D24 or D35. *SupFeed* (index *n*) describes the binary effect of access to supplemental feed pre-weaning or not. *PigsWeanerPen* (index m) describes the continuous effect of the number of pigs in the weaner pen. ϑ is a normal distributed random effect to account for the repeated measures within piglet with an autoregressive correlation structure of order 1 (AR(1)) among the 8 days (index *o*), and ε (index ijnm) refers to the normal distributed residual error.

In models **M1-5,** sow was set as random effect to account for piglets in the same litter but could not be estimated in **M2ab** or in **M4b**. In **M1-M4**, differences are presented as rate ratios per piglet per h (RR) with 95% confidence interval (CI). In **S1**, the results are given as hazard rate ratios (HRR) and corresponding 95% CI. In **M5,** the LSMEANS ± SE are presented. A significant level of $p < 0.05\%$ was chosen, and $p < 0.1$ was considered a trend. The models were performed in SAS 9.4 (SAS Inst., Inc., Cary, NC, USA), except the survival analysis that was carried out in R 3.4.3.

3. Results

3.1. Supplemental feed pre-weaning

The amount of supplemented feed in the +SupFeed groups was recorded at litter level. When averaged according to the litter size on day 12, the amount of milk replacer supplied was 274 ± 110 g/piglet from days 1-12 (~25 g/piglet/day). For the piglets in the WeaningAge D24 group, an average of 709 ± 485 g of dry weight of the liquid feed per piglet was supplied from days 12-24 (~60 g/piglet/day), and for those in the WeaningAge D35 group it was 2251 ± 1422 g of dry weight per piglet from days 12-35 (~100 g/piglet/day). In the +SupFeed and both WeaningAge groups, the percentage of piglets observed ingesting supplemental feed was 98% on day 11 (milk replacer), 93% on day 12 (liquid feed from 08.00 h), 87% on day 13 (liquid feed) ($N = 126$) and 63% on the day before weaning (D24: 40%, D35: 75%, $N = 78$). Of the piglets ingesting supplemental feed the DayBeforeWeaning, all piglets except one also ate at least once on days 11, 12 and 13. The mean ± SD of number of bouts per piglet/12 h per treatment can be seen in Table 3. Across days 11, 12 and 13, the mean was 9.1 ± 7.4 eating bouts per 12 h/piglet.

The number of bouts of ingesting supplemental feed pre-weaning per piglet (M1) was higher on day 11 compared to days 12 and 13, which did not differ from each other ($F_{2,\,411} = 6.39, p < 0.01$, RR in Table 4). There was no effect of BiW or LitterSize on the bouts of ingesting supplemental feed ($p > 0.1$) on any of the observed days.

The rate of ingesting supplemental feed per piglet on the DayBeforeWeaning was 1.2-fold higher when the suckling success on the DayBeforeWeaning decreased by one event of milk letdown (RR = 1.2, $F_{1,71} = 8.62$, $p = 0.01$, CI: [1.07; 1.42]) (**M2a**). WeaningAge and WeaningLitterSize had no effect on the rate of ingestion ($p > 0.1$). Within WeaningAge D35 (**M2b**), increasing WeaningWeight tended to lower the rate of ingesting supplemental feed per piglet DayBeforeWeaning ($p = 0.06$).

Table 3
The raw mean ± SD of supplemental feed ingestion and suckling success pre-weaning and eating and drinking bouts post-weaning per piglet.

Item	Supplemental feed -SupFeed	+SupFeed	WeaningAge D24	D35
Supplemental feed, bouts/piglet/12 h				
D11	-	10.8 ± 8.3[a]	-	-
D12	-	8.8 ± 8.3[b]	-	-
D13	-	8.2 ± 9.2[b]	-	-
DayBeforeWeaning	-	3.7 ± 6.2	2.8 ± 3.4	4.4 ± 5.5
Suckling success, %/piglet				
DayBeforeWeaning	96.0 ± 6.6	83.4 ± 20.3	91.5 ± 12.2	88.7 ± 18.9
Solid feed, bouts/piglet/12 h				
WeaningDay	6.5 ± 12.1	6.8 ± 15.2	0.8 ± 3.5[a]	22.8 ± 18.0[b]
Water, bouts/piglet/12 h				
WeaningDay	2.8 ± 4.2	2.4 ± 3.6	1.2 ± 2.2[a]	6.0 ± 5.0[b]
Solid feed, % scans/piglet				
WeanD1	6.3 ± 6.0	0.1± 0.8	1.8 ± 1.8[a]	14.5 ± 6.7[b]
WeanD6	13.3 ± 7.1	15.7 ± 8.9	12.5 ± 5.7[a]	15.7 ± 9.1[b]

[a,b] designate significant difference in the statistical analysis.
D11, D12 and D13 refer to days 11, 12 or 13 after birth and pre-weaning.
DayBeforeWeaning refers to 24 to 12 h before weaning on either day 23 or 34 after birth, depending on treatment.
WeaningDay refers to 0 to 12 h after the piglets were moved from the farrowing facility into a weaner pen on either day 24 or 35 after birth.
WeanD1 refers to the day after weaning (24 to 36 h after moving to a weaner pen) on either day 25 or 36 after birth.
WeanD6 refers to 6 days after weaning on either day 30 or 41 after birth.
+SupFeed refers to the treatment with access to supplemental feed from day 2 after birth to weaning.
-SupFeed refers to the treatment without access to supplemental feed.
D24 refers to the treatment with weaning on day 24 after birth.
D35 refers to the treatment with weaning on day 35 after birth.

Table 4
Rate ratio (RR) for piglet bouts of ingesting supplemental feed dependent on days 11, 12 and 13 after birth. The supplemental feed was changed from milk replacer to liquid feed on day 12 at 08.00 h.

Variables	Levels ($N = 522$ piglets)	RR	95% CI	*p*
Day	11 vs 13	1.5	1.19; 1.89	< 0.01
	12 vs 13	1.2	0.96; 1.50	
	11 vs 12	1.3	1.03; 1.51	

RR = rate ratio, CI = confidence intervals.
RR for each variable (and level) with corresponding 95% CI and P-values are presented for the overall effect of each variable.

3.2. Eating and drinking behaviour on the day of weaning

On WeaningDay across all treatments, 65% of the piglets did not have an eating observation (i.e. 35% did eat). Five percent was observed eating only once within 12 h while 30% ate at least twice. For the piglets that did eat within 12 h, the mean latency was 3 h (0 h-11 h). Furthermore, 45% of the piglets did not drink water within 12 h, but for those who did drink water the mean latency was 4 h (1 min-11h). The mean bouts of eating per piglet across all treatments was 6.6 ± 13.8 bouts/12 h (median: 0, range: 0-60), and of drinking water it was 2.6 ± 3.8 bouts/12 h (median: 0, range: 0-30). The mean per treatment can be seen in Table 3. The latency to eat on WeaningDay was 3.3-fold shorter in the WeaningAge D35 group compared to the D24 group (HRR = 3.3, CI: [2.01; 5.30]: $p < 0.01$) (Fig. 2B). Also +SupFeed shortened the latency to eat on the WeaningDay by 2.1-fold compared to -SupFeed (HRR = 2.1, CI: [1.26; 3.65]: $p < 0.01$, Fig. 2A). With higher number PigsWeanerPen, the latency increased by 1.3-fold (HRR = 1.3, $p < 0.01$, CI: [1.05; 1.54]). The latency to drink water was also shorter with WeaningAge D35 (HRR = 1.8, CI: [1.05; 2.96]: $p > 0.01$) while +SupFeed increased the latency to drink by 2.1-fold (HRR = 2.1, CI: [1.44; 3.19]: $p < 0.01$), and a higher number PigsWeanerPen shortened the latency (HRR = 1.4, CI: [1.21; 1.68]: $p < 0.01$). Within WeaningAge, there was no effect of WeaningWeight on the latency to eat or drink ($p > 0.1$). Within +SupFeed, a higher number of bouts per piglet of eating supplemental feed the DayBeforeWeaning slightly shortened the latency to eat on WeaningDay (RR = 1.1, $p < 0.01$, CI: [1.01; 1.10]).

The number of bouts of eating and drinking per pig on WeaningDay (**M3a**) was higher with WeaningAge D35 compared to D24 (Eating: RR = 10.9, $F_{1,149} = 7.74$, $p < 0.01$, CI: [2.00; 59.5]; Drinking RR = 6.9, $F_{1,147} = 4.17$, $p = 0.04$, CI: [1.07; 45.2]). There was no effect of SupFeed ($p > 0.1$). With increasing number of pigs in the weaning pen, the frequency of eating decreased (RR = 3.2 for every increase of one pig, $F_{1.149} = 12.9$, $p > 0.01$), but did not affect drinking ($p > 0.1$). Within WeaningAge D35 (**M3b**), lower WeaningWeight slightly increased eating and drinking (Eating: RR = 1.03, $F_{1,38} = 4.48$, $p = 0.04$, CI: [1.01; 1.05]; Drinking: RR = 1.02, $F_{1,38} = 5.08$, $p = 0.03$, CI: [1.01; 1.04]). Contrarily, within WeaningAge D24 (**M3b**), WeaningWeight did neither affect eating nor drinking ($p > 0.1$). In addition, within +SupFeed, there was no effect of the mean number of bouts of ingesting supplemental feed across days 11, 12 and 13 ($p > 0.1$, **M3b**) or on the DayBeforeWeaning on eating or drinking bouts on the WeaningDay ($p > 0.1$, **M3c**).

3.3. Eating days 1 and 6 after weaning

On WeanD1 ($N = 93$ piglets) across all treatments, 48% of the piglets had no eating bouts. The median was eating in 1.4% of the scans. On WeanD6 ($N = 147$ piglets) and across all treatments, only 2% of the pigs had no eating bouts. The median was eating in 10.0% of the scans.

The log-transformed percentage of scans with eating bouts per piglet on WeanD1 and on WeanD6 was higher in the WeaningAge D35 group compared to the D24 group (**M4ab**) (WeanD1: $F_{1,89.9} = 59.03$, $p < 0.01$,

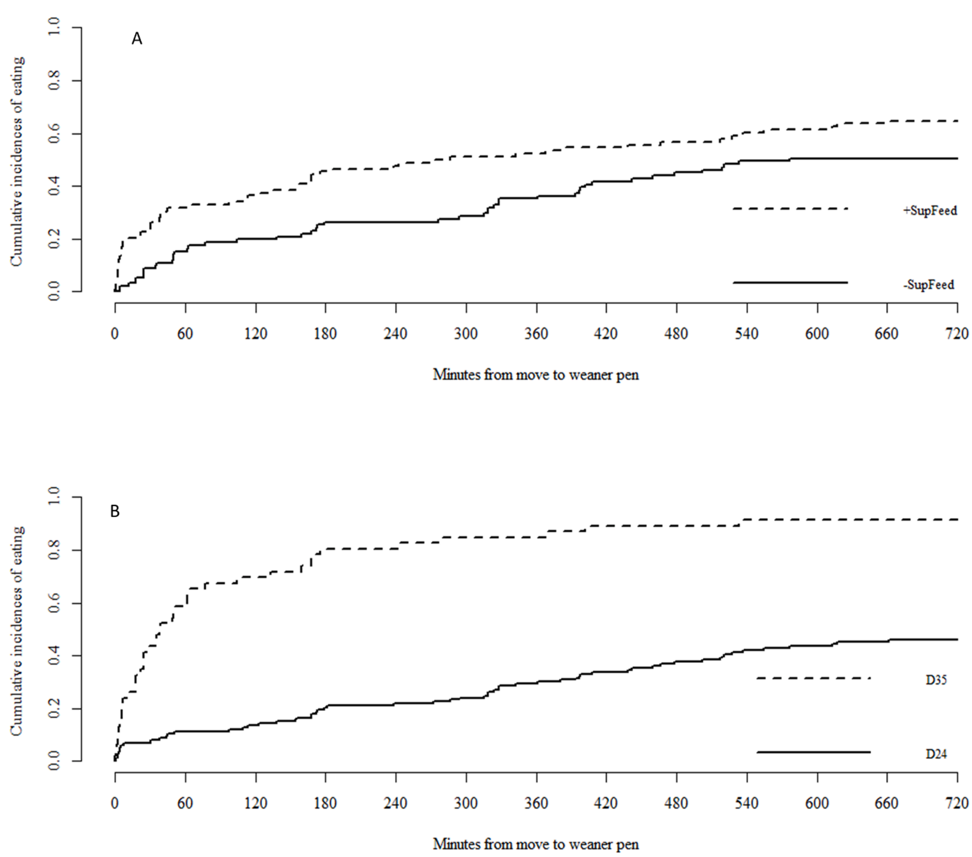

Fig. 2. Cumulative incidence plot of first eating observation after being moved to the weaner pen of piglets A) with or without access to supplemental feed pre-weaning and B) weaned at age 24 or 35 days. Each small jump in the graph indicates an incidence of an eating bout.

WeanD6: $F_{1,143} = 4.68$, $p = 0.03$, raw means ± SD in Table 3). The percentage of scans with eating bouts per piglet on WeanD1 and WeanD6 was neither affected by SupFeed ($p < 0.1$) nor by the mean number of bouts of ingesting supplemental feed across days 11, 12 and 13 ($p < 0.1$).

The daily amount of feed consumed per pen increased with days after weaning ($F_{7,64.4} = 19.03$, $p < 0.01$, 0.7 kg/day for every one increase in pigs in the pen) (**M5**). The amount was also affected by WeaningAge, with later weaning increasing the amount ($F_{1,10.4} = 28.81$, $p < 0.01$, mean ± SD on D35: 8.5 ± 0.7 kg/pen/day, on WeanD24: 2.2 ± 0.7 kg/pen/day). With every increase in the number of pigs in the weaner pen by one, the amount of feed consumed tended to increase with 0.7 kg/day ($p = 0.06$). There was no effect of SupFeed on the amount consumed ($p > 0.1$).

4. Discussion

The aim of the present study was to investigate piglet eating behaviour of automatically provided supplemental milk/feed in the farrowing pen when it transitioned from milk replacer to liquid feed and to study how eating pre-weaning and weaning age affected the latency and bouts of eating and drinking water post-weaning.

4.1. Supplemental feed pre-weaning

The study's hypotheses were that the transition from milk replacer to liquid feed during lactation at day 12 of age would decrease the bouts per piglet of ingesting supplemental feed while more bouts of ingesting supplemental feed pre-weaning would be associated with 1) larger piglets 2) later weaning and 3) fewer successful suckling events the day before weaning. The effect of changing the milk replacer and lower suckling success was supported, but not the effect of weight and later weaning day.

In the present study, almost all piglets (98%) ingested milk replacer at least once on day 11 compared to 59% on day 7 in Kobek-Kjeldager et al. (2020b), who used the same milk replacer as in the current study. This difference can likely be attributed to the different automatic milk supplier and different trough designs used in the two studies. In the present study, the trough was larger, so several piglets could access it at the same time. When providing creep feed, more feeder spaces result in greater feed consumption and longer feeding time (Appleby et al., 1991, 1992), and the same may be the case here. In the present study, the milk supplier was also automatically refilled and made a distinct sound when it did so, whereas in the study by Kobek-Kjeldager et al. (2020a) piglets had to press a vertical tap to release milk replacer. From the video observations and personal observations in the barn of the present study, it was very clear that the piglets learned that the sound meant release of supplemental feed. When the trough was filled, it was often observed that a handful of piglets ran to the trough and ate until it was empty. This resulted in the trough being empty until next filling where the piglets showed the same learned behaviour. Thus, although the automatic supplier was set to refill with the highest frequency to result in the supplemental feed being available at all times, this was not the case in practice. That the automatic supplier was repeatedly emptied resulted in piglets not being able to consume the amount they were motivated for, likely underestimating the ingestion bouts per piglet in this study. Nevertheless, a sequential automatic release of supplemental feed associated with a sound is closer to the nursing behaviour of piglets where the sow calls in the entire litter with a milk grunt every 45-60 min (Brooks and Burke, 1998). A sequential automatic release seems to make it easier for the piglets to learn compared to the milk cup system in Kobek-Kjeldager et al. (2020a) where each piglet needed to learn to activate the cup, and several piglets could not drink at the same time.

Piglets' ingestion of supplementary nutrition decreased in the transition from a milk-based to a cereal-based supplemental feed, which was also suggested by previous results (Kobek-Kjeldager et al., 2020a, b). In that study, the cereal-based supplement from day 12 still contained whey (milk by-product) and had a lower crude fibre content than the liquid feed in the present study. A higher milk and lower fibre content is expected to be more attractive to piglets as it is more similar to sow milk and requires less gut development to digest (Jensen, 1998). Yet, comparison of piglet preferences between the two studies should be done with caution due to some significant differences in the experimental setup (for example in the automatic milk supplier system). Piglet preferences for supplemental liquid feed (e.g. fibre content, aromas, heated vs. non-heated) should rather be investigated in a separate study. Nevertheless, both studies indicate that piglets are less interested in cereal-based compared to milk-based supplements, at least during the period days 11-13 of age.

The birth weight of the piglets did not affect whether the piglets ingested supplemental feed on days 11, 12 and 13, but higher weaning weight on day 35 tended to decrease the eating bouts per piglet the day before weaning. This is contrary to Kobek-Kjeldager et al. (2020a), who found that the larger piglets were more likely to ingest supplemental feed. The lack of a weight effect in the present study may be explained by a better trough design that mediate eating by social facilitation, resulting in the majority of piglets ingesting supplemental feed. The weight effect may also have been removed by a slightly higher birth weight and less weight variation in the present study due to the smallest piglets being excluded if the litter size exceeded 15 piglets on day 2 (piglets up to 1.8 kg removed in the present study compared to 700 g in the former study).

Kobek-Kjeldager et al. (2020a) showed that most piglets drinking milk replacer did it in addition to suckling, which contrasts the results of the present study showing that piglets with lower suckling success had more bouts of ingesting supplemental feed. Moreover, the present study found a numerical lower suckling success and larger variation in the +SupFeed (+SupFeed 83.4 ± 20.3 vs -SupFeed 96.0 ± 6.6). Comparison between the two studies should be made with some caution due to differences in the sampling methods (count data in the present study vs categories from count data in Kobek-Kjeldager et al. (2020a)). The present results indicate that piglets weaned at a later age can ingest supplemental feed as a replacement to suckling, which may relate to a more accessible supplemental feed supplier compared to the study of Kobek-Kjeldager et al. (2020a) as explained above.

The percentage of piglets that ingested supplemental feed numerically decreased from days 11-13 (87-98%) to the day before weaning (D24: 40%, D35: 75%). However, this numerical difference should also be interpreted with caution, as the number of piglets included was lower on the day before weaning due to missing video recordings. Furthermore, without a control group that did not change supplemental feed on day 12, it cannot be ruled out that the lower percentage of piglets on day 23 is a lack of interest in liquid feed that reappears by increasing the age to 34 days.

4.2. Eating and drinking water after weaning

The second hypothesis of this study was that access to supplemental feed in the farrowing pen and/or later weaning would result in a shorter latency to first eating and drinking bout as well as result in more bouts. Later weaning age was the main factor in the present study, making piglets more likely to eat and drink post-weaning and with a shorter latency. Access to supplemental feed in the farrowing pen and ingestion of supplemental feed did not lead to a higher eating or drinking frequency per piglet on any of the observation days or on the total amount of feed consumed per pen in the first week after weaning. The present study could, however, confirm that access to supplemental feed pre-weaning and piglets eating more the day before weaning shortened the latency to first eating observation post-weaning, supporting findings by Bruininx et al. (2002) using solid creep feed. However, access to supplemental milk/feed surprisingly increased the latency to drink water in the present study. In addition, more than half of the piglets did not eat within 12 h after weaning, also in line with previous results

(Bruininx et al., 2001; Bruininx et al., 2002). It has previously been reported that providing supplemental cow milk before weaning, result in a higher post-weaning feed intake (Funderburke and Seerley, 1990). A higher intake post weaning was also achieved by continuing providing supplemental milk replacer post-weaning (Dunshea et al., 1999). In the present study, the same feed was provided pre- and post-weaning: in liquid form pre-weaning and dry meal form post-weaning. Although a greater proportion of pigs ingested the supplemental milk/feed pre-weaning compared to the highly variable intake seen with creep feeding (Pajor et al., 1991; Bruininx et al., 2002; Collins et al., 2013; Heo et al., 2018), showing promise for this strategy, the piglets still experienced a significant fasting period. The presence of multiple stressors at weaning (e.g. mixing and new environment) may explain why supplemental feed could not motivate more eating post-weaning.

The present study supports previous findings about the fact that later weaning increases eating post-weaning (Davis et al., 2006; van der Meulen et al., 2010). With increasing age, piglets may become more motivated to forage due to maturity as suggested in relation to creep feeding (Pajor et al., 1991) and/or due to their nutritional needs not being adequately covered by suckling. Although the sow's milk production peaks around day 20 (Hansen et al., 2012), it already seems to become limiting for piglet growth around day 10 (Noble et al., 2002). In addition, the sow gradually becomes more reluctant to nurse as lactation progresses (Jensen and Recén, 1989; Valros et al., 2002), increasing piglets' motivation to forage. Under semi-natural conditions, this gradual weaning process takes 9-17 weeks (Newberry and Wood-Gush, 1985; Jensen and Redbo, 1987; Stolba and Wood-Gush, 1989). Practicing later weaning in commercial settings would better take into account the natural behaviour and biology of the pigs, and the results from the current study, showing that later weaning increases eating post-weaning, support this. Yet, the effect on gut health and occurrence of diarrhoea by weaning age and supplemental feed needs to be investigated.

5. Conclusion

The results of the present study showed that the majority of piglets ingested liquid supplemental feed pre-weaning, but the ingestion bouts decreased at the transition from milk-based to cereal-based supplemental feed on day 12 of lactation. On days 23 and 34 (the day before weaning), piglets with lower suckling success had more bouts of ingesting supplemental feed. The study showed that later weaning, rather than supplemental feed pre-weaning, increased feed intake post-weaning. However, independent of treatments, piglets experienced a fasting period post-weaning. The effect on piglets' performance, gut health and diarrhoea generation needs to be investigated to evaluate the effectiveness of the proposed strategies (supplemental nutrition and/or weaning age) to reduce the post-weaning diarrhoea incidence.

CRediT authorship contribution statement

Cecilie Kobek-Kjeldager: Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Dar'ya Vodolazs'ka:** Investigation, Writing – review & editing. **Charlotte Lauridsen:** Conceptualization, Funding acquisition, Supervision. **Nuria Canibe:** Project administration, Supervision, Writing – review & editing. **Lene Juul Pedersen:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

None.

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