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ABSTRACT

Colostrum intake, which is critical for piglet survival after birth and growth up to weaning, greatly depends on piglet weight and vitality at birth. Our aim was to identify a set of biological variables explaining individual variations in colostrum intake, preweaning growth and risk of dying. Farrowing traits, morphological traits and colostrum intake were determined for 504 piglets born alive from 37 Landrace × Large White sows. A subset of 203 of these piglets was used to measure plasma neonatal concentrations of metabolites and hormones in blood collected from the umbilical cord at birth. From univariate analyses, we established that colostrum intake was positively associated with plasma neonatal concentrations of IGF-I, albumin, thyroid hormones ($P < 0.001$), and non-esterified fatty acids ($P < 0.05$), and was negatively associated with concentrations of lactate ($P < 0.001$). In a multivariable analysis, the variables explaining the variation in colostrum intake were piglet birth weight and rectal temperature 1 h after birth (positive effect, $P < 0.001$), time of birth after the onset of parturition, and fructose plasma concentrations at birth (negative effects, $P < 0.001$ and $P < 0.05$, respectively). Piglets that died within 3 days after birth had lower neonatal concentrations of albumin ($P < 0.001$), IGF-I and thyroxine ($P < 0.01$) than surviving piglets. Preweaning growth was positively associated with neonatal concentrations of IGF-I, thyroxine ($P < 0.001$), albumin and insulin ($P < 0.05$). Cortisol and glucose concentrations at birth were not related to colostrum intake, neonatal survival or preweaning growth. Multivariable analyses confirmed that colostrum intake was the predominant factor influencing piglet survival within 3 days after birth and preweaning growth. These results provide physiological indicators of piglet colostrum intake, besides birth weight. They also confirm the impact of time of birth during farrowing on colostrum intake and the crucial importance of physiological maturity at birth for postnatal adaptation.

Implications

Colostrum intake depends on piglet weight and vitality at birth. We found significant associations between colostrum intake and piglet physiological traits that are related to piglet maturity and (or) the farrowing process. Low IGF-I, low albumin and high fructose were related to poor maturity at birth, and high lactate was related to a long birth interval. Hence, these variables may characterise piglets at risk of low colostrum intake. The current findings also confirmed the crucial role of colostrum intake for piglet neonatal survival and preweaning growth. They provide indicators that can be used to estimate piglet postnatal survival and growth.

Introduction

Piglet mortality before weaning is a major welfare issue, since mortality rates of all piglets born average 15–21% worldwide and have further increased in recent years in many countries (Koketsu et al., 2021). The 3-day period after birth is critical for ensuring piglet survival. A low consumption of colostrum is the major cause of death during this period (Quesnel et al., 2012). The causes of variability in piglet colostrum intake have been extensively investigated, with a focus on the influence of piglet weight and vitality at birth, and farrowing management (induction, oxytocin administration) (Devillers et al., 2007; Declerck et al., 2017; Hasan et al., 2019). In contrast, the role of the physiological status of the piglet at birth on subsequent colostrum intake and growth needs to be further investigated. Neonatal physiological status results from the intrauterine maturation and the birth process. High plasma concentrations of albumin and IGF-I may

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be relevant indicators of advanced foetal development and maturity at birth (Herpin et al., 1993; Canario et al., 2007), whereas high concentrations of fructose may indicate a lower maturity (Pettigrew et al., 1971; Gondret et al., 2018). High plasma concentrations of lactate reflect hypoxia during delivery and are associated with lower vitality (Herpin et al., 1996; Rootwelt et al., 2012). Maturity and vitality of piglets at birth likely determine their ability to consume colostrum and adapt to their extrauterine life. The current study was undertaken to identify associations between piglet physiological traits at birth and colostrum intake. Its originality was to consider hormonal and metabolic variables associated with neonatal maturity together with variables that are related to the farrowing progress in order to address the relative importance of these two components. We also investigated the relationships between piglet physiological traits at birth, survival within 3 days after birth and growth rate up to weaning.

Material and methods

Animal management

The dataset originated from an experiment that was carried out in the experimental farm of the Chambre Régionale d'Agriculture de Bretagne (Saint-Nicolas-du-Pélem, France) and was fully described previously (Quesnel et al., 2019). From insemination until day 105 of gestation, sows were housed in two different systems. The conventional group-housing system was on a concrete slatted floor and offered 2.4 m^2 of space per gestating sow, while the enriched group-housing system was on deep straw and offered more space per sow (3.5 m^2). In each system, sows were transferred into identical farrowing rooms on a slatted floor at 105 days of gestation. Sows were confined in individual crates during the whole lactation, those were located in individual pens provided with a heating lamp.

Seven primiparous and 30 multiparous Landrace × Large White sows were inseminated with semen from Piétrain boars. Sows in both units were fed the same gestation and lactation conventional diets. Parturition of all sows was induced at 114 days of gestation by an intramuscular injection of 2 mL of cloprostenol (Planate®, MSD Santé Animale, Beaucouzé, France). Interventions during farrowing were kept to a minimum. Parturitions lasted for 201 ± 18 min and litter size averaged 15.5 ± 3.1 piglets. The original litter was kept with the sow for 24 h after the onset of farrowing (**T24**), and no care was given during this period. Beyond T24, piglets were managed according to standard procedures and males were castrated under analgesia at five days of age. Litter size was standardised to approximately 13 piglets by cross-fostering within housing groups. Piglets had free access to water and had access to creep feed from day 10 of lactation onwards. They were weaned at 28 days of age.

Data collection

All live-born piglets (279 females and 225 males) were subjected to measurements of farrowing and morphological traits, and a subset of these piglets (6–7 piglets per litter, distributed throughout the farrowing progress, n = 203) was also submitted to blood sampling for further physiological analyses. Blood samples (3 mL) were collected in heparinised (10 IU of heparin/mL) tubes from the umbilical cord at birth. They were immediately centrifuged for 10 min at 2 600*g* at 4 °C to obtain plasma. Birth order and time of birth of each piglet (stillborn and born alive) were recorded during farrowing supervision. Farrowing traits included birth order, birth interval (interval from birth of the piglet to that of the previous one) and cumulative birth interval (interval from birth of the piglet to that of the first piglet of the litter). Sex, weight, and crown-rump length were recorded at birth, and the rectal temperature of each piglet was measured 1 h after each birth. Body mass index (**BMI**, BW/length^2) and ponderal index (**PI**, BW/length^3) were calculated. Piglets were weighed again at exactly T24. Piglet BW gain between birth and T24 was used to estimate individual colostrum intake, based on the equation developed by Theil et al. (2014). Throughout lactation, the date and causes of piglet death (weakness, crushing or biting by the sow, or suffering from an anomaly such as splayleg or anaemia) were recorded (Quesnel et al., 2019).

Biological analyses

Plasma samples were analysed in duplicate within a single assay. All assays were validated for pig plasma. Plasma concentrations of fructose, glucose, non-esterified fatty acids (**NEFAs**), lactate, and albumin were determined using commercial kits (Glucose RTU and Albumin-kit from Biomérieux, Marcy l'Etoile, France; Fructose-kit from Thermo Electron, Cergy-Pontoise, France, and NEFA-HR(2) from Wako Chemicals GmbH, Neuss, Germany) and an analyzer Konelab 20i (Thermo Fisher Scientific, Courtaboeuf, France). These assays had CV less than 5%. Plasma concentrations of IGF-I were determined after an acid–ethanol extraction (Louveau and Bonneau, 1996) using the IRMA IGF-I kit (Immunotech, Prague, Czech Republic). Sensitivity of the assay was 9.26 ng/mL, and intraassay CV was 12.2% at 28 ng/mL. Concentrations of insulin were determined using a RIA kit (INSULIN-CT; IBA Molecular, Orangeburg, NY, USA). Sensitivity of the assay was 4.6 μUI/mL, and intraassay CV was 5.6%. Plasma concentrations of cortisol, total triiodothyronine (**T3**) and total thyroxine (**T4**) were determined using enzymatic immunoassays (ST AIA-PACK CORT, T3 or T4, TOSOH; Tessenderlo, Belgium). Assay sensitivities were 2 ng/mL, 20 ng/dL and 0.5 μg/dL for cortisol, T3 and T4, respectively, and the intraassay CVs were 3.1, 3.8 and 3.9%.

Statistical analyses

Analyses were done on thirty dependent variables (Table 1). Variables that were not normally distributed were transformed by natural logarithm (birth order and lactate concentrations) or square-root (birth interval and cumulative birth interval). Statistical analyses were performed using SAS (SAS Inst. Inc., Cary, NC, USA). Correlations between piglet physiological traits and birth order, cumulative birth interval and birth weight were calculated with Pearson's coefficients. Because piglet sex and sow parity were identified as factors influencing mortality and colostrum intake, respectively, female and male piglets and piglets from primiparous and multiparous sows were compared using mixed models including sex or sow parity as main factors.

To investigate indicators of colostrum intake, piglets were first categorised according to their level of colostrum intake as proposed by Quesnel et al. (2012): **Low** (less than 390 g), **Medium** (390–550 g), and **High** (more than 550 g). The classification, initially established for colostrum intakes estimated according to Devillers' model (Devillers et al., 2004), was adapted to colostrum intakes estimated by Theil's equation (Theil et al., 2014). Using the MIXED procedure, an analysis of variance was done separately for each morphological, farrowing, hormonal and metabolic piglet trait, with the level of colostrum intake (Low, Medium, and High) as main factor, and the housing system (conventional or enriched) and the sow as random factors. The system effect clustered sows within their housing system during gestation and the nested random sow effect clustered piglets within litters. Then, univariate analyses (mixed models) were performed, where colostrum intake was investigated as a quantitative outcome. These models included

Table 1
List of the traits recorded on sows and their piglets.

Items	Variables (n = 30)	Number of data
Sow and litter traits	Parity, gestation length, farrowing durationLitter size (total born or born alive), litter heterogeneity (within-litter CV of birth weight)	504
Farrowing traits	Birth order, birth interval, cumulative birth interval	504
Piglet traits at birth	Sex	504
Morphology	Birth weight, length, body mass index, ponderal index	
Rectal temperature	Rectal temperature 1 h after birth	
Physiological traits		203[1]
Plasma metabolites	Albumin, NEFA, lactate, fructose, glucose	
Plasma hormones	Cortisol, T3, T4, IGF-I, insulin	
Piglet performance after birth	BW 24 h after birth, BW gain for 24 h after birth, Colostrum intake Colostrum intake per kg of birth weight	476[2]
Piglet survival	Survival within 3 days after birth	504
Piglet growth until weaning	Average daily growth rate from birth to weaning	414[3]

Abbreviations: NEFAs = non-esterified fatty acids; T3 = triiodothyronine; T4 = thyroxine.
[1] Number of piglets submitted to blood sampling at birth.
[2] Piglets that died within 20 h of birth were excluded because their colostrum intake cannot be estimated properly.
[3] Number of piglets at weaning at 28 days.

Table 2
Correlations between piglet hormone and metabolite concentrations at birth and piglet birth order, cumulative birth interval and birth weight.

	Pearson's correlations[1] with		
Items	Birth order	Cumulative birth interval	Piglet birth weight
Birth order	–	0.76***	−0.07
Cortisol, ng/mL	0.39***	0.18*	−0.02
T3, ng/dL	−0.08	−0.02	0.30***
T4, µg/dL	0.00	0.04	0.43***
IGF-I, ng/mL	0.02	−0.01	0.63***
Albumin, g/L	−0.03	−0.10	0.57***
NEFA, µM	0.01	−0.01	0.14*
Lactate[2], mM	0.24***	0.14*	−0.23***
Fructose, mM	−0.11	−0.10	0.00
Glucose, mM	0.30***	0.20**	0.10
Insulin, µIU/mL	−0.29***	−0.12	0.09

Abbreviations: T3 = triiodothyronine; T4 = thyroxine; NEFAs = non-esterified fatty acids.
[1] Coefficient of correlation *r*.
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.

the system and the sow as random effects. Significant explanatory variables in the univariate analyses were kept in the multivariable models (after mean centring). Traits related to sow, farrowing and piglet morphology were considered in a model and piglet plasma traits in another model, these two models being then combined in a final multivariable model. Each model was described in table footnotes. Similarly, piglet average daily growth rate (**ADG**) from birth to weaning was investigated by univariate and multivariate models (mixed models).

Neonatal survival was first investigated by comparing piglets that died within 3 days after birth with those that survived. The mixed model included piglet status (dead or surviving) as main factor, and the housing system (conventional or enriched) and the sow as random factors. Secondly, the binary outcome (dead or surviving) was modelled in a multivariable model using the GLIMMIX procedure, using explanatory variables previously selected via univariate models.

Results

Correlations between piglet physiological traits, birth weight and farrowing traits

Concentrations of five out of the 10 hormones and metabolites studied were positively correlated with piglet birth weight but not with birth order or cumulative birth interval (IGF-I, albumin, T4, T3 ($P < 0.001$), and NEFA ($P < 0.05$), Table 2). Concentration of lactate was negatively correlated with birth weight. Birth order or cumulative birth interval was positively correlated with concentrations of cortisol, lactate and glucose, and birth order was negatively correlated with concentrations of insulin ($P < 0.001$). Plasma concentrations of cortisol, lactate, and glucose were positively correlated with each other ($P < 0.001$), and they were negatively correlated with insulin ($P < 0.001$, Supplementary Table S1). Fructose was not correlated with birth weight or farrowing traits.

Table 3
Morphological and farrowing traits of newborn piglets categorised according to their level of colostrum intake.

Items	Level of colostrum intake[1]			SEM	*P*-value[2]
	Low	Medium	High		
No. of piglets	177	160	139		
Colostrum intake, g/piglet	280[a]	476[b]	662[c]	7	<0.001
Colostrum intake, g/kg BW	240[a]	319[b]	364[c]	8	<0.001
Birth order[3]	9.1[a]	8.9[ab]	8.0[b]	0.4	0.019
Birth interval[3,4], min	13.2	13.0	10.1	1.6	0.388
Cumulative birth interval[3,5], min	121.8	97.4	83.6	6.9	0.071
Piglet BW at birth, kg	1.21[a]	1.54[b]	1.82[c]	0.03	<0.001
Piglet length at birth, cm	23.8[a]	25.6[b]	27.3[c]	0.4	<0.001
Piglet body mass index, kg/m^2	21.2[a]	23.7[b]	24.9[c]	0.5	<0.001
Piglet ponderal index, kg/m^3	91.1	94.3	93.4	3.8	0.429
Rectal temperature 1 h after birth, °C	36.3[a]	37.4[b]	38.0[c]	0.2	<0.001
Piglet BW at T24, kg	1.21[a]	1.64[b]	2.02[c]	0.03	<0.001
BW gain between birth and T24, g	0[a]	105[b]	203[c]	6	<0.001

Abbreviations: T24 = 24 h after the onset of farrowing.
[1] Groups of piglets that consumed a low (<390 g), medium (390–550 g) or high (>550 g) quantity of colostrum. Estimation of colostrum intake was based on the equation developed by Theil et al. (2014).
[2] Effect of the level of colostrum intake estimated in an analysis of variance including the level of colostrum intake as main factor, and the housing system and the sow as random factors; [a,b,c] within a row, means with different superscripts differed ($P < 0.05$). Data are expressed as least-squares means and the greatest SEM, except for transformed variables.
[3] Means and the greatest SEM.
[4] Time elapsed between the piglet birth and the birth of the previous piglet.
[5] Time elapsed between the piglet birth and the birth of the first piglet of the litter.

Table 4
Hormonal and metabolic traits of newborn piglets categorised according to their level of colostrum intake.

Items	Level of colostrum intake[1]			SEM	*P*-value[2]
	Low	Medium	High		
No. of piglets[3]	62	67	64		
Colostrum intake, g	292[a]	476[b]	658[c]	11	<0.001
Piglet BW at birth, kg	1.28[a]	1.54[b]	1.81[c]	0.04	<0.001
Cortisol, ng/mL	135.2	133.5	142.4	6.3	0.451
T3, ng/dL	45.3	47.1	50.0	1.8	0.105
T4, µg/dL	6.2[a]	6.6[ab]	6.9[b]	0.2	0.006
IGF-I, ng/mL	36.8[a]	44.1[b]	52.8[c]	3.1	<0.001
Albumin, g/L	8.0[a]	8.8[b]	9.3[b]	0.2	<0.001
NEFA, µM	18.7[a]	20.2[ab]	21.6[b]	1.2	0.045
Lactate, mM	5.9[a]	5.5[ab]	4.9[b]	0.5	0.041
Fructose, mM	2.5	2.6	2.2	0.2	0.079
Glucose, mM	2.9	3.0	3.3	0.2	0.133
Insulin, µIU/mL	9.6	9.4	9.9	0.5	0.545

Abbreviations: T3 = triiodothyronine; T4 = thyroxine; NEFAs = non-esterified fatty acids.
[1] Groups of piglets that consumed a low (<390 g), medium (390–550 g) or high (>550 g) quantity of colostrum. Estimation of colostrum intake was based on the equation developed by Theil et al. (2014).
[2] Effect of the level of colostrum intake estimated in an analysis of variance including the level of colostrum intake as main factor, and the housing system and the sow as random factors; [a,b,c] within a row, means with different superscripts differed ($P < 0.05$). Data are expressed as least-squares means and the greatest SEM.
[3] Included only piglets submitted to blood sampling at birth.

Piglet neonatal traits associated with colostrum intake

Piglet colostrum intake, which averaged 456 g, ranged from 56 to 1 034 g. When piglets were categorised according to the quantity of colostrum they consumed (Low, Medium, or High), the three groups of piglets differed ($P < 0.001$) in terms of birth weight and its closely correlated variables, i.e., body length, BMI, plasma concentrations of IGF-I and albumin, and rectal temperature 1 h after birth (Tables 3 and 4). Birth order and plasma concentrations of T4, NEFA, and lactate differentiated ($P < 0.05$) piglets having a low and a high consumption of colostrum, the Medium group being intermediate. Fructose concentrations tended to be lower in piglets from the High group than in piglets from the Low and Medium groups ($P = 0.069$).

When considering colostrum intake as a quantitative outcome, various indicators significantly contributed to its variation (Supplementary Table S2). Colostrum intake was influenced by sow parity ($P = 0.03$) and averaged 384 ± 55 vs 488 ± 39 g for piglets born from primiparous and multiparous sows, respectively. Colostrum intake was negatively influenced by farrowing duration ($P = 0.03$), birth order ($P = 0.002$), cumulative birth interval ($P = 0.002$) and litter size ($P = 0.002$) and positively influenced ($P < 0.001$) by piglet birth weight and rectal temperature 1 h after birth. It was not influenced by piglet sex, gestation length and birth interval ($P > 0.10$). Colostrum intake was also positively influenced by plasma concentrations of albumin, IGF-I, T4, T3 ($P < 0.001$) and NEFA ($P < 0.05$) and negatively influenced by lactate concentrations ($P < 0.001$). Concentrations of lactate and fructose also negatively contributed to variation in colostrum intake independently of the effect of birth weight (Supplementary Table S2). In the final multivariable model (Table 5), variables explaining colostrum intake were birth weight and rectal temperature at 1 h, with positive relationships ($P < 0.001$), and cumulative birth interval ($P < 0.001$) and fructose concentrations at birth ($P < 0.05$), with negative relationships (Table 5).

Table 5
Traits that significantly influenced piglet's colostrum intake, the outcome variable, in the multivariable linear mixed models.

Explanatory variables	Estimate	*F*-value	*P*-value
Model 1: Sow, farrowing and piglet traits (n = 170)[1,2]			
Intercept	−0.22		0.436
BW at birth	0.57	97.45	<0.001
Temperature 1 h after birth	0.25	24.26	<0.001
Cumulative birth interval	−0.17	11.85	<0.001
Model 2: Piglet plasma concentrations at birth (n = 170)[1,3]			
Intercept	0.03		0.800
IGF-I	0.29	23.67	<0.001
Albumin	0.22	9.45	0.002
NEFA	0.15	4.77	0.030
Insulin	0.13	4.33	0.037
Lactate	−0.13	3.65	0.058
Fructose	−0.12	3.34	0.070
The two models combined (n = 170)[1,4]			
Intercept	−0.08		0.489
BW at birth	0.55	59.73	<0.001
Cumulative birth interval	−0.17	12.06	<0.001
Temperature 1 h after birth	0.19	11.23	<0.001
Fructose	−0.13	6.47	0.012

Abbreviations: NEFAs = non-esterified fatty acids.
[1] Piglets submitted to blood sampling at birth and that survived for at least 20 h.
[2] Model 1 included sow parity, farrowing duration, number of piglets born alive, cumulative birth interval, piglet birth weight and rectal temperature at 1 h. Colostrum intake was the quantitative outcome variable.
[3] Model 2 included IGF-I, triiodothyronine, thyroxine, albumin, NEFA, insulin, lactate, and fructose.
[4] The model included variables with $P < 0.10$ in models 1 and 2.

Piglet neonatal traits associated with neonatal survival

Out of the 504 piglets born alive, 61 died within the first 3 days after birth. The causes of death were crushing or biting (54%), weakness (26%), and anomalies (splayleg and anaemia, 20%). Piglets that died were lighter and smaller at birth than surviving piglets and had a lower BMI ($P < 0.001$, Table 6). They also had a lower body temperature 1 h after birth, consumed less colostrum and generally did not gain weight during the first day after birth ($P < 0.001$). They were not differentiated from surviving piglets

Table 6
Morphological, farrowing, hormonal and metabolic traits of newborn piglets that died (Dead) or survived (Surviving) during the first 3 days after birth.

	Group			
Items	Dead	Surviving	SEM	*P*-value[1]
No. of piglets (born alive)	61	443		
Birth order[2]	8.5	8.7	0.6	0.739
Birth interval[2,3], min	11.6	12.7	1.8	0.924
Cumulative birth interval[2,4], min	105.4	103.0	11.6	0.975
Piglet BW at birth, kg	1.25	1.53	0.07	<0.001
Piglet length at birth, cm	23.8	25.6	0.6	<0.001
Piglet body mass index, kg/m^2	21.6	23.3	0.6	0.004
Piglet ponderal index, kg/m^3	92.4	92.9	3.7	0.886
Rectal temperature 1 h after birth, °C	36.0	37.2	0.3	<0.001
Piglet BW at T24, kg	1.28	1.64	0.08	<0.001
BW gain between birth and T24, g	−2	109	17	<0.001
Colostrum intake from birth to T24, g	301	484	34	<0.001
Colostrum intake from birth to T24, g/kg	218	314	14	<0.001
No. of piglets sampled	25	178		
Colostrum intake from birth to T24, g[5]	324	491	47	<0.001
Cortisol, ng/mL	128.7	137.0	8.4	0.300
T3, ng/dL	43.7	47.7	2.3	0.066
T4, µg/dL	6.1	6.6	0.2	0.009
IGF-I, ng/mL	36.9	45.1	3.4	0.006
Albumin, g/L	7.8	8.8	0.3	<0.001
NEFA, µM	18.5	20.3	1.4	0.093
Lactate[2], mM	5.9	5.4	0.8	0.439
Fructose, mM	2.4	2.4	0.2	0.775
Glucose, mM	3.0	3.0	0.2	0.960
Insulin, µIU/mL	9.5	9.6	0.5	0.688

Abbreviations: T24 = 24 h after the onset of farrowing; T3 = triiodothyronine; T4 = thyroxine; NEFAs = non-esterified fatty acids.
[1] Effect of piglet group (dead vs surviving). Data are expressed as least-squares means and the greatest SEM, except for transformed variables.
[2] Means and the greatest SEM.
[3] Time elapsed between the piglet birth and the birth of the previous piglet.
[4] Time elapsed between the piglet birth and the birth of the first piglet of the litter.
[5] Colostrum intake of the piglets sampled for plasma analyses.

by farrowing traits. Out of the 203 piglets submitted to blood sampling at birth, 25 died within the first 3 days after birth. Within this subset, piglets that died had or tended to have lower concentrations of albumin ($P < 0.001$), IGF-I, T4 ($P < 0.01$), T3 ($P < 0.10$) and NEFA ($P < 0.10$). Concentrations of cortisol, insulin, lactate, glucose, and fructose did not differ between dead and surviving piglets ($P > 0.10$, Table 6).

Results of univariate analyses are presented in Supplementary Table S3. The risk of dying was not influenced by sow parity, farrowing traits or litter size ($P > 0.10$) but was influenced by sex, with female piglets having a 45% lower risk of dying than males (odds ratio = 0.55, $P = 0.020$). This variable, however, might be biased by the fact that one male within litter was euthanised for tissue sampling and removed from the dataset (Quesnel et al., 2019). The risk of dying decreased when colostrum intake, birth weight, or rectal temperature at 1 h increased ($P < 0.001$).

The multivariable analysis was performed only on traits available for all piglets (n = 504). It did not include piglet physiological traits because the number of piglets submitted to blood sampling was too small to observe significant relationships (only 25 dead piglets vs 178 surviving). Variables kept in the multivariable model were colostrum intake, rectal temperature at 1 h, litter heterogeneity and number of piglets born alive. Colostrum intake was the only factor significantly influencing mortality incidence (estimate: −1.16, *F*-value: 33, $P < 0.001$). When birth weight was introduced in the model instead of colostrum intake, it was the only significant risk factor (estimate: −0.8, *F*-value: 14, $P < 0.001$).

Characteristics of newborn piglets according to sex

At birth, female piglets were lighter than males (1.47 ± 0.04 vs 1.54 ± 0.04 kg, $P = 0.023$) and had a lower BMI (22.7 ± 0.4 vs 23.6 ± 0.5, $P = 0.032$, n = 504). They consumed as much as colostrum as males (468 ± 21 vs 470 ± 21 g, $P = 0.910$) but their consumption relative to birth weight was greater (312 ± 9 vs 297 ± 10 g/kg, $P = 0.029$). In the subset of piglets submitted to blood sampling, females had lower plasma concentrations of NEFA and fructose than males (19.1 ± 1.0 vs 21.5 ± 1.1 μ*M* of NEFA, $P < 0.001$ and 2.3 ± 0.1 vs 2.6 ± 0.1 m*M* of fructose, $P = 0.012$). Other plasma concentrations did not differ between females and males ($P > 0.10$).

Characteristics of newborn piglets according to sow parity

Compared with piglets from multiparous sows, piglets from primiparous sows were lighter (1.28 ± 0.1 vs 1.55 ± 0.1 kg, $P = 0.005$) and smaller (23.8 ± 8.9 vs 25.8 ± 7.2 cm, $P = 0.003$; n = 504). They had a similar average BMI and PI but a lower rectal temperature 1 h after birth (36.2 ± 0.5 vs 37.2 ± 0.4 °C, $P = 0.008$). They consumed less colostrum (see above) but their consumption-to-birth weight ratio was similar compared with piglets from multiparous sows (297 ± 20 vs 308 ± 10 g/kg, $P = 0.633$). In the subset of piglets submitted to blood sampling, piglets from primiparous sows had lower plasma concentrations of IGF-I (36.5 ± 4.3 vs 45.9 ± 3.0 ng/mL, $P = 0.016$) and T4 (6.0 ± 0.4 vs 6.7 ± 0.2 μg/dL, $P = 0.028$) and greater concentrations of fructose (3.1 ± 0.3 vs 2.3 ± 0.2 m*M*, $P = 0.007$), compared with piglets from multiparous sows.

Piglet neonatal traits associated with preweaning growth

Piglet weight at weaning averaged 9.2 ± 0.1 kg and ADG from birth to weaning was 280 ± 3 g/d. Piglets from primiparous sows grew less rapidly than those from multiparous sows (257 ± 12 vs 288 ± 6 g/d, $P = 0.025$, n = 79 and 337, respectively). Birth-to-weaning ADG was not influenced by farrowing traits (Supplementary Table S4). It was negatively influenced by litter size at birth ($P < 0.001$) and positively influenced by piglet birth weight, BMI, rectal temperature 1 h after birth and colostrum intake ($P < 0.001$). It was also positively influenced by neonatal concentrations of T4 ($P = 0.006$), IGF-I ($P = 0.002$), insulin ($P = 0.014$), and albumin ($P = 0.017$). By adding birth weight in the models, only the effect of insulin concentrations remained significant ($P < 0.05$, Supplementary Table S4). Variables kept in the multivariable model were sow parity, number of piglets born alive, piglet rectal temperature at 1 h, colostrum intake and concentrations of T3, T4, IGF-I, albumin, lactate, and insulin (Table 7). Colostrum intake was the major factor influencing average daily growth ($P < 0.001$), and insulin concentration was the only other significant explanatory variable ($P < 0.05$).

Discussion

In the present study, piglet physiological traits were assessed immediately after birth by collecting umbilical blood, before suckling and before any manipulation of the piglet. The umbilical cord contains two arteries and a vein, and blood samples were most often collected from the vein whose wall is thinner. However, it cannot be excluded that some samples of blood were collected from an artery. This is not an issue since we demonstrated high correlations between arterial and venous concentrations of metabolites or hormones ($R^2 > 0.96$ for glucose, fructose, albumin and lactate, $R^2 = 0.86$ for cortisol, unpublished data from Liaubet et al.).

Factors associated with colostrum intake

Results confirmed previous reports that piglet colostrum intake increases with birth weight (Devillers et al., 2007; Declerck et al., 2017; Hasan et al., 2019). There were associations between some hormonal and metabolic traits of piglets at birth and their colostrum intake. The strongest positive associations were with IGF-I and albumin, followed by thyroid hormones, especially T4, and a lower association was observed with NEFA. These associations reflect, at least in part, the impact of birth weight on colostrum intake because concentrations of these variables were positively correlated with birth weight. Yet, these associations may also reflect a role of piglet maturity on colostrum intake. Albumin is

Table 7
Traits that significantly influenced piglets' average daily growth during lactation, the outcome variable, in the multivariable linear mixed models.

Explanatory variables	Estimate	*F*-value	*P*-value
Sow, farrowing and piglet traits (n = 150)[1,2]			
Intercept	−0.11		0.697
Colostrum intake	0.64	54.99	<0.001
Piglet plasma concentrations at birth (n = 150)[1,3]			
Intercept	−0.21		0.594
Insulin	0.26	9.15	0.003
IGF-I	0.19	5.80	0.021
Albumin	0.16	3.38	0.068
The two models combined (n = 150)[1,4]			
Intercept	−0.11		0.473
Colostrum intake	0.61	42.82	<0.001
Insulin	0.15	4.05	0.046

[1] Piglets submitted to blood sampling at birth and that survived up to weaning.
[2] Model 1 included sow parity, number of piglets born alive, piglet rectal temperature at 1 h and colostrum intake. Average daily growth from birth to weaning was the quantitative outcome variable.
[3] Model 2 included triiodothyronine, thyroxine, IGF-I, albumin, lactate, and insulin concentrations.
[4] The model included variables with $P < 0.10$ in models 1 and 2.

essential in transporting various proteins in blood and IGF-I induces mitogenesis in target tissues and is involved in the regulation of tissue and organ development (Morise et al., 2008). Within and across genotypes, both plasma IGF-I and albumin concentrations have been considered as good markers of foetal development and maturity at birth (Herpin et al., 1993; Canario et al., 2007; Gondret et al., 2018). Thyroid hormones are known to play major roles in postnatal thermogenesis and pre- and postnatal tissue development in pigs (Slebodzinski et al., 1981; Morise et al., 2008). Moreover, plasma concentrations of T4 increase in pig foetuses during the last month of gestation (Yao et al., 2017). Therefore, T4 might be one of the determinants of piglet maturity at birth. Non-esterified fatty acids can stimulate hepatic gluconeogenesis in various species and thereby participate in glucose homeostasis after birth (Xie et al., 2015). Colostrum intake was negatively associated with piglet plasma concentrations of lactate at birth. This negative association may be explained, in part, by the modest negative correlation ($r = -0.23$) between lactate concentrations and birth weight. It likely reflects piglet hypoxia at birth. Indeed, increased plasma concentrations of lactate were reported in piglets born later during farrowing as a sign of hypoxia (Herpin et al., 1996). Piglets suffering asphyxia during delivery exhibit delayed time to reach the udder and to first suckling (Herpin et al., 1996; Rootwelt et al., 2012; Langendijk et al., 2018), which is clearly detrimental for colostrum intake (Baxter et al., 2008; Declerck et al., 2017).

Among the numerous piglet and sow traits investigated in the present study, piglet birth weight was the predominant factor explaining the variation in colostrum intake. The second significant factor was cumulative birth interval, which showed a negative relation with colostrum intake. This is consistent with the negative link between lactate concentrations and colostrum intake described above and the impact of piglet hypoxia at birth. In contrast, Devillers et al. (2007) and Le Dividich et al. (2017) reported no relation between birth order and colostrum intake, this may be because sows in their studies were slightly less prolific (one or two piglets less) than in the present study. The third important determinant of colostrum intake was piglet rectal temperature 1 h after birth, which is an indicator of the ability of the piglet to recover from postdelivery hypothermia and which was positively correlated with colostrum intake in earlier studies (Le Dividich and Noblet, 1981; Baxter et al., 2008). Present findings confirm the importance of practices that can reduce the birth interval for the later born piglets, as pointed out by Gourley et al. (2020), and the importance of optimising the thermal environment of the piglets in farrowing crates.

After considering the three major factors of variation for colostrum intake (birth weight, cumulative birth interval and rectal temperature 1 h after birth), fructose remained the only plasma trait affecting this variable. Fructose is produced by the placenta and could be used as an energetic fuel during a maternal fast (Père, 2001). A low concentration of fructose has been suggested to indicate greater maturity at birth (Pettigrew et al., 1971). More recently, fructose concentrations have been shown to decrease during foetal maturation, to be lower in Meishan piglets, which are known to be more mature at birth than Large White foetuses, and to be associated with lower maturity of intestinal and adipose tissues (Yao et al., 2017; Gondret et al., 2018). Fructose can thus be considered as an indicator of piglet immaturity at birth. According to present results, fructose would be a marker that does not depend on birth weight, unlike IGF-I or albumin. Current results therefore demonstrate the importance of piglet maturity at birth and, to a lesser extent, the farrowing process for colostrum intake. The average farrowing duration in the present study was shorter than in many other studies (Oliviero et al., 2019). The farrowing process might have a stronger impact on piglet physiological status and colostrum intake in herds with longer farrowing duration. Furthermore, individual colostrum intake was dependent on sow parity. In the literature, parity effects on colostrum yield are inconsistent (Quesnel and Farmer, 2019). In the present study, primiparous sows produced less colostrum than multiparous sows but the difference was not significant (6.1 ± 0.8 vs 7.4 ± 0.4 kg, $P = 0.13$). It is likely that piglets from primiparous sows consumed less because they were smaller at birth, on average. Consistently, their colostrum intake reported per kg of birth weight did not differ from that of piglets from multiparous sows. Compared with piglets from multiparous sows, they may also have been disadvantaged by a lesser maturity at birth, as suggested by lower plasma concentrations of IGF-I and T4, greater concentrations of fructose and a more severe hypothermia after birth. Being smaller, and therefore more susceptible to heat loss, and potentially less mature, piglets from primiparous sows may thus be at greater risk of dying than piglets from multiparous sows.

Factors associated with mortality within 3 days after birth

Birth weight and colostrum intake were the two major determinant factors of neonatal survival, as previously reported (Devillers et al., 2011; Hasan et al., 2019). Piglets that died within 3 days after birth were smaller than surviving piglets but did not differ significantly with respect to birth order or cumulative birth interval. Consistently, they were differentiated by physiological traits related to piglet birth weight and maturity (albumin, IGF-I, and T4) and not by physiological traits related to farrowing. The effect of birth order on the incidence of mortality varies among studies. A greater risk of dying was reported for piglets born later in the birth order in some studies (Tuchscherer et al., 2000; Baxter et al., 2008) but not in others (Le Dividich et al., 2017).

Sex was another factor influencing the mortality rate, with male piglets being at a disadvantage. This male-biased mortality has been reported for piglets from birth to weaning (Baxter et al., 2012). Despite being heavier and having a higher BMI, male piglets showed poorer thermoregulatory ability up to 4 days after birth than female piglets (Baxter et al., 2012). In the present study, female pigs might have been favoured by their greater colostrum intake per kg of birth weight. They also had lower concentrations of fructose, suggesting a greater maturity at birth, but lower concentrations of NEFA, which might be energetically disadvantageous. Further research is needed to decipher the origins of the greater susceptibility to death of males, observed here shortly after birth.

Factors influencing preweaning growth

Present data showed that colostrum intake was the major determinant factor for preweaning growth rate. Consistently, Declerck et al. (2016) reported the importance of colostrum intake on piglet weight at weaning, and even beyond. Insulin concentrations at birth were the second influencing variable, but were much less important. Together with somatotropin and IGF-I, insulin is involved in the regulation of energy metabolism, body growth, and tissue and organ development, including maturation of the gastrointestinal tract (Morise et al., 2008). Insulin is largely provided by colostrum. Nonetheless, greater plasma concentrations of insulin at birth may be beneficial for piglet maturation before colostrum intake.

Lack of associations with glucose and cortisol concentrations

It is interesting to note that neither glucose nor cortisol were identified as good indicators of colostrum intake, survival to 3 days or preweaning growth. Glucose is an essential source of energy for

foetuses until birth. It may also positively participate in piglet maturity (Lefort et al., 2020). As for cortisol, it is essential because it stimulates foetal maturation and glycogen deposition during late gestation. Furthermore, cortisol concentrations of foetuses near term were associated with a greater ability to survive in lines genetically selected for their survivability to 10 days (Leenhouwers et al., 2002). On the other hand, glucose and cortisol concentrations are increased by the stress of birth, in response to the release of catecholamines during asphyxia (Herpin et al., 1996), which may explain their lack of relationship with postnatal performance and survival. In herds with longer farrowing duration, more piglets are likely to experience more stress at birth. In these situations, a negative correlation between glucose concentrations and colostral intake would be expected.

In conclusion, present results confirm that colostrum intake is the major determinant for piglet neonatal survival and preweaning growth. Colostrum intake by individual piglets depends on their weight and maturity at birth and on time of birth after the onset of farrowing. It was positively associated with concentrations of IGF-I, T4 and albumin and negatively associated with concentrations of lactate and fructose measured in umbilical cord blood collected at birth.

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.animal.2023.100843.

Ethics approval

The experimental protocol (no. 02805-02) was approved by the Ethics Committee in Animal Experiment of Rennes, France and by the French Ministry of Higher Education and Research.

Data and model availability statement

The data are deposited and publicly available in an official repository: https://doi.org/10.57745/P0Y5HP.

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Declaration of interest

None.

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